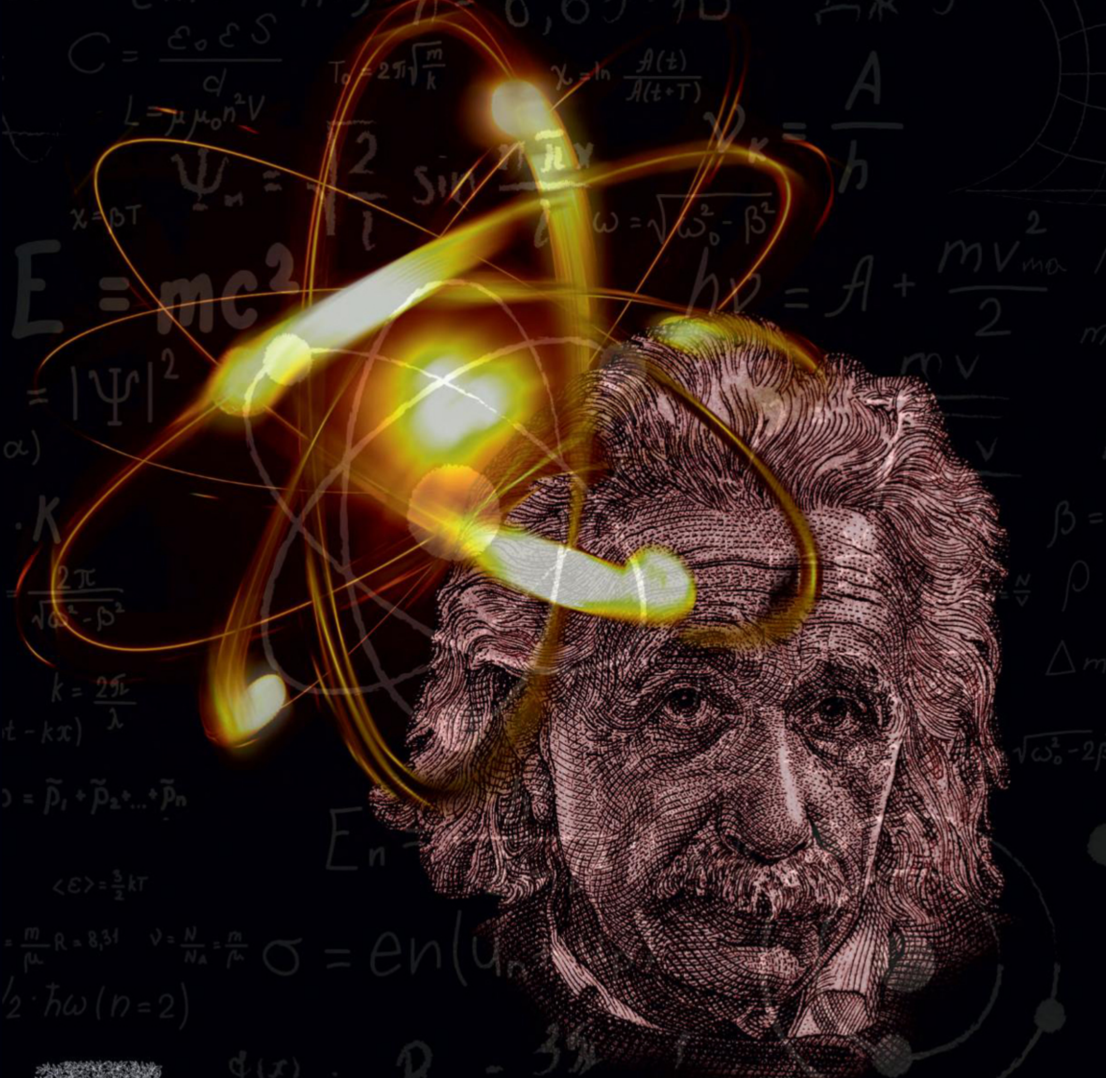
NUCLEAR RADIOACTIVE MATERIALS IN THE OIL AND GAS INDUSTRY



Khalid Al Nabhani

Faisal Khan

ELSEVIER

NUCLEAR RADIOACTIVE MATERIALS IN THE OIL AND GAS INDUSTRY

NUCLEAR RADIOACTIVE MATERIALS IN THE OIL AND GAS INDUSTRY

KHALID AL NABHANI
FAISAL KHAN

ELSEVIER

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-12-816825-7

Publisher: Susan Dennis
Acquisition Editor: Anita A. Koch
Editorial Project Manager: Devlin Person
Production Project Manager: Omer Mukthar
Cover Designer: Christian Bilbow

Typeset by SPi Global, India

Dedication

In the name of Allah, the Most Gracious, the Most Merciful, I dedicate this book to all fellow atomic energy scientists from around the world for their unlimited support, generous advice, and for exchanging information and expertise. This book presents a cutting-edge research in the sciences of nuclear and has valuable information, theories, and modern scientific approaches which form a roadmap for more sophisticated scientific discoveries and applications in the future.

I also dedicate this book to professionals, students, and those who seek to develop science and harness it for the service of mankind.

It is also a pleasure and an honor to dedicate this book to my country Oman and its faithful people, who have always been proud of me as the first Omani scientist among the world's influential and leading scientists known for their outstanding contributions to the nuclear science.

Finally, I would like to dedicate this book as an expression of my sincere appreciation, thanks, and gratitude to my beloved wife "Aisha Al Salmi" and my three lovely sons "Saif, Omar, and Sam" for their tireless support, encouragement, and sacrifice during this very hectic and challenging period of our lives. I sincerely love you all more than you will ever know.

Khalid Al Nabhani

About the Authors

Khalid Al Nabhani has been working since 2017 as a visiting professor at Centre for Risk Integrity and Safety and Engineering (C-RISE), Faculty of Engineering and Applied Science, Memorial University, Canada. He holds a PhD in Engineering from Memorial University in "Safety engineering and risk management of technologically enhanced nuclear radioactive materials in the oil and gas industry." Al Nabhani completed his Doctor of Philosophy degree with distinction in only 2.5 years. Over the last 16 years, he had held a number of managerial and leadership positions related to the engineering of oil and gas industry in the Government of the Sultanate of Oman and a number of oil and gas companies operating in Oman. Al Nabhani has been recently listed as scientist and expert in the scientists and experts' database of the International Atomic Energy Agency (IAEA) and Arab Atomic Energy Agency (AAEA). He is also a member of the American Nuclear Society under the category of experts and professionals. Al Nabhani is one of the scientists known for his outstanding contributions to science in the field of technologically enhanced nuclear radioactive materials and has published five important related scientific papers in addition to his coauthoring contribution in volume two of "Methods in Chemical Process Safety." His areas of research interest include safety engineering and risk management of technically enhanced nuclear radiological materials, the artificial intelligence role in promoting nuclear safety and security, and peaceful applications of atomic energy.

Faisal Khan is a professor and head of the Department of Process Engineering, Faculty of Engineering and Applied Science, Memorial University, Canada. He is a Professor and Canada Research Chair (Senior) of Safety and Risk Engineering. He is a founder of Centre for Risk Integrity and Safety and Engineering (C-RISE), which has over 50 research members. His areas of research interest include offshore safety and risk engineering, inherent safety, risk management, and risk-based integrity assessment and management. He is actively involved with multinational oil and gas industries on the issue of safety and asset integrity. In 2006, he has spent 8 months as risk and integrity expert with Lloyd's Register (UK) a risk management organization. He also served as a Safety and Risk Advisor to Government of Newfoundland, Canada. He continues to serve as a subject matter expert to many organizations that include Llyod's Register EMEA, SBM Modco, Intecsea, Technip, and Qatargas. During 2008–10, he visited Qatar University and Qatargas LNG Company as Process Safety and Risk Management Research Chair. During 2012–14, he served as a visiting professor of Offshore and Marine Engineering at Australian Maritime College (AMC), University of Tasmania, Australia, where he led the development of offshore safety and risk-engineering group and an initiative of global engagement with many international institutions. He is a recipient of the President Outstanding Research Award of 2012–13, CSChE National Award on Process Safety Management of 2014, President Outstanding Research Supervision Award of 2013–14, and recently Society of Petroleum Engineer award for his contribution in Health, Safety, and Risk Engineering. He has authored over 400 research articles in peer-reviewed journals and conferences on safety, risk, and reliability engineering. He has authored five books on the subject area. He is an editor to the Journal of Process Safety and Environmental Protection, Process Safety Progress, and ASME Part A (Risk and Uncertainty Analysis). He regularly offers training program/workshop on safety and risk engineering in different places including St John's, Chennai, Dubai, Beijing, Aberdeen, Cape Town, Doha, and Kuala Lumpur.

Preface

It is critical to realize that technologically enhanced naturally occurring nuclear radioactive materials (TENORM) exposure is truly a global issue due to the global distribution of reserves. In all, 30 years worth of research has shown that there is inadequate awareness in the oil and gas industry worldwide about the issue of worker protection from TENORM, and about the proper disposal of radioactive wastes into the environment. According to the available data, the scientists and experts fear that critical clusters in the workforce of the oil and gas industry, as well as the general public, are at risk of being exposed to different levels of radiation doses; these doses range from low to extremely high levels of radiation under adverse conditions. Such doses often exceed the currently acceptable occupational exposure limits for workers exposed to these materials. However, according to the medical epidemiological and laboratory data, even low doses of exposure can pose the same threat as that of high doses exposure to radiation and eventually increase the chance of developing cancerous diseases.

Moreover, in the light of daily huge global production of oil and gas to satisfy the growing demands worldwide, this has led to increasing the volume of generated TENORM wastes that pose a serious threat to the environment and to the public. However, for economic and political reasons, this industry has been reluctant to admit that its employees involved in their activities have the greatest possibility of being exposed to radiological risks, or to make public aware of their policies regarding radioactive material waste disposal methods in which wastes are disposed directly into the environment, which poses serious health, safety, and environmental risks.

Accordingly, it is clear that there is an urgent need for the development of a detailed scientific approach enhancing awareness, to regulate and manage TENORM issues in the oil and gas industry. In this respect, this book will provide, based on theoretical and practical perspectives, an integrated framework to promote understanding and safety awareness regarding radiological issues in the oil and gas industry that is considered as one of the leading industrial sectors in the world.

Therefore, this book thoroughly investigates, identifies, and attempts to bridge current knowledge and technology gaps associated with the presence of TENORM in the oil and gas industry. Three main gaps have been identified from the available studies that will be addressed in this study and they are: (1) workers in the oil and gas industry face a great risk of being exposed to various levels of radioactivity throughout the oil and gas extraction and production life cycles; (2) high volumes of TENORM waste are generated daily from the petroleum industry that is disposed of directly into the environment and has become a serious concern as another source of radiation exposure to workers, the general public, and the environment; and (3) the lack of a uniform international safety standard, inconsistencies, and conflicts in existing regulations and legislation designed to manage TENORM risks in the oil and gas industry, and the inability of these measures to provide enough protection for the workers, general public, and the environment.

I believe this book is a unique book with unique features that combines valuable academic resources that can be taught in many universities around the world for graduate and undergraduate students or used as a research reference for many researchers, scientists, because it discusses all issues related to TENORM in the oil and gas industry based on the method of combining the theoretical approaches and practical experience, which have been supported and proven by the scientific facts and theories that have never been discussed before and were first disclosed in this book. It can also be used as a standard reference for the professionals, oil and gas industry, nuclear industry, and regulation bodies because it is considered to be the first scientific book dedicated to TENORM safety to provide a comprehensive and well-researched framework starting with fundamental concepts, problem identification, and solutions development supported with quantitative risk analysis and dynamic accident modeling related to radiation protection and radioactive waste management with a closer scientific look into available regulations and guidelines to examine and analyse their efficiency and reliability in providing enough protection to workers, the general public, and the environment against radiological risks in the oil and gas industry.

In the end, successfully completing many aspects of this work would not have been possible without the generous scientific and intellectual contributions by my fellow scientists from around the world. I would also like to take this opportunity to thank Memorial University for granting me the time and facilities to work on this book. Gratitude and appreciation are extended to Professor Faisal Khan who is one of the world's influential and leading scientists known for his landmark contributions to science for his great effort and outstanding contribution in joining me on the journey of writing this

book. Tremendous gratitude and thanks are due to all MUN and C-RISE academics and professionals who offered me continued support that allowed me to overcome challenges and obstacles with determination and enthusiasm.

I am also truly indebted to my beloved wife Aisha Al Salmi and my three lovely sons (Saif, Omar, and Sam) for their tireless support, encouragement, and sacrifice during this very hectic and challenging period.

Khalid Al Nabhani

List of Acronyms, Symbols, and Units

ACIR	Advisory Commission on Intergovernmental Relations
AD	Anno Domini
AEC	Atomic Energy Commission
AER	Alberta Energy Regulator
ALARP	As low as reasonably practicable
AML	Acute myeloid leukemia
Al	Aluminum
API	American Petroleum Institute
APPEA	Australian Petroleum Production & Exploration Association Limited
Ba	Barium
$BaSO_4$	Barium sulfate
bbl	Barrel
BC	Before Christ
BCE	Before Common Era and Before Christ Era
BEIR	Committee on the Biological Effects of Ionizing Radiation
BHA	Bottom hole assemblies
BRF	Branching factor
BOP	Blowout preventer
BSS	Basic safety standards
Ca	Calcium
CaC_2	Calcium carbide
$CaCO_3$	Calcium carbonate
CARBOLOG	Carbon organic LOG
CBL	Cement bond log
CEPN	Centre d'étude sur l'évaluation de la protection dans le domaine nucléaire
C_2H_2	Acetylene
Ck	Consequences, e.g., [(C2), mishap (C3), incident (C4) accident (C5), and catastrophe (C6)]
C-NLOPB	Canada-Newfoundland and Labrador Offshore Petroleum Board
CNSC	Canadian Nuclear Safety Commission
CNSOPB	Canada-Nova Scotia Offshore Petroleum Board
CO	Carbon monoxide
CO_2	Carbon dioxide
CRCPD	Conference of Radiation Control Program Directors
C-RISE	Centre for Risk, Integrity, and Safety Engineering (Memorial University)
DCF	Dose Conversion Factor
DCRLs	Derived Consideration Reference Levels
DNA	Deoxyribonucleic acid
DOE	Department of Energy
DPB	Dispersion prevention barrier
E&P	Exploration and production

ED	Exposure duration
EDSPB	Early detection safety prevention barrier
Eh	Activity of electrons
EIA	Energy Information Administration
EMSPB	Emergency Management Safety Prevention Barrier
ENOR	Enhanced naturally occurring
EORT	Enhanced oil recovery technologies
EPEA	Environmental Protection and Enhancement Act
ESP	Electric submersible pump
ESAA	Environmental Services Association of Alberta
ETA	Event tree analysis
ETF	Environmental transport factor
EURATOM	European Atomic Energy Community
Fe	Iron
FPSO	Floating production, storage and offloading
FPS	Floating production system
H_2	Deuterium
H_3	Tritium
He	Helium
HPWJ	High-pressure water jetting
HSE	Health, safety, and environment
H_2O	Water
H_2O_2	Hydrogen peroxide
H_2S	Hydrogen sulfide
HAZAN	Hazards analysis
HAZID	Hazard identification
HAZOP	Hazards and operability
HEMP	Hazard and effects management process
HDPE	High-density poly-ethylene
HINAR	High natural radioactivity
IAEA	International Atomic Energy Agency
IAEA-TECDOC	IAEA Technical Documents
IOGP/IAOGP	International Association of Oil and Gas Producers
ICRP	International Commission for Radiological Protection
IISPB	Isolation integrity safety prevention barrier
ISR	In situ recovery
JSP	Job safety plan
LCM	Lost circulation material
LNG	Liquid natural gas
LNT	Linear nonthreshold
LOM	Level of organic maturity
LOT	Leak off test
LPPE	Leaded personal protective equipment
MEA	Multilateral environmental agreements
MD	Measured depth
Mg	Magnesium
M&OSPB	Management & Organization Safety Prevention Barrier

N	Neutron
NARM	Naturally accelerator produced radioactive materials
NAS	National Academy of Science
$\mathbf{N_{c,k}}$	Number of abnormal events of consequence
NaCl	Sodium chloride
NCRP	National Council on Radiation Protection and Measurements
NDDOH	North Dakota Department of Health Division
NEB	National Energy Board
$\mathbf{NO_2}$	Nitrogen dioxide
NOC	National Oil Companies
NOR	Naturally occurring radionuclides
NORM	Naturally occurring nuclear radioactive materials
NRC	Nuclear Regulatory Commission
NRPB	National Radiological Protection Board
NSCA	Nuclear Safety and Control Act
OPL	Oil Prospecting License
ORP	Oxidation reduction potential
P(Ck)	Consequences occurrence probability
PDC	Polycrystalline diamond compact
P(Xi)	Failure probability
Pb	Lead
PBUH	Peace be upon him
PFN	Prompt fission neutrons
pH	Activity of hydrogen ions
PJSM	Prejob safety meeting
Po	Polonium
PNS	Postnormal science
PP	Precautionary principles
PPE	Personal protection equipment
PPE&EDSPB	Personal protection equipment and exposure duration safety prevention barrier
QRA	Quantitative risk assessment
R	Resistivity
Ra	Radium
RC	Risk coefficient
RESRAD	Residual radioactivity (software model)
RMN&EWS	Radiation Monitoring Network and Early Warning System
RPB	Release prevention barrier
SF	Source factor
SGRL	Spectral gamma-ray logs
SHIPP	System hazard identification, prediction and prevention
Si	Silicon
Si(O)	Initial contaminated zone concentration of radionuclide
SMART	SHIPP Methodology and Rational Theory
$\mathbf{SO_2}$	Sulfur dioxide
SOE	State-owned companies
Sr	Strontium

$SrSO_4$	Strontium sulfate
$t+1$	Next time interval
TCP	Thermo-chemi-nuclear Conversion Plant
TCT	Thermo-chemi-nuclear Conversion Technology
TD	Total depth
TDS	Top drive system
TEDE	Total effective dose equivalent
TENORM	Technologically enhanced naturally occurring nuclear radioactive materials
TENR	Technologically enhanced natural radioactivity
Th, Th-232	Thorium
ThO_2	Thorianite
$ThSiO_2$	Thorrite
TOC	Total organic carbon content
TRA	Task risk assessment
U, U-233	Uranium
USA	United State of America
US EPA	United State Environmental Protection Agency
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UK	United Kingdom
UO_2	Uranite or uranium dioxide
$USiO_4$	Coffinite
UO_2^{2+}	Uranylion
UO_2CO_3	Uranium carbonate
WHO	The World Health Organization
Xi, SB_k	Safety barriers

Units of measure

|	Given symbols for the conditional probability
Bq	Becquerel
Bq/cm^2	Becquerel per square centimeter (s)
Bq/g	Becquerel per gram
Bq/Kg	Becquerel per kilogram
Bq/L	Becquerel per liter
Bq/mL	Becquerel per Milliliter
μ Bq	Micro-Becquerel
°C	Degree(s) Celsius
cm	Centimeter(s)
g	Gram
g/yr	Gram per year
Gy	gray
hr	Hours

kW	Kilowatt
m	meter
MeV	Mega (million) electron-volts
m/s	Meter per second
m^2	Square meter(s)
m^3	Cubic meter(s)
m^3/day	Cubic meter(s) per day
mR/hr	Milli roentgens per hour
mrem/yr	Millirem(s) per year
mSv	Milli Sievert
mSv/h	Milli Sievert per hour
mSv/yr	Milli Sievert per year
µSv/h	Micro-Sievert per hour
pCi/yr	Picocurie(s) per year
pCi/g	Picocurie(s) per gram
pCi/mL	Picocurie(s) per milliliter
ppm	Parts-per-million
risk/yr	Risk per year
Sv/yr	Sievert per year
T Bq	Tera Becquerel
T U/year	Tons of uranium per year
µ R/h	Micro-roentgens per hour

CHAPTER ONE

An overview of operational and occupational safety in onshore and offshore oil and gas extraction and production processes

Chapter outline

Nuclear Radioactive Materials in the Oil and Gas Industry
https://doi.org/10.1016/B978-0-12-816825-7.00001-7

1.1 Introduction

The coal took the lead in the energy sector in the 1950s then oil and gas have emerged to take the lead as a vital source of energy, but oil and gas are associated with a lot of challenges due to their extraction process complications as well as their physical and chemical properties. These days, the oil and gas industry is one of the largest industrial and economic sectors in the world where millions of people are working in the industry around the clock to meet the higher global demand for energy. Working in the oil and gas industry is extremely risky. Despite all the efforts made by stakeholders in the oil and gas industry to prevent accidents and eliminate the possibility of operational or occupational accidents, however, these efforts seem to be ineffective to provide enough protection to the workers, health, and the environment.

Fatal accidents, severe injuries, loss of assets, and damage to the environment are common risks associated with the extraction and production processes of oil and gas. The safety in oil and gas industry is an official and popular concern, where many of the oil and gas industries located near residential areas and have a great impact on human and the environment, which necessitates the application of the most accurate safety and security standards to ensure the safety of life and property. The fears of disasters often float and the history of the oil and gas industry has not been free of catastrophic events that have long been classified as one of the greatest historical disasters.

The oil and gas industry is facing a lot of challenges to extract and deliver oil in a safe manner; therefore, the industry and the global economic conditions require a greater focus on safety to achieve these objectives. Accordingly, safety is the basis for the success of industrial processes. Companies should realize that the success of their business is not possible without the promotion of a culture of safety, which ensures that the infrastructure is sound, and that work is conducted in a safe manner by introducing the latest scientific techniques.

The oil and gas industry has focused throughout its history on making safety its top priority. This is a good indicator to raise awareness and knowledge about safety issues while doing business. However, the industry still needs to do a lot to improve safety culture and system and one of the key things is the adoption of the scientifically based solution; quantitative and dynamic approaches for such complicated and integrated systems. Scientific studies and available statistics show that the main causes of accidents in the oil and gas industry are usually:

1. 88% human errors.
2. 10% equipment failure and workplace design.
3. 2% errors unforeseen risks.

The oil and gas industry has made great strides in strengthening occupational and operational safety measures by applying the highest safety standards, regulations, advance training, personal protective equipment, design improvement, and many other precautionary measures. However, all of these have not been able to prevent occupational or operational accidents and disasters. This could be attributed to the fact of not shedding the light on human errors and unforeseen risks that are the main factors behind the continuity of the accidents and the inability of current qualitative methodologies that are not necessarily based on scientific evaluation currently used by the industry to anticipate unforeseen risks, or to address, analyze human errors, and quantify them.

For example, if the human errors were not behind them, then the machines will either continue to work safely according to what they have been programmed or will stop due to mechanical defects, but the main danger lies in the wrong human decisions as well as the inability to predict unforeseen risks that usually end up in a disaster.

If all the incidents in the oil and gas industry, both large and small, were reviewed and investigated, the investigation reports will reveal that the main causes were human error and inability to predict the unforeseen risks. Thus, the important question is why are all the safety systems in the industry not able to prevent or reduce the frequency of accident occurrences? The simple answer is that the risk assessment methods used in their safety systems are classical and qualitative approaches and not necessarily based on the scientific evaluation to predict the risks at a very early stage.

1.2 History of hydrocarbons explorations

The first time oil is mentioned in historical writings was around 500 BC when the famous Greek historian Herodotus was known as the "Father of History" wrote of oil pits near Babylon where it was used for lighting the streets (Bacon et al., 2000). While, the first mention of humans extracting oil for a purpose came in 347 AD when the Chinese used bamboo (Groysman, 2014). In what is now modern-day Azerbaijan but back then called Baku, people used oil-rich soil and distilled oil for heating and house lighting between the 7th and 13th century, rather than wood, which was common at the time (Alakbarov, 2000). Historians believe that Baku can be considered the very first place producing oil around the world. Oil wells were dug manually near the end of the 16th century. As late as 1800, Baku was still an oil and gas pioneer.

In the west, historians believe that the first commercial oil well to be recorded in North America was dug out in Ontario in 1858 (Osif, 2016). That said, it was hand-dug. While, Wikipedia (2019) argues that the first deepest oil well was drilled near Marietta, Ohio—completely by accident. It was initially drilled in search of saltwater. It was drilled down to about 475 ft. and was able to produce one barrel of oil per week. Moreover, Colonel Edwin Drake is considered to have been the first person to use drilling pipes in the first oil-producing well in the United States. They were drilled to a depth of 18.2 m and produced about 35 barrels a day (Considine and Considine, 2013). That was in 1859, and his well near Titusville (Fig. 1.1), Pennsylvania, is considered the birthplace of modern

Fig. 1.1 Colonel Edwin at his first successful oil well in 1859 near Titusville. *(From Wikipedia, 2019. Drake Well. Available from: https://en.wikipedia.org/wiki/Drake_Well).*

Fig. 1.2 The first commercially oil-producing well in Germany, drilled in 1859. *(From Craig, J., Gerali, F., Macaulay, F., and Sorkhabi, R. (Eds). 2018. History of the European oil and gas industry. Geological Society of London, Special Publication, 465, 1–24, who sourced it from Rinehart, I. 1930. Report on the Oil Fields of Northwest Germany. Lord Baltimore Press, Baltimore, MD).*

oil drilling using drill pipes. Following this major milestone, the southern United States followed suit to help create the modern oil industry.

On the other hand, Craig et al. (2018) has mentioned that the first European wells were manually dug in Poland in 1853, Romania in 1857, Germany in 1859 (Fig. 1.2), and Italy in 1860. While the introduction of mechanical cable drilling rigs started in Europe in the early 1860s.

1.3 Philosophy of the hydrocarbon origin

The word petroleum was derived from the Ancient Greek "petra" which means the "rock" and "oleum" which means "oil" and it refers to a naturally occurring viscous liquid comprised of hydrocarbons and usually vary in color from reddish, yellowish, greenish, dark brownish to blackish depending on its composition (Demirbas, 2009). Oil is also known as "Naphtha," indicating that oil tends to be found beneath the earth's surface (Johnston, 2011). Based on the historical data, oil was primarily used for light before it was used in a different application. Oil was refined to kerosene, becoming an alternative energy source for lamps, replacing sources such as whale oil.

But exactly what makes oil useful for these purposes? According to Schobert (2013), its all about the composition of the crude oil that is almost comprised of about 82%–87% carbon by weight of carbon and about 12%–15% hydrogen by weight of hydrogen. There is also oxygen, sulfur, and nitrogen present in much smaller percentages.

Crude oil is found in underground reservoirs. It is a liquid that flows freely from porous rocks to other areas formed by nonporous rocks. These are called oil traps or bearings, and they form the reservoirs. Oil is found quite deep in the underground so that scientists often have trouble pinpointing the science behind its formation. Not knowing the oil's original environment makes it very difficult to figure out exactly what happens to create oil and make it the way it is when it is extracted. Oil can also vary greatly from one oil field to the next, and this inconsistency leads to some confusion regarding its actual origin. Accordingly, scientists don't entirely understand where oil composite comes from, or how it originates in nature. However, there are several scientific theories out there that attempt to explain how crude oil is formed. The Organic Basis Theory and Inorganic Basis Theory are the most prominent ones.

1.3.1 Organic basis theory

Many Scholars such as Simanzhenkov and Idem (2003) argue that this is a very well-known and much-propagated theory that posits that crude oil could be comprised of the remains of formerly living organisms, animals, and plants, especially of marine organisms, such as algae. The theory suggests that these remnants come together with other organisms over the course of millions of years at the bottom of the ocean, mixes with sand and minerals and then are turned into sedimentary rocks due to the high-temperature environments that are created when the earth's crust moves because of active volcanos that shape rocks into layers, which then produce organic residue chock-full of hydrogen and carbon. Such high temperatures and pressure provide a good environment for additional chemical reactions with bacterial activity to bring oxygen, sulfur, and nitrogen out of organic compounds.

1.3.2 Inorganic basis theory or what called metallic theory

Many Scholars, such as Simanzhenkov and Idem (2003) also argue that this theory contrasts greatly with the organic basis theory, hence its name. It posits that petroleum's origin is inorganic, and possesses a mineral origin stemming from exposure to deposits of metal carbides found in the ground, such as calcium carbide. Calcium carbide reacts with water composed of unsaturated hydrocarbons as per chemical reaction of the following equation:

$$CaCO_3 \rightarrow CaC_2 + H_2O \rightarrow C_2H_2(\text{Petroleum}) \quad (1.1)$$

However, carbide deposits are quite scarce. It is difficult to imagine that these deposits were ever present in any appreciably large enough quantity to form the amount of crude oil that exists in the world today. Carbides are found naturally in volcanic rocks. The Inorganic Basis Theory or the Metallic Theory argues that the release of hydrocarbon gases occurs from craters of volcanoes. One of the most prominent supporting factors of this theory is the recorded refilling of oil wells near volcanic areas, as well as newly created oil fields near similar areas. This evidence does not fit effectively with the organic basis theory, leading some proponents to follow this one.

While these two theories certainly are very popular, it must be noted that none of them managed to be proven scientifically and conclusively. The origin of crude oil is still a mystery and more scientific evidence needs to be explored to solve this mystery. This study reveals that there is a strong relationship between hydrocarbons and naturally occurring nuclear radioactive materials in which both were found in the same rocks that contain hydrocarbon. Not only that but also found that the substances responsible for forming hydrocarbons are the same as the one from uranium and naturally occurring radioactive materials. These discoveries may change the way scientists think about the natural creation of petroleum in the future.

1.3.3 Modern theory in the interpretation of the relationship between the presence of naturally occurring nuclear radioactive materials and hydrocarbons

According to the analysis of the outcomes of many scientific studies, which are in line with the geochemistry of both uranium and thorium that are the main sources of TENORM and that are found abundant in rock reservoirs that contain significant quantities of hydrocarbons, scientifically it has been proven that oil is inherent in the shale formations and derived directly from the substances that exist within the porous cavities of sedimentary and even broken sedimentary/igneous rocks up to several kilometers deep because of the volcanic reactions, whereas most of the uranium is also inherent in the shale formation and from the same organism substances.

In this context, Swanson (1960) argue that some black shales are referred to be a good potential source of both oil and uranium as they contain up to one hundred times more uranium than other common sedimentary rocks as well as contain same substances that are responsible for both of oil and uranium. The substances responsible for both oil and uranium are two types of organic substances; the first type called sapropelic organism substances, which generally yield 4 or 5-times oil more than the humic organism substances, which are the second type that creates a reducing and acidic environment and responsible for the concentrating and deposition of uranium in the black shales.

This rigorous scientific interpretation may make the world rethink its old theories related to the origins of oil. Therefore, shale is considered a radioactive formation of different radioactivity concentration.

1.4 Oil and gas industry structure

The world has witnessed an increase in the production of hydrocarbons over the past few years to meet the increase in the globally demanded energy. The oil and gas industry consists of three different streams through which the extraction and production of oil and gas (Samuel Hsu and Robinson, 2017). These streams are illustrated in Fig. 1.3 and are:

1. *Upstream activities*, also known as the exploration and extraction activities. This includes the search for and recovery of crude oil and gas using seismic technology then followed by a drilling operation to extract the oil from the reservoirs.
2. *Midstream activities*, which are the process between the upstream and downstream activities and entail the gathering, separation, and transportation of crude oil and gas. This is the step in which the crude oil and gas are sent to refineries or to an export terminal to be shipped out.
3. *Downstream activities* include refineries, petrochemical plants, distribution networks, and retailers that sell the final product. Refining and marketing oil and gas make oil and gas available to customers and ready for the final use.

These three different crude oil-related activities can be handled in a variety of business models by companies. Some may be fully integrated, meaning that one company is responsible for all the three different streams at the same time. This kind of business appeared earlier in the century but has begun to disappear because companies find it easier and more cost effective to only focus on one stream rather than tackling all three. While in the modern

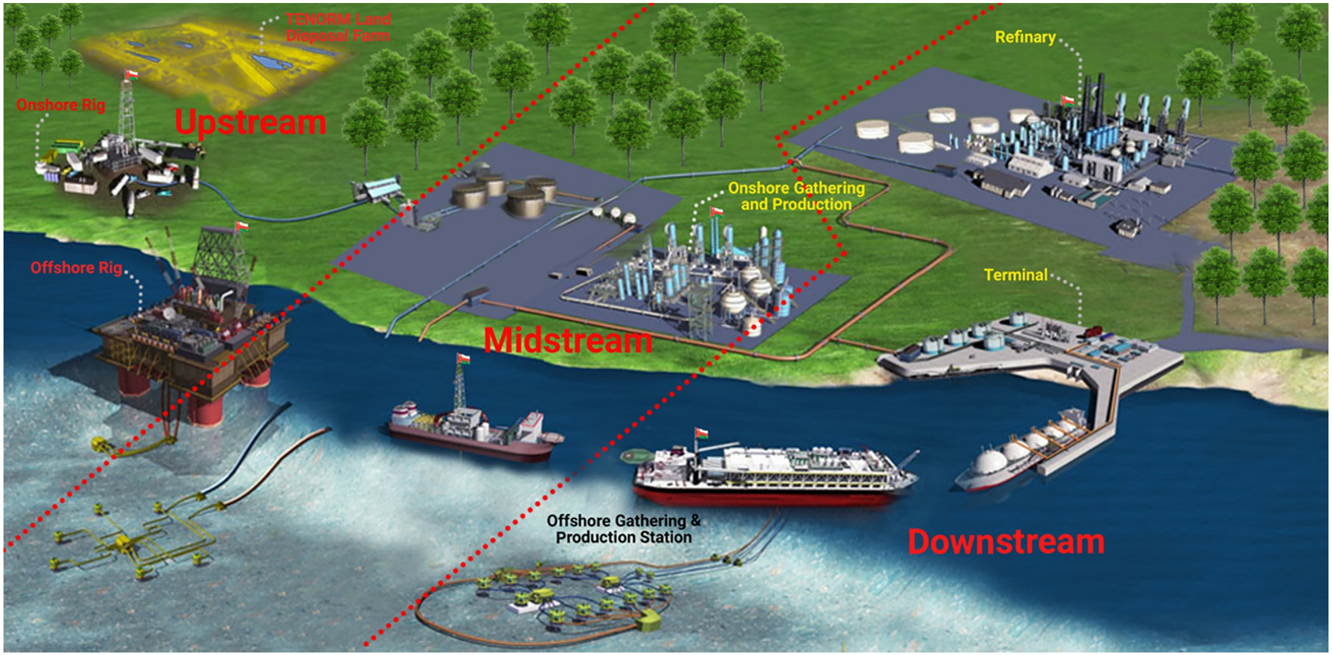


Fig. 1.3 Oil and gas industry streams.

business models, some companies find it more economical in focusing on one stream to increase production and exploration activities rather than spending their time in solving operational and technical problems. Most companies pick a sector they are more professional in, such as drilling, exploration, production, refining, or marketing, and keep developing it.

The biggest energy companies worldwide are either fully or partly owned and are operated by the government particularly in countries that rely mostly on oil for its economic and gross domestic product growth. Government-operated companies, commonly called state-owned companies (SOCs) or National Oil Companies (NOC), control about 90% of the world's oil and gas reserves and 75% of the world's crude oil production (Dorsman et al., 2018; ALNabhani et al., 2016a, 2016b). Operating companies or SOCs contract out oil and gas exploration and production related work, including drilling and exploration, to other companies referred to as contractors, who may also subcontract part of his scope of work to smaller contractors who are called subcontractors. These jobs vary in size, and therefore the companies contracted to tackle them can vary greatly in size, the scope of work, and work quality.

For example, in the upstream portion of the process, a great deal of reliance is placed on service and contracting companies providing a wide range of specialized technical services, including but not limited to: geophysical surveys, earthmoving, moving rigs, drilling, directional drilling, cementing, logging, tubing, casing, running services, perforation simulation, inspection, and many other services, all of which are required to make drilling and production operations happen. The relationship between contractors and the oil companies that utilize their services has become intrinsically linked to how both kinds of companies operate to the degree that many contractors are able to integrate into the structure and culture of the companies they work for. These operations can also become quite complicated and must be carefully regulated, as oil work can be very dangerous, depending on the specific part of the process.

1.5 An overview of oil and gas extraction and production process

1.5.1 Exploration surveying phase

According to Oil Industry International Exploration and Production Forum (1997), oil and gas exploration, extraction, and production processes are summarized as the following, the first step in the petroleum production process is the exploration surveying, this involves the search for hydrocarbon-bearing rock formations (Fig. 1.4). Geological maps are reviewed to find major sedimentary/shale basins. Aerial photography is used as a preliminary stage of exploration of a large-scale area, as experts can identify landscape formations, such as faults or anticlines that might house precious oil reservoirs. A field geological assessment details the findings in question and is often conducted by a professional geologist. Geologists in the oil and gas industry use three different survey techniques to explore oil and gas, which are: magnetic, gravimetric, and seismic (Jahn, 1998).

Assaad (2008) describes the magnetic technique based on the idea that the earth acts as a magnet. Therefore, it uses variations in the intensity of the magnetic field coming from the rocks present underground, particularly the basement and igneous rock that is relatively highly magnetic (Jahn, 1998). The gravimetric technique uses the change in the density of earth as each material has different density and characteristics and the density variation indicates rock types, saturation, fault zone, and many other geological characteristics. This method can measure a very small variation of the earth's gravity up to $\sim 10^{-6}$ g (Jahn, 1998).

On the other hand, the seismic technique is the most common assessment method used by seismologists in the oil and gas industry. This method identifies the geological structure and uses the reflective properties of sound waves and reflected time on different kinds of rock strata under the ground or at the bottom of the ocean using different types of sound wave generators (Fig. 1.4). Basically, an energy source sends a pulse of acoustic energy into the ground as a wave, traveling through the earth transmitting data back up to indicate the different geological strata.

Receivers called geophones or seismometers receive these signals above the ground. While Hydrophones are used for the underwater application

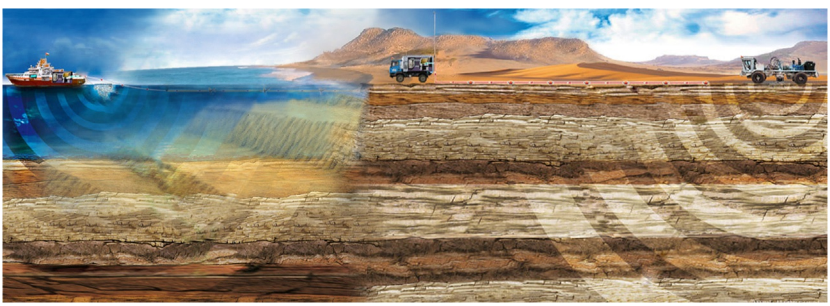


Fig. 1.4 Onshore and offshore oil and gas exploration surveying.

that can receive these returned signals. The received signals are then transmitted by cables to a mobile laboratory where seismic data are analyzed and simulated to simulate stratum characteristics to determine the rocks containing oil and gas (Song, 2015). At the laboratory, they are amplified, filtered, digitized, and recorded on magnetic tapes so they can be studied to determine if the spot in question might house an oil or gas reservoir.

1.5.2 Extraction phase

Exploration drilling

Once one of the exploration surveying techniques have identified a geological structure that could house oil and the hydrocarbons' presence, then it is a must to be confirmed physically where important information like the thickness, extensions, and the internal pressure of the potential reservoir must also be confirmed (Oil Industry International Exploration and Production Forum, 1997; Jahn, 1998). This is accomplished by drilling exploratory boreholes into what is referred to as exploration wells. Usually, the first exploration was an oil well called wildcat (Bourgoyne et al., 1986; Jahn, 1998).

The location of any drill site depends on the internal nature of the geological formation being drilled into. In the case of geological obstacles, such as mountains, ponds or any other geological obstructions that may hamper the drilling operation, a directional drilling method is used to accomplish the drilling mission away from that obstacle.

In the onshore drilling operations, when the oil is discovered at the exploration field, a team of earthmovers constructs an operation pad at the site in question to accommodate the equipment that will be used for drilling, as well as support services and living accommodations for the crews running the site. Different kinds of pads can be constructed, depending on terrain, soil conditions, seasonal constraints, well depth, rig size, and many other technical aspects.

While offshore drilling operations use self-contained Mobile Offshore Drilling Units, also known as MODUs, which can either be bottom support rigs or floating rigs. Jack-ups, semisubmersibles, and drillships are all commonly used mobile rigs for offshore drilling operations (Fig. 1.6). However, what kind of rig is used depends on the depth of the water, the condition of the seabed, and the prevailing weather at the time. Wind and waves are both taken into consideration when determining which kind of rig to use.

For the onshore drilling operations, it has been taken in to consideration the design of the drilling rigs and the associated equipment to be easily assembled and disassembled to ensure faster transfer of drilling rig equipment from one location to another, also to ensure that the completion of drilling operations faster than conventional rigs due to the fact of the high rental rates per day. The new generation of drilling rigs has been designed to be more compacted and fully automated drilling rigs to save both time and money throughout the drilling process. These rigs can be moved in a variety of different ways from one location to another, either by land, air, or sea, depending on the ease of access, the location of the drill site, and the size and weight of the drilling rig being transported. This process is called Rig move that is usually subcontracted to a contractor who is called a Rig Move contractor.

Once the drilling rig reaches the drill site, the rig and camp are assembled. The camp is a self-contained space providing worker accommodations, catering facilities, radio communications, and waste-disposal provisions. Often, this support camp is located some distance away from the immediate space of the drilling rigs. On the other hand, almost all drilling operations done today are executed by rotary drilling rigs for both onshore and offshore, which comprise six main systems as illustrated in Fig. 1.5: the power system, the hoisting system, rotary system, the drilling fluid circulating system, well-control system, and the well-monitoring system (Bourgoyne et al., 1986).

Drilling operations

When the rig arrives at the drilling location and set up is completed and the drilling operation is started, this process is called well-spudding, where the drilling bit is connected to the drill pipes, and the drilling fluid called mud is continuously sent down the drill pipe and back to the equipment on the surface. Bourgoyne et al. (1986) revealed that drilling fluid is used during drilling operation to cool and lubricant the drilling bit, it circulates rock cuttings, and builds what is known as mud cake inside the well in order to keep it solid from washing out, and to balance the underground hydrostatic pressure to prevent any well kick, which is one of the major risks that exist during the drilling process.

The potential for uncontrolled flow from the reservoir to the surface is prevented using a series of hydraulically actuated steel rams able to quickly close around the drill pipe and casing to seal the well to prevent the uncontrolled flow. This equipment is used as a secondary safety barrier if the drilling mud, which is the first safety barrier failed, and this equipment is called a blowout preventer (Bourgoyne et al., 1986). Once each section is drilled,

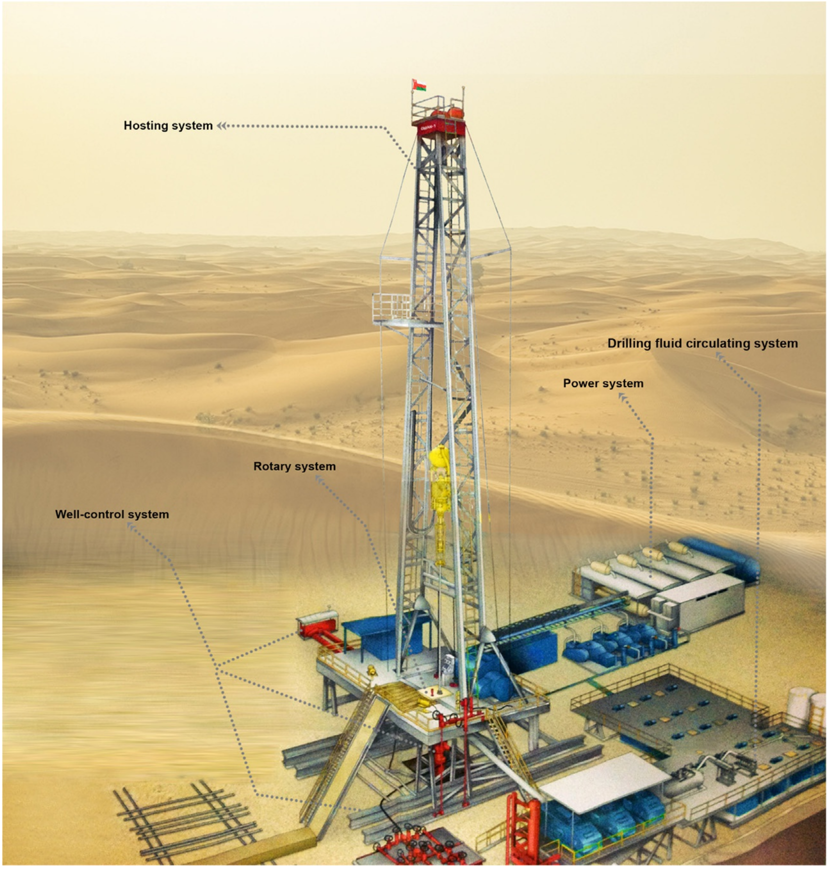


Fig. 1.5 Onshore drilling rig components.

the steel casings are lowered into the borehole and are cemented into place. This essentially gives rigid structural support to maintain the borehole's formation and integrity. It also isolates the underground formations.

Drilling operations are a continuous operation around the clock, and usually, there are two to three shifts on duty to accomplish this job working from 8 to 12 h per shift for 2 weeks and then having a week off. The time taken to accomplish the drilling task depends on the depth of the formation, the unforeseen technical problems encountered during the drilling operation, such as total losses, pipe stuck, well control issue, equipment failures, and many other factors. Often, 10–20 days are required to complete shallow drilling operation; while for the exploration drilling well, it may take from 3 to 5 months as drilling may extend to 7 km or more. Well testing and completion may take another month to figure out flow rates, the pressure of the formation, and the best completion design to be used.

If the drilled well is found commercially with viable quantities of hydrocarbons, a wellhead valve assembly is installed. However, if the well does not house commercially viable quantities of the necessary hydrocarbons, the well is plugged and abandoned using a cement plug (Smith, 1993). Open rock formations are also sealed with a cement plug to prevent the fluids from traveling up toward the surface. The wellhead and top joint of the casing are cut underground and sealed with the same kind of plug.

Appraisal wells

If exploratory drilling is successful, the third step is additional wells are drilled to figure out how large the oil field is and reduce the uncertainty by gathering more details about the field (Jahn, 1998). Contour mapping techniques are used to accomplish this task. These additional wells used to determine the size of an oilfield are called "appraisal wells," as they are not necessarily intended for extraction but rather the appraisal of a field's commercial viability (Jahn, 1998). The appraisal stage itself can also be used to figure out if additional seismic work is required or not. This process is essentially the same one used in the exploration well process. Vertical or deviated or directional or multilateral drilling techniques can be used during this phase from a site near the original borehole to appraise the reservoir. This can help lower the environmental footprint of the area affected by the drilling operation.

Development and production wells

The appraisal process is completed via drilling the number of appraisal wells in the oilfield, and the size of the oil field has been determined with all important information. More development or production wells are drilled depending on how large the reservoir of oil is. Multiple wells can spring from one single pad, or multilateral drilling is often employed to reduce the amount of land used and the cost of the infrastructure that must be brought in and constructed to make the operation run. In some cases, hundreds to thousands of wells are required in the oilfield.

Well completion

According to Perrin (1999) well completion started when the drilled well is concluded. Well completion, therefore, is a process required to make the well produce by connecting the drilled borehole and the pay zones.

Thus, these pay zones are subjected to many treatments during well completion, such as well-perforation, fracturing, productivity optimization, and acid stimulation treatment to enhance reservoir production. Finally, the drilled wells are completed using different types of tubing and lifting pumps, and each one draws oil up from a different layer of the reservoir. Therefore, well completion depends on six main factors Perrin (1999), which are: (1) the well's purpose; (2) drilling method; (3) the reservoir; (4) the production; (5) completion technique; and (6) the environment.

At this stage of the process, the blowout prevention equipment gets replaced by a "Christmas Tree" and is then ready to produce oil. The well flow rate is dependent on a variety of factors, including the properties of the reservoir rock, the pressures present underground, the oil's viscosity, and the ratio of oil to gas, and formation pressure. It should be noted that these factors are not necessarily constant throughout a well's commercial life, and oil can't always reach the surface without the aid of some sort of artificial lift, or an injection of gas or water to keep reservoir pressures maintained. These methods are known as enhanced oil recovery technologies, as they assist in the process of bringing the oil up to the surface. This is common in the process, as enhanced recovery technologies can keep a reservoir's lifespan going in the long run, helping to optimize production rates, and bringing up high viscous oil.

Well completion can be done by the same drilling unit or by another smaller unit. A workover service unit is usually used, depending on the day rate of each unit.

1.5.2.1 Workover services

Not only well completion but also the day-to-day maintenance operations are conducted in oil wells by work over or hoist rigs. This includes monitoring, safety, and security programs that continue throughout the lifespan of the well. Downhole servicing is one of the common work over duties using a wireline unit or a hoisting rig or a work over rig to maintain production. The operator of one of these rigs uses enhanced oil recovery technologies to make oil recovery methods more efficient and fruitful. Water, gas, chemicals, gases, and heat might be used to bring up even more oil than the primary method is able to.

1.5.3 Production and distribution phase

When the hydrocarbon gets to the surface in onshore activities, it is brought through pipelines to production and gathering stations that are located near the oilfield, which separates the produced fluids, such as oil, gas, water, and other debris (Termeer, 2013). The size of this station will vary depending on the reservoir being drawn from, oilfield size, and the nature of the fluids expected to be produced, along with the methods of export.

Gathering and production facilities process these by-products free the oil from dissolved gases prior to export. Wet gases are stabilized and have their liquids removed, whereas separated water and other debris are disposed of either in landforms, or in evaporation ponds, or reinjected into geological formations, or used for enhanced oil recovery technologies.

The offshore midstream is a little different from onshore midstream. The offshore midstream can combine both drilling and production operation on the same platform. According to Lombardo (2003), offshore midstream is called offshore floating production, storage, and offloading (FPSO) and may take different forms of semisubmersible structure, or jack-up production unit, or a ship (Fig. 1.6). FPSO is usually a permanent structure to

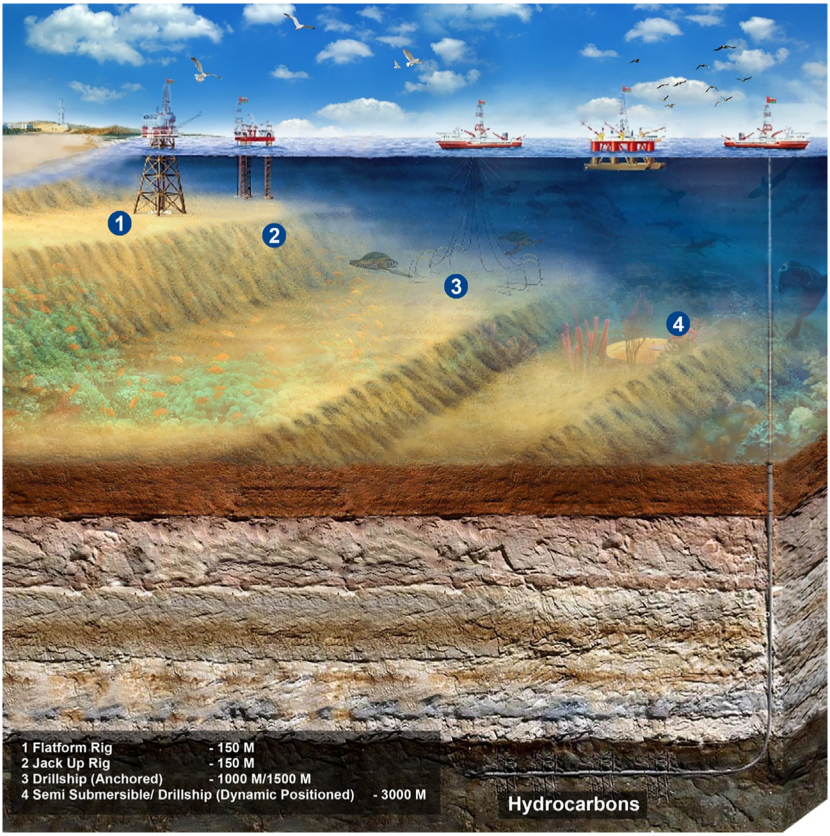


Fig. 1.6 Offshore drilling rigs classifications.

support the facilities needed for such extraction and production. It is designed to serve as the hub for drilling, crude oil recovering, gathering, and processing. Accordingly, the offshore floating production, storage, and offloading system may include storage and offloading system and thus called FSO, or floating production system and thus called FPS, or floating storage system and thus called FSU.

As many as 40 wells or more may be drilled from this one platform. More platforms might be built and linked via undersea flow lines to this central facility, but that all depends on the size of the oil field at hand. Areas with shallow water might need smaller platforms, and new technologies have come about to optimize these kinds of operations. Remotely operated undersea systems are a prominent one, negating the need for other platforms. This technology can be used in deeper water as well, as some environments cannot necessarily support such platforms. Ships and semisubmersibles are often used when platforms are not economical, servicing undersea wells regularly.

The offshore drilling process may seem different due to the different kinds of structures required as well as both upstream and midstream can be combined into one platform. However, the underground drilling processes are the same as onshore drilling processes.

1.5.4 An overview of TENORM presence during oil and gas extraction and production process

In onshore and offshore oil and gas production activities, a mixture of TENORM, oil, gas, water, and sand are brought to the surface via drilled wells through downhole completion and production equipment. Oil and gas are lifted to the surface TENORM and may precipitate in the form of scales in the completion and wellhead equipment because of the temperature and pressure change. This mixture then passes to midstream equipment via a separator, which removes the gas. The gas, after further processing, is relayed to a gas purification plant downstream where TENORM may still exist in a gas form, such as radon even after the gas has been purified. Meanwhile, the oil stream is further pumped to midstream production from upstream facilities via flow lines where TENORM may exist in the follow lines and keep emitting gamma radiation.

Gathering and production stations then remove the geological formation water and sand that are extracted with the oil and gas and contaminated with TENORM. After separation, the contaminated formation water with TENORM (also called production water) is either discharged to the ocean or sea or used for reinjection purposes, which enhance recovery in the depleted formations and enhances the original naturally occurring nuclear radioactive materials and converts them into technologically enhanced nuclear radioactive materials. Oily sludge and sand contaminated with TENORM obtained from the reservoir are also removed and disposed of on farmlands or sometimes the sea.

A portion of the TENORM, oil, and gas mixture is deposited in the form of solids on internal surfaces of the oil field production, gathering, and refinery equipment. Pipelines then carry crude oil to downstream facilities for further refining. Another portion of the TENORM still cannot be removed during the refining process due to its solubility with hydrocarbons. Accordingly, the refined products of both oil and gas may still contain TENORM that will be later either distributed locally for domestic and industrial purposes such as filling stations, factories, and power plants or shipped to other countries.

Therefore, TENORM coexists with oil and gas during different stages of production as shown in Fig. 1.7 (ALNabhani et al., 2015, 2016a, 2016b).

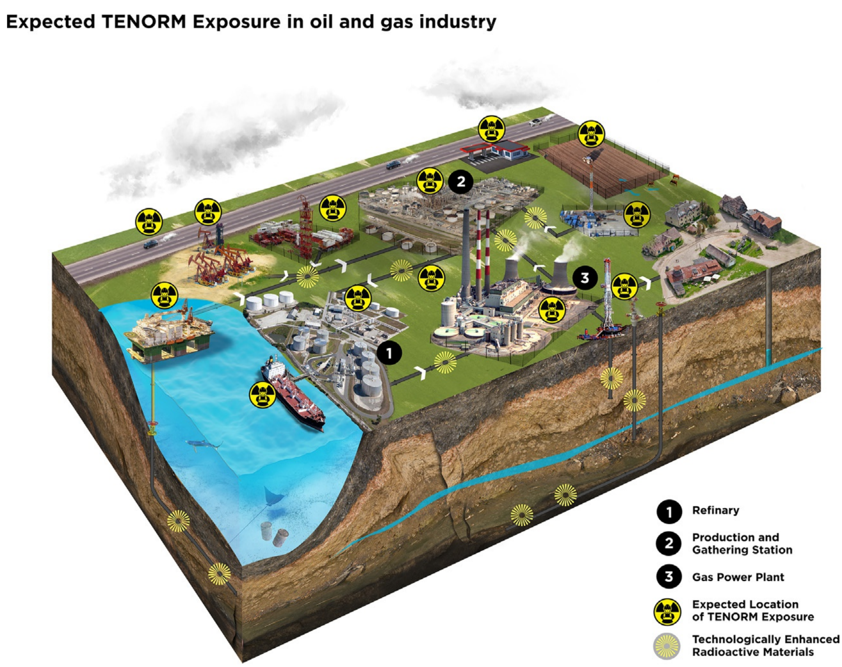


Fig. 1.7 Distribution of TENORM in the petroleum exploration and production processes.

There is a growing concern as to how the massive volumes of millions of tons of TENORM wastes in the form of produced water, scales, sludge, and contaminated equipment that are produced by the global petroleum industry can be managed and disposed of in a safe manner.

1.6 Hypothetical scenario of oil and gas drilling operation[1]

This hypothetical scenario simulates real and safe onshore drilling operation for oil and gas extraction.

1.6.1 Well objective

The hypothetical scenario for drilling an onshore exploration well called Oman-2 and is scheduled to be drilled in block Nizwa-07 in the northwest of Oman. A heavy exploration-drilling rig will be used for this project with a capacity to drill into a depth up to 5400 m. The proposed duration for this project is 105 days as shown in Table 1.1.

The first primary objective of the well is to facilitate the exploration of potential zones where hydrocarbon reserves are suspected to exist in the Fiqa reservoir between Natih and Nahr Umar as well as between Khuff and

Table 1.1 Oman-2 well time breakdown versus depth

Hole section (in.)	Depth (TD/MD)	Interval (m)	Casing (in.)	Accumulated time (days)
22″	30 m	0–30 m Vertical	18⅝″ CSG	1
16″	1800 m	30–1800 Vertical	13⅜″ CSG	19
12¼″	3800 m	1800–3800 Vertical	9⅝″ CSG	27
8½″	5000 m	3800–5000 Horizontal	7″ LNR	35
6⅛″	5400 m	5000–5400 Horizontal	4½″ LNR	23

[1]This is a hypothetical scenario for illustration purpose only and in principle is close to real operation. Geological formations names and depths are assumed in this hypothetical scenario may resemble or slightly differ from one location to another due to geological faults.

Upper Gharif reservoir. This is in accordance with the initial interpretation of the seismic surveys conducted in 2010. The second primary objective of Oman-2 is to use source rock and secondary formations to explore the potential extension of pay zones and to produce hydrocarbon by fracking the tight reservoir to enhance hydrocarbon production. This will be done by drilling a vertical pilot hole to a depth of 5000 m then to drill horizontally to a depth of 5400 m. The third primary objective of illustrating this hypothetical scenario is to show where radiological risks are expected during the drilling operation (Fig. 1.8).

The secondary objective of this project is to collect geological data stored in reservoir rocks at vertical depths between 1800 and 2700 m. This information will aid the future activities aimed at developing the fields in block Nizwa-07. Processes such as mud logging, coring, and wireline Logging is proposed to be used to evaluate this well. Finally, well will be completed according to the updated completion program based on collected data.

1.6.2 Well-plan

The hypothetical exploration well Oman-2 well is planned to be drilled in 105 days as per the following time breakdown vs depth.

Total ± 105.

1.6.3 Drilling operation program summary for well Oman-2

1. Drill top-hole section 22″ to total depth (TD) ±30 m measured depth—MD.
2. Run and cement 18⅝″ conductor casing.
3. Drill surface hole section to depth 1800 m MD using 16″ bottom hole assemblies (BHA).
4. Run and cement 13⅜″ surface casing
5. Run 12¼″ BHA to drill intermediate hole section to 3800 m MD.
6. Run open hole logs.
7. Run and cement 9⅝″ production casing (two-stage cement).
8. Run 8½″ “BHA to drill 8½″ hole section
9. Pull out of hole BHA and run coring tools.
10. Plug and abandon 8½″ open hole
11. Kick off the cement plug and sidetrack at 4700 m with 129.7°
12. Run directional 8½″ BHA to drill targeted formation at TD 5000 m MD.

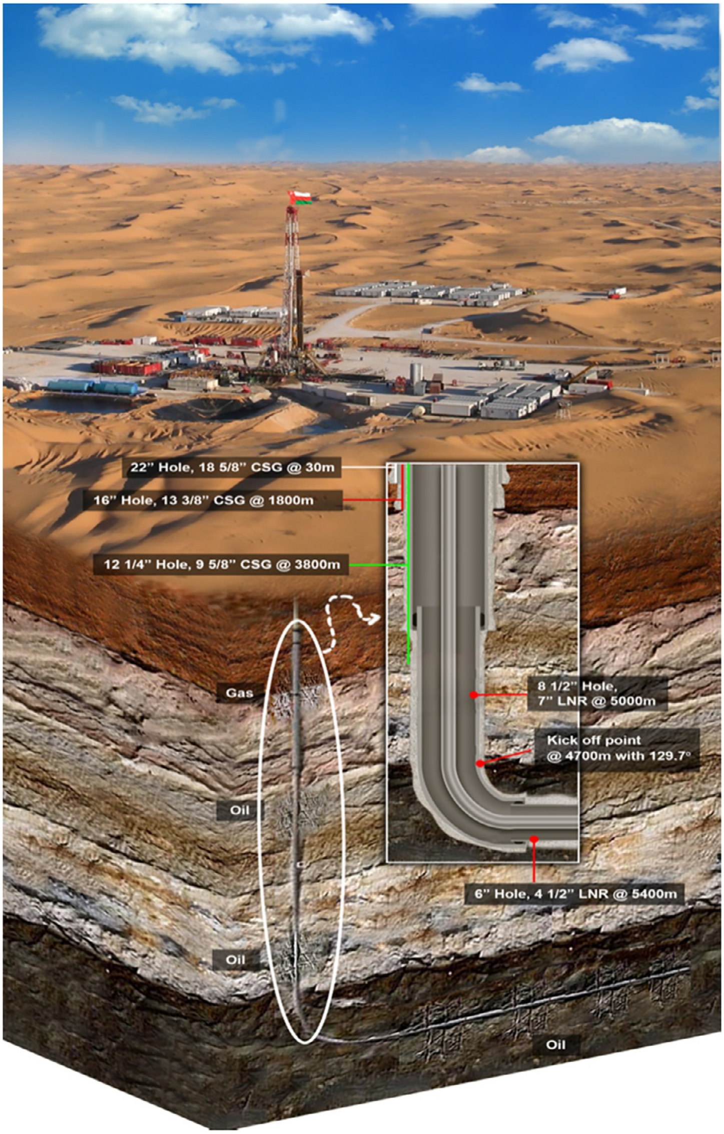


Fig. 1.8 Oman-2 well schematic.

13. Run and cement 7″ liner.
14. Run directional 6″ BHA to drill to the reservoir at TD 5400 m MD
15. Run open hole logs
16. Run and cement 4½″ liner.
17. Complete the well according to the completion program.

1.6.4 General pre-spud checklist

It is imperative that a pre-spud checklist is done on a well that has been marked to be drilled. The essence of this check is to ensure that all the conditions of spudding are in place and drilling can be commenced. These pre-check processes are aimed at promoting a safe and economical drilling process as per the plan. Errors while drilling are not accepted because they could potentially result in huge losses due to a high daily rig rate as well as cause production delay that will hinder the plans for daily oil and gas production from the wells, which is estimated at 80,000 barrels of oil and 10 m^3 of gas, respectively, depending on the reservoir.

The below pre-spud checklist is proposed for the exploration well (Oman-2) and can be used as an example of a typical and systematical checklist for a safe drilling operation. This checklist reminds drilling crew, and other service contractors about important steps required for a safe and economical drilling operation as well as expected radiological risks, which includes but is not limited to:

1. Organize a pre-spud meeting with the entire workforce who has a role to play in the well construction and emphasize of the radiological risk and required safety precautions at the start of radiation alarms according to radiation protection plan.
2. Confirm that all communication equipment and backups are fully functional.
3. Determine the turbidity of the brackish water will be used for drilling.
4. Carry out a comprehensive rig acceptance testing and confirm the functionality of other equipment and sensors on the checklist.
5. The drilling contractor should inform the operating company that all the pre-check conditions are done at least 24 h before the scheduled spudding.
6. A proper inspection of every item in the drilling rig should be done to ascertain rig acceptance and a radiation protection plan is explained well to all crew members and service contractors.
7. Inspect all sensors; calibration gauges, and then proceed to complete the documentation for the entire process. Copies of the documentation should be sent to the operating company before the commencement of spudding.
8. Inspect the supplied barite and cement onboard to ensure that it is adequate for the process. Arrangements must be made for an extra 50 tons of these products as backup.
9. Inspect the materials provided for the initial top-hole sections to ensure the quantity at the rig is sufficient.

10. Create an inventory that are up to the prescribed industry standard to access the drill pipes, heavy weight drill pipes, drill collars, lifting subs, elevators, tongs, safety clamps, and slips, crossovers, BOP, and fishing tools before the commencement of spudding..
11. The BOP equipment is to be tested on the test stump before spud as well as the pre-charge pressure test shall be conducted on the accumulator bottles.
12. Confirm the alignment of the TDS over the cellar.
13. Ensure that the trip tank has been adequately calibrated and that all lines, pumps, and related equipment are ready to be switched when necessary.
14. Organize a pre-phase meeting, which should include the entire team involved in the drilling process for the first top-hole section.
15. Ensure that there is a pre-job safety meeting (PJSM) organized before any operation while drilling well Oman-2.
16. Conduct a visual inspection of the conductor casing.
17. Inspect the wellhead equipment to ensure they are up to the standards of the well specification. This inspection will also ascertain that they are at the location.
18. Obtain the approval of the operating company prior to well spudding.

1.6.5 Drilling 22″ top-hole section

Objective

The primary aim of drilling the 22″ top-hole section is to enable the installation of an 18⅝″ conductor to fortify the upper section. It is also meant to prevent the unconsolidated Fars formations group from sloughing after circulation is lost in that could be noticed in Dhulaima or Taqa formation.

Operation summary

The process of drilling a 22″ conductor hole will involve the use of a 22″ mill tooth bit. The depth of the section TD is 30 m. Drilling of the vertical hole is done across the Fars formation groups. Finally, run and cement the 18⅝″ conductor at the designated depth.

Operational risks expected while drilling 22″ hole section

1. Excessive shocks and vibrations, which could cause accidents and injuries due to dropping objects. In the event of this problem encountered during drilling, a shock sub in BHA is to be deployed. The recommendations are to drill using controlled parameters (reduces the RPM and increases the WOB, avoid neutral points in the shock sub, and maximize the

application of soft torque.). It is also imperative to avoid running sensitive tools or BHA components that are known to be vulnerable to shock and vibrations.

2. Total losses may be encountered as may be seen. If this problem encountered stop drilling and use hi-vis sweeps or LCM bills, keep a close eye into the shaker to see if there are returns. If total losses still exist after all attempt to cure it by LCM materials, then consider cement plug, if no cement returns observed then reduce the flow rate and continue pumping cement until the returns are seen at the cellar.
3. *Tight* spot might be encountered during running conductor, if so, then consider performing a wiper-trip, spot hi-vis pill at the bottom, never attempt to push the casing down.

1.6.5.1 Recommended safe drilling procedures

1. Hold PJSM. Discuss job data, procedures, contingency plans, safety, environment, communication means and assign responsibilities among crewmembers.
2. Keep Bottom Hole Assembly for drilling 22″ hole section ready for operation.
3. Pick up 22″ BHA, start drilling.
4. Drill to TD at ±30 m MD using spud mud.
5. At section TD, sweep the drilled section with hi-vis pill and circulate hole clean.
6. Pick up and run 18⅝″ conductor casing.
7. Pump mud until good mud returns are observed at the cellar.
8. Cementing crew to perform PJSM (discuss job data, procedures, safety, environment, communication means and assign responsibilities among crew members).
9. While circulating, the cementing crew prepare for the cementing job (mix cementing products and cementing lines to be rigged up to the floor).
10. Pressure test cementing lines to 1500 psi.
11. Pump 20 bbl of freshwater ahead as a spacer.
12. Start mixing and pumping the cement slurry as per the cementing program.
13. Stop pumping cement as soon as cement is seen at the cellar.
14. Rig down cementing lines and wait on cement.
15. Cut 18⅝″ casing above the deck.
16. Lay down landing joint.

1.6.6 Drilling 16″ hole section

Objective

The primary objective of the drilling this section is to seal and isolate any unstable formation zones and to shut off the lost circulation zones across Hadramaut, Aruma, and Wasia formations group.

Operation summary

The drilling of 16″ hole section will be drilled using 16″ polycrystalline diamond compact (PDC) bit across Hadramaut and Aruma formations group using inhibited water-based mud. The 13⅜″ casing will be set at TD ±1800 m. The purpose of using a 13⅜″ casing is to effectively isolate the unstable zones such as Umm Er Radhuma, Fiqa, and Natih, as well as to provide an adequate control of pressure while drilling the next 12¼″ hole section.

Operational risks expected while drilling 16″ intermediate hole section

1. Total losses may be encountered. If this problem is encountered, stop drilling and use hi-vis sweeps or LCM bills and keep a close eye into the shaker to see if there are returns. If total losses still exist after all attempts to cure it by LCM materials, then consider cement plug, if no cement returns observed then reduce the flow rate and continue pumping cement until returns are seen at the cellar.
2. Tight spot might be encountered during running conductor, if so then consider performing a wiper trip, spot hi-vis pill at the bottom, never attempt to push the casing down.
3. There is a rare possibility of the emergence of Low activity concentration of radioactive materials while entering Natih, Shargi formation in Fiqa as well as during penetration Nahr Umr where these formations are geologically made of shales.

Recommended safe drilling procedures

1. Hold PJSM for the drilling job. Discuss job data, procedures, contingency plans, safety issues, environment, communication means, and assign responsibilities among crew members
2. Run in hole 16″ Bottom Hole Assembly for drilling 16″ hole section.
3. Drill out cement plugs and float collar and float shoe of 22″ surface hole section.

4. Drill till the top of Wasia, circulate and continue drilling up to TD 1800 m MD, take gyro surveys every stand, and optimize drilling parameters.
5. Sweep at TD with hi-vis pills, circulate and clean the well.
6. Perform a flow check.
7. Perform wiper trip to the previous shoe.
8. Ream all tight spots and report if any.
9. Hold PJSM for 13⅜″ casing job. Discuss job data, procedures, contingency plans, safety, environment, communication means, and assign responsibilities among crewmembers.
10. Run in hole 13⅜″ casing to casing point and wash down as required if any obstruction.
11. Circulate hole.
12. Cementing crew performs PJSM prior cementing job. Discuss job data, procedures, safety, environment, communication means, and assign responsibilities among crewmembers.
13. Pressure test cementing lines to 3000 psi.
14. Pump 50 bbl of water as a spacer.
15. Mix and pump first-stage lead slurry and first-stage tail cement slurry at a constant rate.
16. Drop and Inflate first-stage displacement plug.
17. Wait on cement and circulate confirming full returns.
18. Flow check the well.
19. Prepare for second-stage cement job.
20. Pump 50 bbl of water as a spacer.
21. Mix and pump second-stage slurry.
22. Wait on cement.
23. Nipple up and pressure test 13⅝″ −10 k BOP stack
24. Use plug-type tester and pressure test BOP for 5000 psi for 15 min.

1.6.7 Drilling 12¼″ intermediate hole section

Objective

The primary objective of the drilling in this section is to seal and isolate any unstable shale zones that are possibly discovered in the Wassia, Khamaha, and Sahtan formations group.

Operation summary

The drilling of intermediate hole section will be drilled using 12¼″ PDC bit across Wassia, Khamaha, and Sahtan formations group that usually include

Nahr Umr, Shuaiba, kharabib, Lekhwair, Salil, Hanifa, Tuwaiq, Dhruma, and Mafraq formations. The 9⅝″ intermediate casing will be cemented in two stages at TD ± 3800 m. The purpose of using a 9⅝ intermediate casing is to effectively isolate the shale, and unstable zones in the formations indicated above, and to provide adequate control of pressure while drilling the next 8½″ hole section.

Operational risks expected while drilling 12¼″ intermediate hole section

1. One of the potentials encountered during drilling 12¼″ intermediate hole section is the experience of partial or total losses. This happens when the drilling section is not properly monitored that may lead to a well control issue. The consequence of this is a loss of the first safety well control barrier (drilling fluid). In the event of this occurrence, the drilling parameters should be closely monitored. Also, lost circulation materials (LCM) should be added to the drilling mud before it enters the Shuaiba zone (the potential zone where losses occur in between Wassia and Khamah). If losses are not cured, then proceed with another attempt, the cement plug. Commence drilling with not less than a mud density of 11 ppg of mud cap in the annulus.
2. Well control, this situation is one of the consequences of uncontrolled partial/total losses, which will consequently cause the formation pressure to overwhelm hydrostatic pressure exerted by drilling fluid. Keep kill sheet ready. The surge and swab during pull out of hole/run in hole should be closely monitored. If the problem of uncontrolled well persists, then proceed to use the "Bullheading" killing method or any appropriate well-killing methods.
3. Poor cement job and a build-up annulus pressure. This will consequently lead to difficulties to control the well; hence, a formation integrity test and the use of LCM slurry is required to reduce any potential losses. If the problem persists, the annulus should be isolated with the use of two-stage cement layers with an inflatable casing packer. Finally, an evaluation of the cement job should be done by means of a cement bond log (CBL).
4. The release of H_2S gas is expected from any deeper formation when penetrated because of the lack of additional data from another offset well since this well is the first exploration well drilled in block Nizwa-07, H_2S gas is proven to be toxic to human beings even at a minute concentration. At higher concentrations, this gas is known to be a killer,

flammable, and corrosive on contact with metals. Processes such as maritime transportation, fishing, manned oil, and gas infrastructure in the downstream sector could potentially be affected in the event of a blowout because of the H_2S gas explosion. The consequences of this event are the loss of life, interference in business activities, legal liabilities, compensation claim, fines, and possible legal prosecution. It is important that a surface blowout of H_2S gas is promptly taken care of and controlled to avoid the loss of life or injuries, fire or explosions at the location. Safety measures to prevent these accidents are the installation of sensors that must be tested and ascertained to be fully functional. H_2S drill and emergency escape drills should be regularly conducted at the location with identified masterpoints.

5. Exposure to different levels of radiation. This is due to unpredictable emissions from technologically enhanced naturally occurring nuclear radioactive materials, which are deposited with the return drilling fluid and drilling cuttings as drilling through Nahr Umar. And above Shu'aiba that contains a large amount of shale. The workforce is at the risk of exposure to gamma radiation emissions that are highly penetrative and can spread as far as a few centimeters to a hundred meters as indicated by the IAEA (2008). There is also the risk of ingestion and inhalation of alpha and beta particles while breaking out connections at mud circulating system. To prevent this catastrophe at a location, the preventive measures stipulated by the TENORM safety management made by ALNabhani et al. (2017a, 2017b) should be adopted and strictly adhered to.

Recommended safe drilling procedures

1. Hold PJSM for the drilling job. Discuss job data, procedures, contingency plans, safety, environment, communication means, and assign responsibilities among crew members.
2. Run in hole 12¼″ bottom hole assembly for drilling 12¼″ hole section.
3. Drill out cement plugs and float collar and float shoe of 16″ hole section and drill ±3 m of the new formation.
4. Perform a formation integrity test—FIT (is a test of the strength and integrity of a new formation as well as test strength of shoe. It is the first step after drilling a casing shoe track to start drilling a new section) and a leak off test—LOT [pressure test shoe and formation until formation break down to find the fracture pressure (fracture gradient) of formation and shoe, which helps to manage drilling fluid density in drilling this

new section]. The result of the test must be shared with the operating company prior to any further action to be taken in drilling further this section.

5. Drill till the top of Shu'aiba, circulate and continue drilling up to TD 3800 m MD, take surveys every stand and optimize drilling parameters.
6. Sweep at TD with hi-vis pills, circulate and clean the well.
7. Perform a flow check.
8. Perform a wiper trip to the previous shoe.
9. Ream all tight spots and report if any.
10. Hold PJSM for logging job. Discuss job data, procedures, contingency plans, safety, environment, communication means, and assign responsibilities among crewmembers.
11. Rig up wire line tools and perform hole logging between Fiqa and Nahr Umr, and Shu'aiba formations.
12. Retrieve wear bushing.
13. Secure the well and repressure test 9⅝″ casing ram using the test mandrel, test pressure should be to 80% of the collapse of the pipe or the working pressure of the flanges.
14. Hold PJSM for 9⅝″ casing job. Discuss job data, procedures, contingency plans, safety, environment, communication means and assign responsibilities among crewmembers.
15. Run in Hole 9⅝″ production casing to casing point and wash down as required if any obstruction.
16. Circulate hole clean to the loss zone.
17. Cementing crew performs PJSM prior cementing job. Discuss job data, procedures, safety, environment, communication means, and assign responsibilities among crewmembers.
18. While circulating, the cementing crew prepare for the cementing job. Mix cementing products and cementing lines to be rigged up to the floor. (First-stage tail should extend ±150 above the 9⅝″ casing shoe. The lead slurry should extend to the total loss zone, or 40 m above the cementing stage tool if full circulation maintained through drilling operations. 50% excess for open hole should be considered in the cement volumes calculation.)
19. Pressure test cementing lines to 3000 psi.
20. Mix and pump first-stage lead slurry and first-stage tail cement slurry at a constant rate.
21. Inflate internal casing packer to open-stage collar
22. Wait on cement and circulate confirming full returns.

23. Flow check the well.
24. Lift the 13⅜″ BOP stack and install 9⅝″ casing slip and rest BOP stack.
25. Mix and pump second-stage slurry.
26. Nipple up and pressure test 13⅜″ −10 k BOP stack
27. Use plug-type tester and pressure test BOP for 5300 psi for 15 min

1.6.8 Drilling 8½″ hole

Objective

The primary objective of drilling 8½″ hole is to evaluate the reservoir rock in Akhdar group formations such as Minhur, Jilh, Sudair, and Khuf. This will be achieved by drilling first a pilot vertical hole using 8½″ PDC bit then side-track to create a secondary wellbore to collect more geological formation from group formations using coring technique and finally to land 7″ liner prior the reservoir. NaCl polymer mud with mud weight between 10 and 11 ppg will be used to drill this section.

Operation summary

This hole will be drilled across the Akhdar formations group where 7″ liner will be set at TD ±5000 m MD to provide structural support for the well.

Major expected operational risk while drilling 8½″ hole section

1. Well Control, this situation is one of the consequences of uncontrolled partial/total losses, which will consequently cause the formation pressure to overwhelm hydrostatic pressure exerted by drilling fluid. Keep kill sheet ready. The surge and swab during pull out of hole/run in the hole should be closely monitored. If the problem of uncontrolled well persists, then proceed to use the "Bullheading" killing method or any appropriate well-killing methods.
2. The release of H_2S gas is expected from any deeper formation when penetrated because of the lack of additional data from another offset well is because this well is the first exploration well drilled in block Nizwa-07, H_2S gas is proven to be toxic to human beings even at a minute concentration. At higher concentrations, this gas is known to be a killer, flammable, and corrosive on contact with metals. Processes such as maritime transportation, fishing, manned oil and gas infrastructure in the downstream sector could potentially be affected in the event of a blowout because of the H_2S gas explosion. The consequences of this event are the loss of life, interference in business activities, legal liabilities, compensation claim, fines, and possible legal prosecution. It is important that a

surface blowout of H_2S gas is promptly taken care of and controlled to avoid the loss of life or injuries, fire or explosions at the location. Safety measures to prevent this accident are the installation of sensors that must be tested and ascertained to be fully functional. H_2S drill and emergency escape drills should be regularly conducted at the location with identified masterpoints.

3. Exposure to different levels of radiation. This is due to unpredictable emissions from technologically enhanced naturally occurring nuclear radioactive materials, which are deposited with the return drilling fluid and drilling cuttings as drilling through Nahr Umar. And above Shu'aiba that contains a large amount of shale. The workforce is at the risk of exposure to gamma radiation emissions that are highly penetrative and can spread as far as a few centimeters to a hundred meters as indicated by the (IAEA, 2008). There is also the risk of ingestion and inhalation of alpha and beta particles while breaking out connections at mud circulating system. To prevent this catastrophe at a location, the preventive measures stipulated by the TENORM safety management made by ALNabhani et al. (2017a, 2017b) should be adopted and strictly adhered to.

Recommended safe drilling procedures

1. Hold PJSMs for the drilling operation. Discuss job data, procedures, contingency plans, safety, environment, communication means, and assign responsibilities among crewmembers.
2. Run in hole 8½″ bottom hole assembly for drilling 8½″ hole section.
3. Drill out the stage tool, cement plugs, and float collar of the previous section.
4. Drill to ±2 m above the float shoe, circulate bottoms up.
5. Perform casing pressure test to ±5500 psi
6. Continue drilling out float shoe to about ±4 m of new formation, circulate hole clean.
7. Hold PJSM and perform formation integrity test and the result must be shared with the operating company.
8. Continue drilling 8½″ pilot hole section to the coring point at 4000 m, coring interval will be (4000–4500 m).
9. Sweep the hole and perform flow check.
10. Perform wiper trip to the previous shoe.
11. Hold PJSM and perform coring operations.
12. Pull out of hole coring BHA.

13. Remove wear bushing and perform BOP pressure test.
14. Continue drilling 8½″ pilot hole section to TD 5000 m MD.
15. Circulate hole clean.
16. Flow check and pull out of the hole to the surface.
17. Hold PJSM to start 8½″ hole logging program.
18. Perform a wiper trip.
19. Hold PJSM then proceed8½″ hole plug and abandonment to start the sidetrack section at TD 4700 m MD.
20. Batch mix and pump the cement slurry and batch mix and pump of kick off plug.
21. Rig down cement equipment.
22. Hold PJSM run in hole sidetrack bottom hole assembly until tag top of cement and initiate sidetrack hole.
23. Pull out of hole side track BHA and run in hole directional BHA and deviate as per directional plan of 129.7 degrees and set parameters to finally have a horizontal well at 5000 m.
24. Pull out if hole directional BHA and *circulate* hole clean.
25. Spot hi-vis/hi-density pill in open hole.
26. Flow check and pull out of the hole to surface.
27. Hold PJSM and *run* in hole 7″ liner.
28. Set the liner hanger and set the hanger by slacking off the *liner* weight.
29. Bleed off pressure.
30. When liner weight has been lost (a deviated well *maybe* not clear easily) and the tool is released, set down again on top of the liner to compensate for upward hydraulic forces.
31. The cement volume to be calculated based on the volume from the caliper log data plus 50% excess.
32. Hold PJSM, rig up cement equipment and pump cement slurry for 7″ liner as per cementing program.
33. Rig down cement equipment.
34. BOP stack will remain the same, as was on previous section 10k arrangement.
35. Use plug-type tester and pressure test BOP for 5500 psi for 15 min

1.6.9 6″ hole horizontal section

Objective

The main objective of drilling in this section is to drill horizontally from 5000 to 5400 m and therefore have horizontal hole access for more production through paying zones Khuff and Upper Gharif.

Operation summary

The plan is to drill horizontally of ±400 m of 6″ hole section to TD 5400 m MD across shale and reservoir rocks in Khuff and Upper Gharif formation using salt polymer mud of 11 ppg. The 6″ horizontal hole will be cased with 4½″ cemented liner. Finally, the well will be stimulated with multistage fracturing equipment.

Major expected operational risk while drilling 6″ hole section

1. Well control, this situation is one of the consequences of uncontrolled partial/total losses, which will consequently cause the formation pressure to overwhelm hydrostatic pressure exerted by drilling fluid. Keep kill sheet ready. The surge and swab during pull out of hole/run in the hole should be closely monitored. If the problem of uncontrolled well persists, then proceed to use the "Bullheading" killing method or any appropriate well-killing methods.
2. The release of H_2S gas is expected from any deeper formation is penetrated because of the lack of additional data from another offset well is because this well is the first exploration well drilled in block Nizwa-07, H_2S gas is proven to be toxic to human beings even at a minute concentration. At higher concentrations, this gas is known to be a killer, flammable, and corrosive on contact with metals. Processes such as maritime transportation, fishing, manned oil, and gas infrastructure in the downstream sector could potentially be affected in the event of a blowout because of the H_2S gas explosion. The consequences of this event are the loss of life, interference in business activities, legal liabilities, compensation claim, fines, and possible legal prosecution. It is important that a surface blowout of H_2S gas is promptly taken care of and controlled to avoid the loss of life or injuries, fire or explosions at the location. Safety measures to prevent these accidents are the installation of sensors that must be tested and ascertained to be fully functional. H_2S drill and emergency escape drills should be regularly conducted at the location with identified masterpoints.
3. Exposure to different levels of radiation. This is due to unpredictable emissions from technologically enhanced naturally occurring nuclear radioactive materials, which are deposited with the return drilling fluid and drilling cuttings as drilling through Nahr Umar. And above Shu'aiba that contains a large amount of shale. The workforce is at the risk of exposure to gamma radiation emissions that are highly penetrative and can spread as far as a few centimeters to a hundred meters as indicated by

the (IAEA, 2008). There is also the risk of ingestion and inhalation of alpha and beta particles while breaking out connections at mud circulating system. To prevent this catastrophe at a location, the preventive measures stipulated by the TENORM safety management made by ALNabhani et al. (2017a, 2017b) should be adopted and strictly adhered to.

Recommended safe drilling procedures

1. Hold PJSM for the drilling operation. Discuss job data, procedures, contingency plans, safety, environment, communication means, and assign responsibilities among crewmembers.
2. Run in hole 6″ bottom hole assembly (including directional drilling tools) for drilling 6″ hole section.
3. Drill out landing collar and float collar to ±2 m above float shoe of the previous section.
4. Perform a casing pressure test to ±4500 psi for 15 min.
5. Continue drilling out float shoe and 4 m of the new formation.
6. Hold PJSM and perform Formation Integrity Test.
7. Continue drilling 6″ horizontal section to well TD at ±5400 m MD.
8. Perform Flow check.
9. Perform a wiper trip to the previous shoe.
10. Circulate hole clean, sweep the hole with hi-vis pill.
11. Pull out of the hole to surface.
12. Hold PJSM and Run in hole 6″ wireline logging equipment.
13. Pull out of hole and rig down wireline logging tools.
14. Circulate hole clean
15. Spot hi-vis pill on bottom
16. Hold PJSM and run in hole 4½″ liner to the TD.
17. Set hanger by slacking off the Liner weight
18. Bleed off pressure to zero.
19. Circulate bottom up and Hold PJSM for 4½″ liner cement job
20. Rig up cement tools and pressure test lines to 6000 psi.
21. Cement 4½″ liner with 50% open hole excess
22. Ensure well is static and rig down cement equipment.
23. Well to be completed as per the completion program assigned to this well.
24. Finally, drilling equipment and service contractor tools must be checked for any presence of radiation contamination; and if found, then they are marked and sealed properly for further treatment or safe disposal.

1.7 HSE management system used for oil and gas extraction and drilling operation

1.7.1 Qualitative HSE risk assessment matrix

Theoretically, it is one of the main priorities of stakeholders in the oil and gas industry to adopt and adhere to the adequate safety measures during exploratory and drilling explorations. While, practically the situation may be different, where some senior rig managers are paying more attention to drill wells that are faster and striving to achieve more cost saving for their companies. This could compromise the adoption of safer practices that can result in serious catastrophes. Most of the accidents that have happened in the past were because of negligence and wrong decision-making that were based on qualitative and classic risk assessments.

Other causes include working at a quicker pace due to the pressure to meet targets during a drilling project, problems could also arise due to frequent modifications made to the drilling processes and production plans, and the high drilling rigs' rental rate especially in cases where the drilling project has been outsourced based on cost per feet, cost per day or well lump-sum conditions. It should be noted that the safety measures and environmental risk assessment provision currently being used in the oil and gas industry are associated with a lot of uncertainty due to lack of advanced QRA.

These safety provisions are observed to be static and void of the capacity to be applied dynamically under unforeseen events or in cases where the standard processes of the normal integrated system have been modified. For example, there are many techniques which are used by in the oil and gas industry to establish safety management and risk assessment plans as part of their HSE management system, such as the risk assessment matrix, Hazards and Effects Management Process, Hazard Identification (HAZID), Hazards Analysis (HAZAN), Hazards & Operability (HAZOP), Task Risk Assessment (TRA), QRA, Job Safety Plan (JSP), and Hazard and Effects Management Process (HEMP).

Most of these safety tools are not necessarily scientifically based, or based on accurate numerical evaluation, or developed by means of academic expertise, and ignorance or inability to quantify important factors leads to accidents such as human errors, equipment failure, lack of considering psychological factors that focus on the science of behavior and the mind. This could provide an explanation for the continued occurrence of accidents despite the efforts that have been put in place to prevent such accidents or to improve the safety measures in the industry.

The illustration of Fig. 1.9 is an actual example of a risk assessment matrix that is widely and commonly used for the drilling operation in the oil and gas industry. It is scientifically discovered to be insufficient enough to provide enough protection to workers or safe operation as it is a qualitative tool associated with a high level of uncertainty and based on historical data. Hence the need for reevaluation before it is developed into a quantitative dynamically applicable risk assessment that covers all possible emergencies and the unforeseen risk that could occur at any time and not necessarily has occurred before or it can occur as integration of abnormal events in the drilling operation in both main system and its subsystem.

1.7.2 Qualitative hazard and effect management process

Many of the oil and gas industries use risk assessment matrix to actualize Hazard and Effect Management Process (HEMP) as a part of their Safety Management System. HEMP is one of the key tools used by the industry to control risks expected in the workplace, equipment, properties, and environments. In cases of failure in controls, HEMP helps manage the impacts of incidents as well. Thus, its working principle is exactly as bow tie technique.

The HEMP provides only a qualitative framework for managing health, safety, and environment—related hazards because of using the risk assessment matrix. Which is based primarily on a qualitative assessment of risk's frequency occurrence.

HEMP has four main steps (Fig. 1.10), which are:

1. Hazard identification.
2. Risk assessment.
3. Risk control.
4. Recovery measures.

Hazard identify

The first HEMP step is identifying the hazards and risks related to workforce, equipment, materials, and environment, including routine and nonroutine activities. HAZID in HEMP is based on three main ways which are: (1) through experience; (2) the use of a checklist; and (3) reference to regulations, code, and standards.

PROJECT TITTLE	:
DESIGN STAGE	:
PROJECT REF	:
DATE	:
APPROVED BY	:

`Drilling Operation Risk Assessment Matrix

LIKELIHOOD
What is the chance of the risk occurring?

CONSEQUENCES / RATING
How severe could the outcomes be if the risk event occurred?

	Frequent 5	Probable 4	Occasional 3	Remote 2	Improbable 1
Catastrophic	High 25	High 20	High 15	Medium 10	Low 5
Accident (Critical)	High 20	High 16	Medium 12	Medium 8	Low 4
Incident (Moderate)	High 15	Medium 12	Medium 9	Low 6	Low 3
Mishap (Minor)	Medium 10	Medium 8	Low 6	Low 4	Low 2
Near Miss (Insignificant)	Low 5	Low 4	Low 3	Low 2	Low 1

S.N	Risk	Hazard & Consequences	Likelihood	Consq Level	Risk Level	Preventive Measures	Risk down to level	Action Group
1	Inadequately trained rig move crewmember Potentially may cause multiple fatalities, injuries, loss of assets due to crash or rollover, or dropped load, and lifting accidents, etc.	Hazard & Consequences	(3) Occasional	(5) Catastrophic	15	Review the planned procedure for rig move. Adhere to the professional standards for lifting and transportation of rigs. Carry out an audit of all the processes done during the transportation process. Establish a reliable emergency management plan. Conduct PJSM and operational safety meetings. Training. PPE. Set up an effective emergency response plan. Check weather forecasting	5	Rig Manager, Rig Move Leader, and HSE Manager
2	Difficulties in obtaining medical support in the desert on time	Potentially cause multiple fatalities, injuries because the nearest hospitals or health facilities are usually far away from the remote desert even by the helicopter in case of emergency situations.	(4) Probable	(3) Moderate	12	Ensure that provisions for rig medics, rig clinics, and a flying ambulance have been made at the location and they are fully functional and ready for any emergency. (flying ambulance are not available in many oil producing countries like in the Middle East) First Aid provisions in line with the highest industry standards must be in place. An effective communication system. Ensure that an emergency plan meets the highest standards of the onshore exploration industry is ready for use.	6	Rig Manage/ Corporate/ HSE Manager

Fig. 1.9 The risk assessment matrix for the drilling rig operation, which simulates exactly the real ones used widely in the oil and gas industry.

(Continued)

3	Environmental damages, e.g., contamination as a result of a spillage or inadequate waste disposal methods which are directly deposed of into the ground or atmosphere	Spillage of Diesel, drilling fluid, Mud, Chemicals, nuclear radioactive materials, cement, cement additives, and drilling waste such as contaminated cuttings (average volume of Cuttings is about 500 m3 per well). Unfenced drilling waste and water pits that animals drink from or fall in.	(4) Probable	(4) Critical	16	⚲ Develop and setup an Effective Environmental Management and protection Plan. ⚲ Develop and set up a Spill Control, and Waste handling and Management Plan. ⚲ Organize regular spill and containment emergency response drills Establish a Clean-up Plan. ⚲ Ensure that the right storage facilities have been used to store hazardous chemical drums and skids properly. ⚲ Proper communication and reporting system. ⚲ The Appropriate Signs and labels should be clearly visible at strategic points at the location.	3	Rig Manager, HSE Manager, and Mud Engineer
4	Dropped objects: rig components, parts, tools, pipes, hoisting equipment.	Potentially of single and multiple fatalities due to dropped objects in the rig floor or into the wellbore	(3) Occasional	(4) Critical	12	⚲ Adopt the training programs for drop tools ⚲ Organize regular site safety meetings. Well should be adequately covered up. ⚲ Restricted areas around the location must be clearly identified to prevent unnecessary risk exposure at the location. ⚲ Encourage personal communication according to the regulations at the location. ⚲ Frequent inspections of all masts and hanging tools at the location. ⚲ Tool Box talk. ⚲ Compliance with the safety standards related to unsafe objects dropped on the floor. ⚲ PPE. ⚲ Emergency Response Plans.	6	Rig Manager/ All Rig crew members/HSE Manager, and Medic
5	Fire/explosion caused by flammable materials such as diesel, Oil Based Mud, formation gas (H_2S), welding gas, paint, thinners, Electricity, blowout and Well control challenges.	Potentially cause multiple fatalities, loss of assets, corporate reputation, and environmental pollution	(3) Occasional	(5) Catastrophic	15	⚲ Explosion-proof electrical equipment must be used. ⚲ Danger zones must be identified and labelled. ⚲ Provision of an adequate storage facility for flammable materials. ⚲ Install reliable gas and smoke detection systems. ⚲ Enforce a strict "No Smoke, No cell phone" policy. ⚲ Inspect fire safety equipment regularly to ensure they are adequate, certified and ready for use. ⚲ Setup a reliable fire response plan. ⚲ Valid and authorized hot permit to work systems. ⚲ Organize regular fire and explosion drills. ⚲ Inspect ongoing fire prevention practices and the professional use of equipment. ⚲ Inspect fire alarm systems and the associated sensors to confirm they are fully functional. ⚲ Professionals training in the operation of fire alarm systems. ⚲ Regularly organize fire and explosion emergency responses and proper evacuation strategies. ⚲ Evacuation plan Establish a reliable medical emergency plan. ⚲ Perform more fire drills Monitor the proficiency of the rescue team in place at the location. ⚲ Regularly and clearly communicate the communication plan usable in the event of an emergency. ⚲ PPE. ⚲ Ensure that the rig fire pump; and extinguishers, firefighting system fully functional. ⚲ Facilitate the proper well control procedures.	6	Rig Manager/ all Crewmembers, HSE Manager, Firefighting Team, and Medic

Fig. 1.9—cont'd

(Continued)

6	Mechanical lifting risks e.g using cranes, winches, and man lifts	Potentially cause single or multiple fatality and serious injuries due to dropped loads or while performing man riding operations or human error during the control of lifting gear.	(4) Probable	(4) Critical	16	Ensure the use of only certified equipment at the location. The standard lifting operations procedures should be adhered to. Make provisions for a dedicated bucket lifting procedure. Confirm all permits presented by staff selected to operate critical lifts. Enforce the use of fall protection harness for all staff. Establish a system of color-coded for all lifting gear. Cranes and mechanical lifting must be inspected and are certified. Organize compulsory onshore Crane Supervisory Training. Ensure that the rigger selected to operate the crane and forklift has been professionally trained and authorised in rigging and the processes of carrying on effective communication with the operators. Enforce the use of restive vests or jackets by the riggers. Engage the services of highly trained and certified slingers. Rigger and banksman training. PPE. Hold PJSM. Establish an adequate medical emergency plan.	4	Rig Manager, Crane operators, All crewmembers, HSE Manager, and Medic
7	Inadequate HSE awareness or the unprofessional coordination of the contractor and sub-contractors on site	Potentially cause fatalities, injuries and related operational accidents	(3) Occasional	(4) Critical	12	Enforce "operation stop card" intervention procedure. Confirm the possession of adequate work permits by the workforce. Enforce the need for contractor HSE training and management plan. Regularly imitate a comprehensive inspection and audit for all processes. PPE. Hold PJSM	6	Rig Manager, HSE Manager
8	Security threats (physical or electronic in the form of piracy, terroris , armed conflicts, criminality, drug, and alcohol).	Potentially cause fatalities, injuries, and loss of assets.	(3) Occasional	(5) Catastrophic	15	Personal Security Plan. (Physical scan check/ electronic security plan). Professionally setup an Emergency and Evacuation Response Plan. Enforce the use of recommended cameras that must be installed at all locations such as the drilling unit, control room; these cameras should be monitored non-stop by the HSE and security team. Establish a Fire and Explosion Emergency Plan. Organize regular security drills. Communication Plan. Enforce a strict NO drug and Alcohol policy. Check points.	6	Rig Manager, All crewmembers, HSE Manager, security team, Corporate
9	Exposure to Technologically Enhanced naturally occurring nuclear radioactive materials	Potentially cause fatalities, and chronic Carcinogenic diseases	(5) Frequent	(4) Critical	20	Enforce adherence to the procedure for handling nuclear radioactive hazardous materials and adherence to safety procedures set by ALNabhani et. al (2015, 2016 & 2017). PPE. Advocate the importance of regular medical checkup. Confirm the full functionalities of TENORM sensors and detectors. Confirm the effectiveness of the TENORM Safety tprevention barriers set by ALNabhani et. al. (2017).	6	Rig Manager, Corporate, and HSE Manager

Fig. 1.9—cont'd

(Continued)

10	High risk/ non-routine operations such as but not limited to confined space entry, working at heights, working on energized equipment, critical lifts...	Potentially cause fatalities, injuries, loss of assets due to explosion, fire, H2S, carcinogenic diseases.	(3) Occasional	(4) Critical	12	PTW system. Training. Safety meetings. Toolbox talk. Create awareness for the recommended operational procedures. Safe Communication. Advocate the Buddy System. Confirm the effectiveness of the Emergency Responses Plan. Confirm the effectiveness and reliability of the sensors and detectors set up at the location.	4	Rig Manager, All crew members, HSE Manager
11	Harsh Environment / weather such as : Strong Storms/ winds cyclones/ High temperature/ Fogs	Operations, rig movements, well construction activities logistics, diving satellite communications will be put at risk, and consequently increase the chances of fatalities, injuries, loss of assets.	(3) Occasional	(5) Catastrophic	15	Regular monitoring of the weather forecast 24 hours daily. Establish an alternative means of communication. Ensure that all operations are temporarily suspended in the event of harsh weather conditions. Ensure that the emergency response team and evacuation team are always ready. Reduce risk by clearing out risky places. Lower the drilling mast.	6	Rig Manager, and HSE Manager
12	Poor storage facilities and conditions for food and drinking water, and poor hygiene conditions	Potentially cause fatalities due to the poisoning	(2) Remote	(3) Moderate	6	Regular monitoring of the weather forecast 24 hours daily. Establish an alternative means of communication. Ensure that all operations are temporarily suspended in the event of harsh weather conditions. Ensure that the emergency response team and evacuation team are always ready. Reduce risk by clearing out risky places. Lower the drilling mast.	2	Rig Manager, Camp boss, and Catering in charge
13	Operational miscommunication	Potentially lead to injuries, damage to equipment or the environment.	(4) Probable	(3) Moderate	12	Engage a professional translator to effectively pass important information to the workforce into their language during safety meetings (e.g English, Arabic, Hindi). All labels on equipment at the location must be translated to the language of the workforce. Professional training on operation and communication signals. Supervisors during shift change must give detailed operational handover.	4	Rig Manager, All crew members, and HSE Manager
14	Infectious diseases contracted from different crew members engaged from different countries	Potentially cause serious diseases due to the fast spread of infectious diseases	(2) Remote	(4) Critical	8	Take necessary immunizations. Regular medical checkup and immunizations system update. Medical emergency response plan.	3	Rig Manager, All crewmembers, HSE Manager, and Medic
15	Risk of high pressures lines, high-pressure vessels, or while performing pressure tests or while maintaining pressurized equipment, (i.e., trapped pressure)	Potentially lead to fatalities or injuries, explosions, damage to equipment or the environment	(3) Occasional	(4) Critical	12	Install safety clamp. Warning signs and barriers. PTW system. Frequent Maintenance and audit. Integrity checks to evaluate pressure equipment. PPE. Hold PJSM.	5	Foreman, Mechanics, Mud Engineer, Driller, Drilling Engineer, Services contractor. e.g cementing, H2S, fracturing, perforation.

Fig. 1.9—cont'd

(Continued)

16	Release of H2S while drilling or blowout	Potentially lead to fatalities or injuries and intoxications due to toxic gases that may cause explosions	(5) Frequent	(4) Critical	20	• Valid H2S training. • All personal monitors and detectors are valid, calibrated and certified. • Extra H2S equipment must be made available before penetrating the reservoir. • The rig-up line to the flare if applicable. • Regular H2S safety drill. • Ascertain the readiness of the kill pump unit onsite beginning from penetrating the reservoir till the release of a rig. • H2S Emergency and Evacuation Response Plan. • Regular BOP tests. • Set up the mud weight combined with adequate over balance and the scavenger chemicals to prevent an experience of well flow. • Ensure that the shut-in procedures while drilling and tripping are fully functional. • Adequate breathing apparatus must be provided; these materials must be regularly checked calibrated and positioned strategically at different locations in the rig and within the rig accommodation. • Ensure that the escape route is always free from any obstruction. • Master point clearly identified. • People counting versus cards.	5	Rig Manager, Driller Engineer, Mud Engineer, HSE Manager and H2S Contractor
17	Greenhouse emissions	Approximately 10 k tones of CO2 per well expected to be released per oilfiled	(4) Probable	(3) Moderate	12	• Adhere to the standard environmental protection procedures. • Frequent equipment maintenance. • Filters installations.	3	Corporate, and HSE Managr
18	Top Drive and travelling block System and other hoisting equipment fall down due to excessive vibrations while drilling or lack of maintenance	Potentially lead to fatalities or injuries and damage to equipment	(3) Occasional	(4) Critical	12	• BHA design (e.g., use of shock absorber, insure drilling parameters optimization). • Establish a top drive system or set up a regular inspection procedure. • Limit the access of unauthorized workers in the identified hazardous zones. • Emergency Response Plan. • PPE. • Keep close eye on slip-and-cut procedures in case of draw work.	4	Drilling Managr, Drilling Engineer, Driller, and HSE Manager
19	well control issue.	Kick can develop into a serious blowout. This will cause the weight of the drilling mud to become less than the formation pressure. The well killing method is not appropriate, well control equipment failure, consequently causing blowout and potential of fatalities or injuries, loss of assets, damaged reputation and environmental damage.	(3) Occasional	(5) Catastrophic	15	• Setup a close monitoring for the well such as flow checks to detect any kick signs. • Monitor drilling parameters. • Ensure that sufficient mud weighting chemicals have been made available. • Use only certified and tested well control equipment. • The important members of the workforce must possess valid well control certificates. • Regularly organize well control safety drills. • Regularly organize well emergency control and evacuation response plans.	5	Drilling Managr , Drilling Engineer, Driller, and HSE Manager

Fig. 1.9—cont'd

Risk assessment

The second step in HEMP is assessing the identified hazards. At this point, the likelihood that the hazards could result in an accident and the consequence of its occurrence is taken into consideration as per the following equation:

$$\text{Risk} = \text{Consequences} \times \text{Likelihood} \tag{1.2}$$

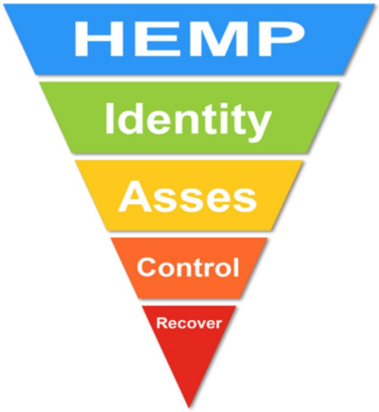


Fig. 1.10 HEMP main steps.

The risk is, therefore, mathematically expressed as a function of the severity of a consequence and the likelihood of the consequence. Unfortunately, the likelihood during risk assessment is determined based on the available historical data. Moreover, this method is unable to quantify environmental or health consequences. Thus, these are the main weaknesses of this method in addition to its inability to consider or anticipated new risks that never happened or may appear because of complex integrated systems in the oil and gas industry. Thus, this process is associated with a high level of uncertainty. Finally, the outcomes of the assessed identified hazards used by the oil and gas industry to prioritize events to control the risks identified. Despite that, this could explain why continual accidents still occur.

Risk control

The third step in HEMP process is risk control and this should include prevention, mitigation, and recovery measures. There are different types of control plans that are commonly used in the oil and gas industry, such as

- hazards/risks elimination plan (e.g., exposure time reduction and equipment design)
- Substitution measure (e.g., hazardous equipment or material could be substituted for less hazardous ones, design modification, and automation)
- Engineering controls: (e.g., equipment design and PPE)
- Administrative controls (e.g., job procedures)

The use of control measures depends on the outcomes of risk assessment and priorities determined by company management. Unfortunately, management decisions may differ from one company to another even though they claim that "safety is first, or top priority." In fact, we have seen many cases from reputable companies whose management decisions ultimately end in catastrophic events costing them billions of dollars in exchange for little saving of dollars and time.

Recovery measures

The aim of HEMP is to prevent the release of the hazard if the last line of defense and all the control fails. In this case, HEMP attempts to finally mitigate the effect of the hazard released with an attempt to reduce losses and return to the normal safe operation. The main recovery measures are usually the emergency plan available at the sites such as fire emergency plan, firefighting plan, evacuation plan, emergency shutdown plan, alarms, rescue plans, medical plan, compensation plan, and many another recovery plans.

Therefore, HEMP is basically designed in the form of a bow tie diagram, which is a graphical representation of how a hazard can be released, what the consequences of the release might be, and finally how the consequences might be prevented or mitigated (Fig. 1.11). From a safety engineering point of view, the bow tie may not be a useful tool for the complex and integrated system due to its limitations in quantifying with high certainty the effectiveness of the safety barriers, the degree of safety barriers failures, tracking the root causes, predicting at a very early stage the hazards and consequences so that effective control barriers and recovery measures can be assigned.

The overall objective of HEMP is to reduce risks to as low as reasonably practicable (ALARP). However, it is not always sufficient to mitigate a specific risk to ALARP. In general, the oil and gas industry use generic standards that are not sufficiently designed to mitigate a specific risk to ALARP.

Moreover, ALARP It is a controversial issue in the scientific community due to its lack of scientific evidence about the quantitative basis on which it is determined that the risk is acceptable or low or practicable other than the cost gained in compromise the safety of small group of people in exchange of more political and economic benefit in which ALARP can be viewed as a utilitarian philosophy (Oughton and Hansson, 2013). ALARP's main principle is that if more expenditure above ALARP point, then it is useless to keep putting more investment to reduce the risk further (Fig. 1.12). ALARP leaves the doors open for the company's interpretation and therefore undermine the legal liability that is hard to be proved because of the uncertainty level associated with.

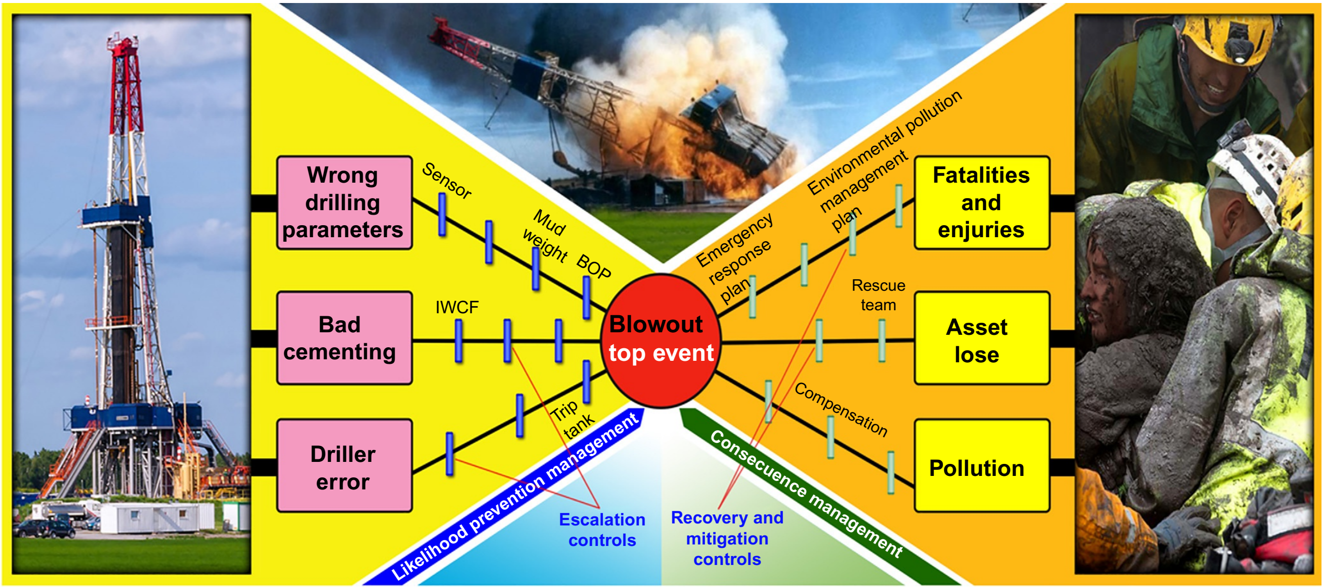


Fig. 1.11 A Bow tie example for drilling rig blow out.

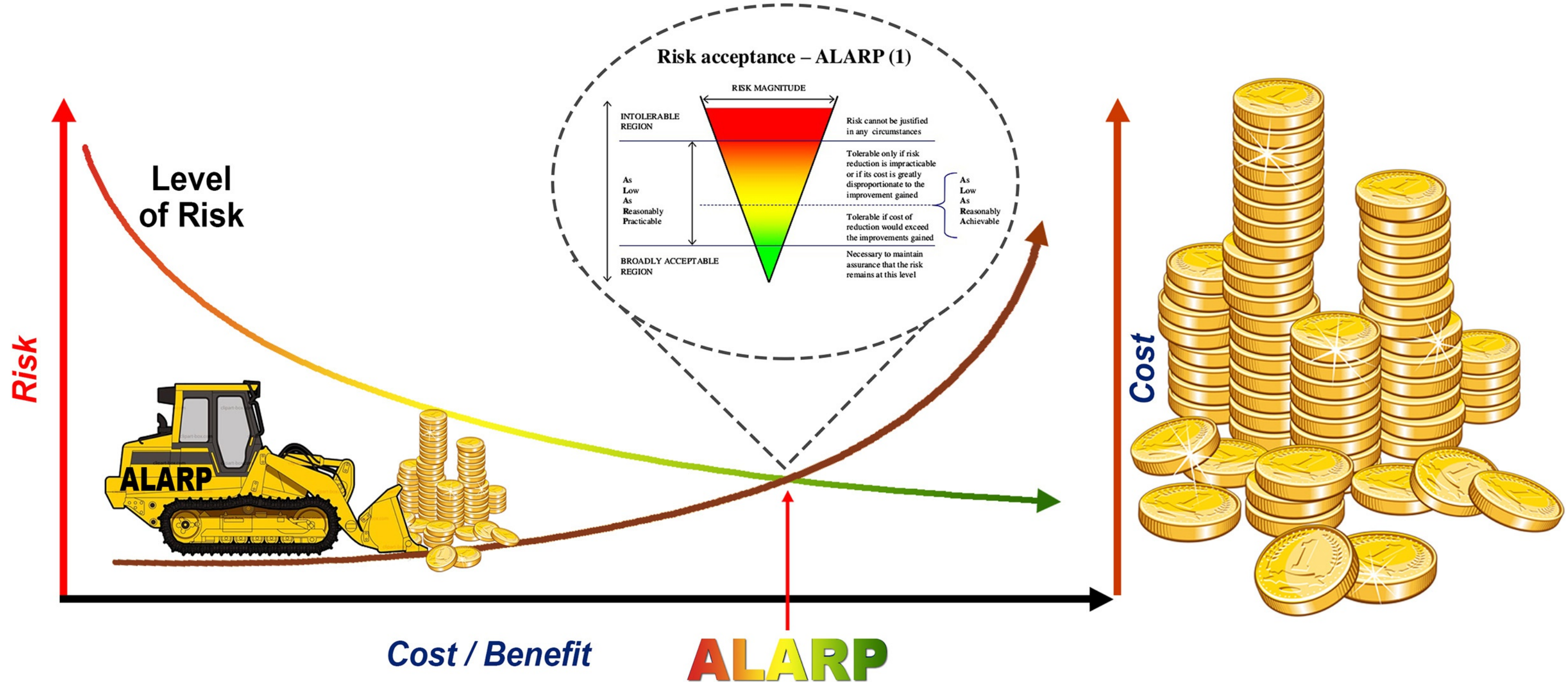


Fig. 1.12 ALARP.

1.8 Conclusion

The production of oil and gas has increased dramatically due to the high global demand and has resulted in increased technological risks due to the adoption of new production technologies. This raises a serious concern for the workers, the public, and the environment. It is rather unfortunate that the current measures to facilitate safety risk assessments and the deployment of the management tools in the oil and gas industry are not enough to mitigate, control, and prevent accidents because they are not necessarily based on scientific evaluation. It is, therefore, incredibly difficult to eliminate accidents in a complex and integrated system like the oil and gas industry using qualitative risk assessment and management system.

Based on the continual accidents in the oil and gas industry and related analytical studies, the most viable solution should be a focus on occupational health and safety through developing adequate safety measures that will prevent operational and occupational risks during oil and gas extractions and production operations. This can be achieved by promoting adoption of scientific-based approach that provides a systematic platform and comprehensive dynamic risk assessment framework management based on safety barrier performance evaluation and dynamic updating of abnormal events in the system and its subsystems.

Thus, frequently, mitigation of all types of accidents including occupational accidents can be achieved early by providing the appropriate safety measures and barriers that are effectively and dynamically maintained, these accidents do not have to escalate into life-threatening situations. This situation could be improved significantly by predicting, controlling, and mitigating exposure at the source and by emphasizing the prevention of incidents to achieve an inherently safer design to maximize safety.

Moreover, it is important for the oil and gas industry to consider in their safety and risk management system effective scientifically based solutions to conduct studies on human behavior from the psychological perspective. It is necessary to promote the development of this effort because occupational accidents are still happening, and this will have negative impacts on society. Future studies should be carried out using advanced dynamic modeling and QRA, which involve contributions from academic and technical experts who should play active roles in the oil and gas HSE management system.

References

Alakbarov, F., 2000. An overview Baku: city that oil built. Azerbaijan International 10.2, 28–33. Summer.

ALNabhani, K., Khan, F., Yang, M., 2015. Review technologically enhanced naturally occurring radioactive materials in oil and gas production. Process Safety and Environmental Protection (99), 237–247.

ALNabhani, K., Khan, F., Yang, M., 2016a. Scenario-based risk assessment of TENORM waste disposal options in the oil and gas industry. Journal of Loss Prevention in the Process Industries 40, 55–66.

ALNabhani, K., Khan, F., Yang, M., 2016b. The importance of public participation in legislation of TENORM risks management in the oil and gas industry. Process Safety and Environmental Protection 102, 606–614.

ALNabhani, K., Khan, F., Yang, M., 2017a. Management of TENORMs produced during oil and gas operation. Journal of Loss Prevention in the Process Industries 47, 161–168.

ALNabhani, K., Khan, F., Yang, M., 2017b. Dynamic modeling of TENORM exposure risk in the oil and gas industry using SMART approach. Journal of Petroleum Exploration and Production Technologies, 1–14.

Assaad, F., 2008. Field methods for petroleum geologists: A guide to computerized lithostratigraphic correlation charts case study: Northern Africa. Springer Science & Business Media, pp. 1–112.

Bacon, C.A., Calver, C.R., Boreham, C.J., Leaman, D.E., Morrison, K.C., Revill, A.T., Volkman, J.K., 2000. The petroleum potential of onshore Tasmania: a review. In: Geological Survey Bulletin. Mineral Resources Tasmania, p. 71.

Bourgoyne, A., Millheim, K., Chenevert, M., Young, F., 1986. Applied Drilling Engineering. 2, Society of Petroleum Engineers (SPE), pp. 1–502.

Considine, D., Considine, G., 2013. Van Nostrand's Scientific Encyclopedia. Springer Science & Business Media, pp. 2388–3524.

Craig, J., Gerali, F., Macaulay, F., Sorkhabi, R. (Eds.), 2018. History of the European oil and gas industry. Geological Society of London, Special Publication 465, 1–24.

Demirbas, A., 2009. Biohydrogen: For Future Engine Fuel Demands Green Energy and Technology. Springer Science & Business Media, pp. 1–276.

Dorsman, A., Ediger, V., Karan, M., 2018. Energy Economy, Finance and Geostrategy. Springer, pp. 1–274.

Groysman, A., 2014. Corrosion in Systems for Storage and Transportation of Petroleum Products and Biofuels: Identification, Monitoring, and Solutions. Springer Science & Business Media, pp. 1–297.

IAEA, 2008. Radiotracer Residence Time Distribution Method for Industrial and Environmental Applications. IAEA, Vienna.

Jahn, F., 1998. Hydrocarbon exploration and production. In: Developments in Petroleum Science. 49. Elsevier, pp. 1–396.

Johnston, J., 2011. Desilver, C. (Ed.), A Manual of Chemistry, on the Basis of Turner's Elements of Chemistry; Containing, in a Condensed Form, all the Most Important Facts and Principles of the Science, eighth ed. In: 1872, Original from the New York Public Library, pp. 1–530.

Lombardo, L., 2003. Overview of floating production, storage and offtake (FPSO) services agreements. AREL Journal, 468–484.

Oil Industry International Exploration and Production Forum (OIEPF), 1997. Environmental Management in Oil and Gas Exploration and Production: An Overview of Issues and Management Approaches. UNEP/Earthprint, pp. 1–68.

Osif, B., 2016. Using the Engineering Literature, second ed. CRC Press, pp. 1–600.

Oughton, D., Hansson, S., 2013. Social and Ethical Aspects of Radiation Risk Management. Newnes. vol. 19. Elsevier, pp. 1–408.

Perrin, D., 1999. Well Completion and Servicing. Editions Ophrys, pp. 1–313.
Samuel Hsu, C., Robinson, P., 2017. Springer Handbook of Petroleum Technology, second ed. Springer, pp. 1–1238.
Schobert, H., 2013. The Chemistry of Hydrocarbon Fuels. Butterworth-Heinemann, pp. 1–356.
Simanzhenkov, N., Idem, R., 2003. Crude Oil Chemistry. CRC Press, pp. 1–402.
Smith, D., 1993. Handbook on Well Plugging and Abandonment. PennWell Books. Technology & Engineering, pp. 1–399.
Song, W. 2015 Locating petroleum sources using DSP techniques, (Master Thesis). The Pennsylvania State University.1–34.
Swanson, V., 1960. Oil Yield and Uranium Content of Black Shales: Uranium in Carbonaceous Rocks. Geological Survey Professional Paper 356-A, US Atomic Energy Commission.
Termeer, C., 2013. Fundamentals of Investing in Oil and Gas. Chris Termeer, pp. 1–308.
Wikipedia, 2019. Drake Well. Available from: https://en.wikipedia.org/wiki/Drake_Well.

Further reading

Rinehart, I., 1930. Report on the Oil Fields of Northwest Germany. Lord Baltimore Press, Baltimore, MD.

CHAPTER TWO

Fundamentals of technologically enhanced naturally occurring nuclear radioactive materials in the oil and gas industry

Chapter Outline

2.1 Introduction to nuclear radioactive materials

Atom has been first revealed in a very precise scientific way more than 1400 years ago as it has been mentioned in several verses in the Holy Quran

Nuclear Radioactive Materials in the Oil and Gas Industry
https://doi.org/10.1016/B978-0-12-816825-7.00002-9

and the Hadith. For instance, Allah "May He be glorified and exalted" revealed in the Nobel Quran in Surah Yunus, verse 61:

> *And not absent from your Lord is any [part] of an atom's weight within the earth or within the heaven or [anything] smaller than that or greater but that it is in a clear register.*

Moreover, Allah "May He be glorified and exalted" also revealed prior 1400 years ago in several verses in the Holy Quran and the Hadith that atom has a weight, which has been confirmed recently by the modern science and said in the Nobel Quran in Surah Az-Zalzalah, verse 7:

> *So, whoever does an atom's weight of good will see it.*

The atom is one of the miracles of Allah mentioned in his holy book for more than 1400 years ago. It exists in both the earth and other planets. The Quran not only stresses the importance of the atom but also revealed the fact of the presence of the subatomic particles, where many nuclear elements have not yet been discovered by a human. Moreover, the Quran draws the attention to the existence of the atom, the subatomic particles, and other science related fact that modern physics has recently discovered. Taking into consideration that; people who lived in the era of the Prophet Mohammad (PBUH) did not have any idea about the atom or its subatomic particles and their compounds. This confirms the scientific miracle of the Quran.

Since then, the first theory of the atom was dated back to the fifth century B.C.E. when Greek scientists and philosophers built their theory of atoms on the work of ancient philosophers. They proposed the principle of identity that states that "matter was composed of atoms" (Ray and Hiebert, 1970). They have reached this conclusion primarily through deductive reasoning, logic, and mathematics but without conducting any experiments or providing a concrete scientific proof. Accordingly, the term "atom" comes from the Greek word for indivisible. These theories were disregarded until the 16th and 17th centuries because religious intellectuals considered the theory to be a materialistic view of the world that denied the existence of spiritual forces (Ray and Hiebert, 1970).

At the beginning of the 19th century, scientists, such as John Dalton and Jöns Jakob Berzelius, revived the atomic theory by using quantitative and experimental data (Ray and Hiebert, 1970). For example, John Dalton who is a British chemist and considered as a pioneer in establishing the science of modern and quantitative chemistry who has based his atomic theory on Democritus' ideas and believed that atoms are indivisible and indestructible. Additionally, he held a belief that different atoms form together to create all matter. In the new atomic theory, Dalton added his own ideas that all atoms of a certain element are identical and combining in simple whole numbers. However, the atoms of one element will have different weights and properties than atoms of another element. Moreover, atoms cannot be created or destroyed.

The modern science came and proved the fact mentioned by Allah 1400 years ago in the holy book "The Quran" that atoms are not the smallest particles of matter and revealed that atoms are made from smaller subatomic particles. The modern science revealed that the center of an atom is the nucleus and contains protons and neutrons. Electrons are arranged around the nucleus in energy levels or orbits. Both protons and electrons have an electrical charge. The proton is positive and the electron is negative. The neutron is neutral, and the total number of electrons orbiting around an atom is always the same as the number of protons in of that nucleus. The number of protons in an atom is used to refer to the atomic number. Atoms are arranged in the periodic table according to the increase in their atomic number. In this context and particularly in 1911, Ernest Rutherford, a physicist from New Zealand, is the one who discovered the atomic nucleus.

Between 1911 and 1920, Rutherford conducted experiments with cathode-ray tubes and found protons and neutrons have approximately the same mass (Charlie Ma and Lomax, 2012). He also theorized that there was also a neutral particle within the nucleus. The nucleus is held together by a strong force. This force amid to overcome the repulsive electrical force between protons. Based on the size of the nucleus, some atomic nuclei are unstable because the binding force varies for different atoms. These atoms will then decay into other elements to become more stable.

2.2 Basics in the science of nuclear radioactive materials

2.2.1 Radioactivity

Radioactivity was discovered by Henri Becquerel in 1896 when he was trying to find out whether natural phosphorescent materials emitted similar rays or not. He discovered that the uranium salts emitted rays that could pass through a metal sheet or thin glass (L'Annunziata, 2016). Further, Becquerel provided evidence that uranium metal gave off more intense radiation than the salts of that element. The new radiation produced ionization, and the intensity of the radioactivity could be measured by this. Thus, Becquerel was the first to provide evidence that some of the radiation emitted by uranium and its salts were similar in properties to electrons (L'Annunziata, 2012).

In 1898, Marie Curie discovered that not only uranium gave off the mysterious rays discovered by Becquerel, but also thorium did as well. Pierre and Marie Curie observed that the intensity of the spontaneous rays emitted by uranium or thorium increased as the amount of uranium or thorium increased. They concluded that these rays were a property of the atoms or uranium and thorium; thus, they decided to coin these substances as radioactive. The emanation of the spontaneous rays from atoms would now be referred to as "radioactivity."

Additionally, they found that another radioactive element with chemical properties like bismuth was present in pitchblende. She named this new element, polonium. They found a second new radioactive element in the pitchblende ore with chemical properties close to that of barium, and they named that new element "radium," from the Latin word radius meaning "ray." It is worth mentioning that Underhill (1996) stated, "Radium is of primary concern not only because it is radioactive, but also because it is chemically toxic."

Radium may be almost as toxic as polonium and plutonium, the most toxic element known to man. (It is estimated that one teaspoon of plutonium could kill 100,000 people, due to its chemical toxicity alone.) Due to its chemical properties, radium is termed a "bone seeker." Kumar and Dangi (2016) stated that in 1900, the French chemist and physicist, Paul Villard discovered while studying radiation emitted by radium a highly penetrating radiation in the form of electromagnetic waves that is consisting of photons.

In 1903, Ernest Rutherford was the first to name that highly penetrating radiation discovered by Villard as gamma rays. A few years prior to Villard's discovery, Rutherford in 1899 had already named two types of nuclear radiation as "alpha" and "beta," which he characterized based on their relative penetrative power in that the alpha radiation would be more easily absorbed by the matter than beta radiation. In harmony with this nomenclature, Rutherford assigned the term gamma rays to the more penetrating radiation (L'Annunziata, 2012). Therefore, radioactivity is the emission of radiation originating from a nuclear reaction or because of the spontaneous decay of unstable atomic nuclei.

The term radioactive decay refers to the process where unstable atomic nuclei decay with the loss of energy by the emission of elementary particles (such as alpha particles, beta particles, and neutrons) or energy such as gamma rays in the form of photons or electromagnetic waves to reach stability. These types of radioactive decays are usually referred to as ionized radiations. The energy emitted by these radiations are often enough to cause damage to biological cells, therefore, it is a serious health risk. Thus, radiation is the primary cause of safety concerns related to nuclear energy (Kumar and Dangi, 2016).

2.2.2 Types of radioactive decay

There are several types of particles or waves that may result from the decay of unstable atom to reach stability by losing its excess energy in form of particles or energy emission that is called ionizing radiation. There are many modes of radioactive decays, but the most common ones are: (1) alpha radioactivity; (2) beta radioactivity; and (3) gamma radioactivity.

The first and most common form of ionizing radiation is alpha radiations that comprise of a helium nucleus, which are made up of two protons and two neutrons. Alpha radiation is always associated with the release of an energy Q and most alpha particles have energies between 4 and 6 MeV (IAEA, 2008) This energy is equivalent to kinetic energy of alpha particles, the energy of recoil daughter nucleus, and the energy lost as gamma radiation from the daughter nucleus when it is at excited status as a result that helium nucleus is tightly bound. Alpha decay chemically represented by

$$_{Z}P^{A} \rightarrow {}_{Z-2}D^{A-4} + {}_{2}He^{4} + Q_{\alpha}\left(Q_{\alpha} = K_{T} = E_{\alpha} + E_{recoil} + E_{\gamma}\right) \tag{2.1}$$

where P is the parent nuclide, D is the daughter nuclide, and Q is the equivalent to the total kinetic energy during the alpha particles decay process (Fig. 2.1).

For example, the decay of alpha particles from Th^{228} will release energy equivalent to 5.5 MeV as shown by

$$_{88}Th^{228} \rightarrow {}_{88}Ra^{224} + {}_{2}He^{4} + Q_{\alpha}\left(Q_{\alpha} = K_{T} = E_{\alpha} + E_{recoil} + E_{\gamma}\ @5.5\,MeV\right) \tag{2.2}$$

Using Einstein's equation of mass and energy, we can calculate the energy equivalence to mass loss as following:

$$E = (\Delta m)c^2 \tag{2.3}$$

Therefore, large atoms often decay by discharging an energetic alpha particle. Alpha particles are relatively large and positively charged; and for that

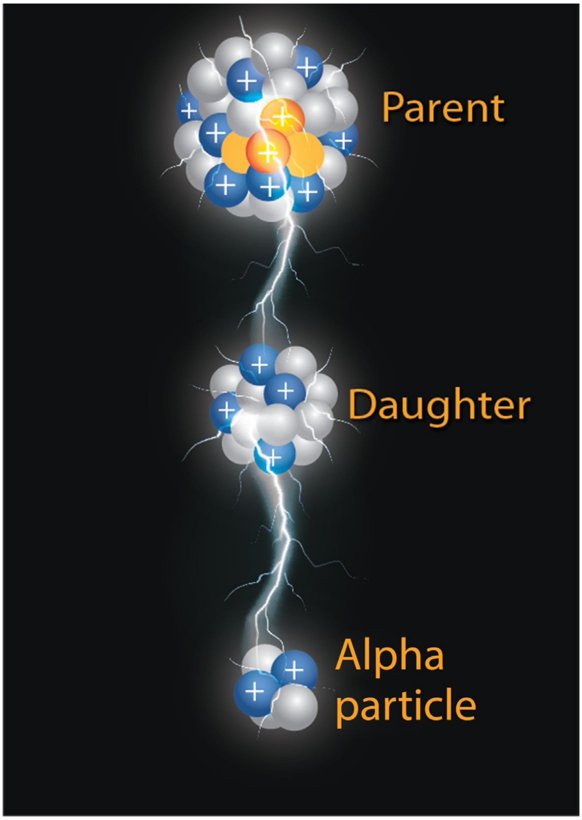


Fig. 2.1 Alpha decay.

reason, do not penetrate through matter easily. Nevertheless, these particles can cause extreme damage to materials by dislocating atoms as they slow.

The second form of radioactive decay is the beta particles radiations that are high-energy and high-speed electrons. They are emitted from the nucleus-decayed neutron when the neutron to proton ratio is too high. Conservation of charge requires a negatively charged electron to be emitted because neutrons are neutral particles and protons are positive, and this is known by negative beta decay (β-decay) and chemically represented by Eq. (2.4). Some isotopes decay by means of converting a proton to a neutron, in consequence emitting a positron (β+decay) as shown by.

$$^{A}P_{Z} \rightarrow {}_{Z+1}D^{A} + {}_{-1}\beta^{0} + \nu + Q_{\beta-} \quad \text{(Negatron)} \tag{2.4}$$

$$\left(Q_{\beta} = K_{T} = E_{\beta} + E_{\text{recoil}} + E_{\nu} + E_{\gamma}\right)$$

where P is the parent nuclide, D is the daughter nuclide, ${}_{1-}\beta^0$ is the negative beta particle, ν is the antineutrino, and K_T is the total kinetic energy released during beta decay (Fig. 2.2).

Example: ${}_{92}U^{235} \rightarrow {}_{93}Np^{235} + {}_{-1}e^0 + \nu + Q_{\beta-}$.

$$^{A}P_Z \rightarrow {}_{Z-1}D^A + {}_{+1}\beta^0 + \nu + Q_{\beta+} \quad \text{(Positron)} \tag{2.5}$$
$$\left(Q_\beta = K_T = E_\beta + E_{recoil} + E_v + E_\gamma\right)$$

where P is the parent nuclide, D is the daughter nuclide, ${}_{+1}\beta^0$ is the positive beta particle, ν is the neutrino, and K_T is the total kinetic energy released during beta decay (Fig. 2.3).

Example: ${}_{19}K^{38} \rightarrow {}_{18}Ar^{38} + {}_{+1}\beta^0 + \nu + Q_{\beta+}$

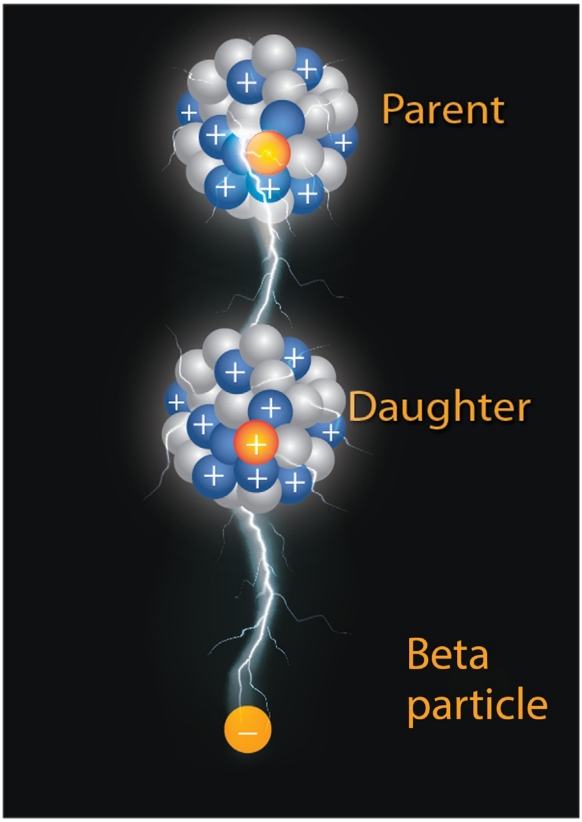


Fig. 2.2 Beta decay (β^- decay).

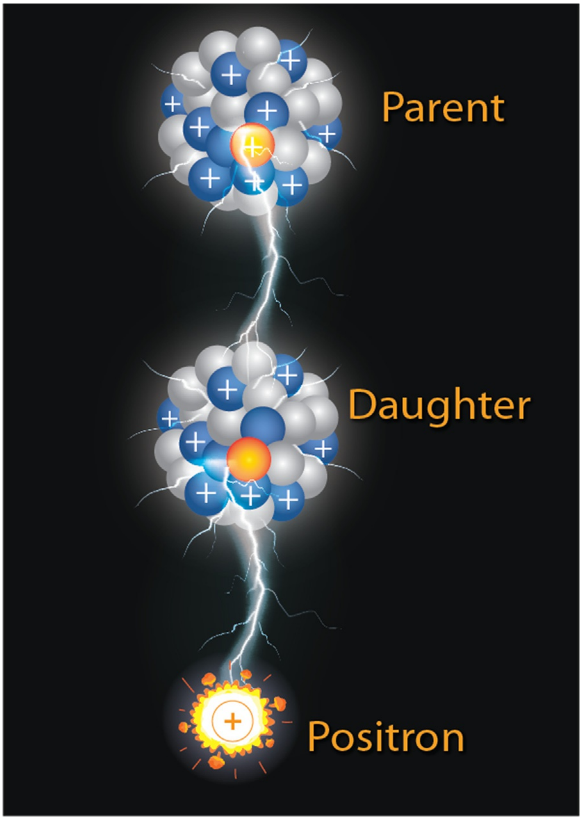


Fig. 2.3 Beta decay (β^+ decay).

The third type of the radioactive decay is gamma rays, which are photons that are emitted from the nucleus when it is in an excited state and often an atom will de-excite by emitting an electromagnetic wave that chemically represented by Eq. (2.6). IAEA (2008) stated that "Gamma rays are more energetic, and their energies range from ten thousand to ten million electron volts and depending on their initial energy, gamma rays can travel up to hundreds of meters in the air and can easily penetrate through most of the materials." This radiation requires lead shielding because they have no charge and can penetrate most matter easily. Therefore, people who are exposed directly to either alpha, beta, and gamma radiations through direct skin contact or internal contamination through ingestion or inhalation are an extremely serious health risk that may develop into cancerous diseases.

$$^{A}P*_{Z} \rightarrow {}_{Z}D^{A} + {}^{0}\gamma_{0} \quad \text{(Gamma emission)} \tag{2.6}$$

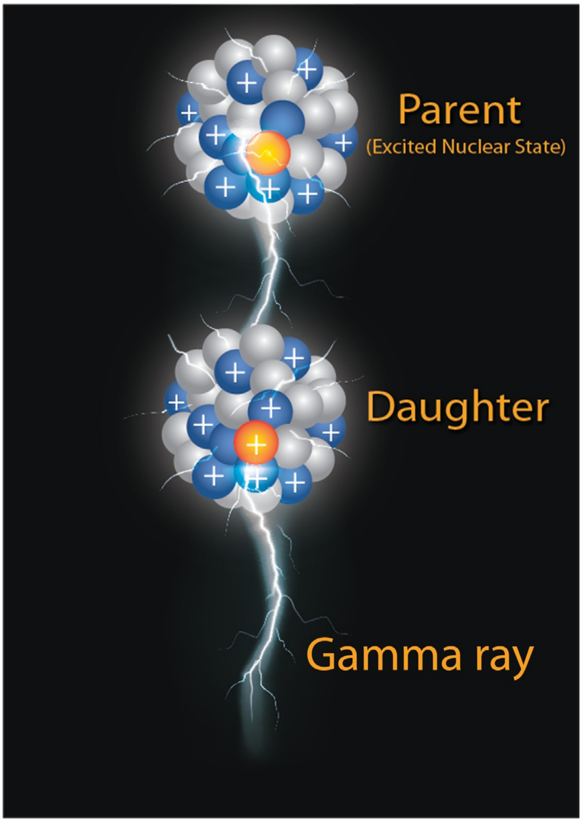


Fig. 2.4 Gamma decay.

where P^* is an excited parent nuclide, D is the daughter nuclide, and γ is the gamma emission (Fig. 2.4).

Example: ${}_{92}U^{235} \rightarrow {}^{0}\gamma_{0} + {}_{92}U^{235}$.

2.3 Technologically enhanced naturally occurring radioactive materials in oil and gas formations

2.3.1 An overview

Radioactivity accompanying the recovery of petroleum products was first discovered more than a century ago in wastes from crude oil exploitation (Elster and Geitel, 1904). Himstedt (1904) and Burton (1904) also reported the presence of higher than background concentrations of naturally occurring radioactive materials (NORMs) in crude petroleum. The presence of

NORM was also reported in numerous Russian and German research studies between 1920 and the 1930s (Al-Farsi, 2008). However, from a radiation protection point of view, an official survey had not been conducted until the early 1970s (AEC, 1972).

After the discovery of threatening levels of NORM in a North Sea oil platform in 1981, researchers began investigating the presence of NORM in crude petroleum and petroleum industry wastes (Kolb and Wajcik, 1985; Smith, 1987; Wilson and Scott, 1992; IAEA, 2003a,b). As a result of these studies, exposure to NORM was recognized as a serious health and safety issue during the extraction and production of oil and gas. This study is a prolog for further investigation of some important knowledge gaps related to technologically enhanced naturally occurring radioactive materials (TENORM) that have not yet been addressed in detail. This includes but is not limited to an understanding of the nuclear facts of NORM associated with oil and gas production, quantifying the likelihood of TENORM radiation exposure, the possibility of developing (cancerous) chronic diseases, and investigating the risk assessment of current practices.

The focus of the present study is to examine the presence of radioactivity in the oil and gas industry with the intention of highlighting the hazards to humans and the environment. It discusses the presence of TENORM in oil and gas formations and provides an overview of the geochemistry, radioactivity, solubility, and mobility of such substances. This study also reviews how the new technologies adopted by industry to enhance the production of oil and gas can enhance NORM to produce technically enhanced naturally occurring nuclear radioactive material (TENORM). The focus is placed in the presence of TENORM in produced water and wastes. All the issues mentioned above signal an urgent need to develop new approaches for dynamic risk assessment and management of TENORM as part of an integrated process of occupational safety and risk management system.

NORM is a term widely used to refer to radioactive materials that are naturally occurring in gases, liquids, and solids created by natural processes. In rare instances, naturally occurring radionuclides (NOR) is used as a synonym of NORM (Vandenhove, 2002), although this acronym focuses on the radioactive elements rather than the materials in which the radionuclides are stored (Knaepen et al., 1995). Bradley (2003) introduced the term NARM (naturally accelerator produced radioactive materials). These radioactive materials are artificially produced during the operation of atomic particle accelerators. They occur in the context of medical applications, research fields, and industrial processing.

The term TENORM is used to describe the natural radioactive materials in which the concentration of radionuclide is enhanced by man-made procedures. The terms TENR and ENOR are also used to describe technologically enhanced natural radioactivity and enhanced naturally occurring radioactivity (Edmonson et al., 1998), respectively. Paschoa and Godoy (2002) replenished usage of the acronym HINAR to describe the areas affected by high natural radioactivity. The acronym was used initially in 1975 in the first international conference, held in Brazil, which dealt with both NORM and TENORM (Cullen and Franca, 1977).

National and international organizations have further refined NORM and TENORM definitions. The International Association of Oil and Gas Producers (IAOGP) defined NORM as naturally occurring radionuclides that are present at varying concentrations in the earth's crust and can be concentrated and enhanced by processes associated with the production of oil and gas. This "enhanced" NORM, often known as TENORM, can be created when industrial activities increase the concentrations of radioactive materials or when the material is redistributed because of human intervention or some industrial processes (IAOGP, 2008). The US Environmental Protection Agency (US EPA) defined "NORM as the materials which may contain any of the primordial radionuclides or radioactive elements as they occur in nature, such as radium, uranium, thorium, potassium, and their radioactive decay products that are undisturbed as a result of human activities" (US EPA, 2008).

The US EPA defined "TENORM as naturally occurring radioactive materials that have been concentrated or exposed to the accessible environment as a result of human activities such as manufacturing, mineral extraction, or water processing and technologically enhanced means so that the radiological, physical, and chemical properties of that radioactive material have been altered by having been processed, or beneficiated, or disturbed in a way that increases the potential for human and/or environmental exposures" (US EPA, 2008). The Canadian Nuclear Safety Commission defined NORM as the materials found in the environment that contain radioactive elements of a natural origin and which contain uranium and thorium (elements that release radium and radon gas once they begin to decay) and potassium (CNSC, 2014).

Table 2.1 summarizes different definitions of NORM from different literature reviews.

This study considers TENORM as geo-phys-thermo-chemical processes in which the concentration levels of radionuclides of NORMs are

Table 2.1 Development of NORM definitions

S. No.	Acronym	Definition	Interpretation
1.	NOR	Naturally occurring radionuclides	Emphasis on the radioactive elements and not on the materials where the radionuclides are stored in (Knaepen et al., 1995)
2.	NORM	Naturally occurring radioactive material	All solid radioactive materials being created by natural process (Vandenhove, 2002)
3.	NARM	Naturally accelerator produced radioactive materials	Natural radioactive materials being artificially produced during the operation of atomic particle accelerators (Bradley, 2003)
4.	TENR	Technologically enhanced natural radioactivity	Natural radioactivity is technologically enhanced (Edmonson et al., 1998)
5.	ENOR	Enhanced naturally occurring radioactivity	Natural occurring radioactivity is technologically enhanced (Edmonson et al., 1998)
6.	HINAR	High natural radioactivity	Focused on areas affected high natural radioactivity (Paschoa and Godoy, 2002)
7.	TENORM	Technologically enhanced naturally occurring radioactive materials	Radionuclide content of natural radioactive materials is enhanced by man-made procedures (Common in industries and highly used)

enhanced by human intervention or industrial practices used in oil and gas exploration, extraction, and production activities. This enhancement is characterized by an artificial enrichment of the activity concentration of radionuclides of NORM given in the SI unit [Bq/kg] related to dry mass for each radionuclide. The principal radionuclides are isotopes of unstable atoms with a high atomic and mass number of elements. These elements belong to the radioactive series headed by the three long-lived isotopes, uranium-238 (uranium or U series), uranium-235 (actinium series), and thorium-232 (thorium or Th series) in which decay exceeds the threshold of 200 Bq/kg dry mass (StrSchV, 2001). This can be vindicated by the correlation of the ambient gamma dose rate of 1 mSv/year measured 1 m above the ground and the corresponding radionuclide concentration of 200 Bq/kg homogenously distributed in the ground (UNSCEAR, 1993, 2000).

The artificial enrichment of NORM in the oil and gas industry can arise in many different ways as a result of enhanced oil recovery technologies (EORT) and other industrial practices used during oil and gas exploration, extraction, and production activities (Bou-Rabee et al., 2009; Bourdon et al., 2015; Dresel and Rose, 2010; Farooqui et al., 2009; IAEA, 2013; Krane, 1978; Leopold, 2007; Organo and Fenton, 2008). For example, during oil exploration, remote-sensing methods of mapping and explosive seismic associated with seismic exploration processes may enhance the activity concentration of NORM. In addition, NORM enhancement can be affected by drilling operations, and well-logging activities such as; induced neutrons well logging and radioactive tracers that are used in evaluating the formation, the effectiveness of well cementing, underground water, and crude oil flow direction; enhanced oil recovery technologies including well stimulation processes such as well acidizing, well perforation, and formation fracking activities that use produced water mixed with radioactive materials, which already contains high activity concentrations levels of NORM as a medium to fracture-producing zone and consequently enhancing activity concentration of NORMs that are already exist in those fractured rock formations; the disposal of TENORM waste and reinjecting of produced TENORM wastes into underground formations where they originally came from and contribute in more accumulation, enhancement, and further reactions. This practice is common for TENORM waste disposal management in the oil and gas industry; thermal heating process; thermal injection process; and injection of various amounts of radioisotopes used in the secondary recovery flooding fluids to facilitate and track the flow. All these new technologies and human interventions are significantly contributing to the NORM's activity concentration enhancement.

In affirmation of what has been mentioned above, Avwiri and Ononugbo (2011) assessed the NORM content encountered during hydrocarbon exploration and production in Ogba/Egbema/Ndoni fields and concluded that:

- In the host community soil, field soil, and field sediment samples, the concentration of the gross alpha and beta (particles decayed from NORM) was higher than that of the control samples from a non-oil-bearing community. According to the oil and gas industry, this enhancement attributed due to industrial activities used in the oilfield to enhance oil and gas recoveries as well as due to current practices adopted by the oil

and gas industry in disposing of oilfield wastes contaminated with radioactive materials directly into the geological formations.
- The contour maps of the studied area showed a nonlinearity of the distribution of radionuclide. The enhanced gross alpha and beta radioactivity in the contour maps might not be from geological constituents of the area and could be due to new technologies deployment and industrial activities in that area to enhance oil and gas recoveries as well as the disposal methods for radioactive waste produced.

Furthermore, from the perspectives of nuclear physics and chemistry, NORMs are made of natural materials formed by a large number of molecules or ionic compounds where atoms join by chemical or electromagnetic bonding to form substances. These atoms are basically made of three types of subatomic particles: neutrons and protons in the nucleus and electrons orbiting the nucleus. The instability of the nucleus of each atom renders radionuclides radioactive as it tries to release its excess energy by emitting particles or nuclear radiation in the form of alpha particles (emitting nucleons), beta particles (emitting an electron or positron), or gamma rays (electromagnetic waves consisting of photons) (Gopalakrishnan, 1998).

These three radiation types are found to be the most common in the oil and gas industry, and gamma radiation is the riskiest one. The neutron emission may lead to fission because of nuclear reactions or the radioactivity decay process in which the nucleus of an atom splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and photons (in the form of gamma rays) and releases a very large amount of energy even when measured by the standards of radioactive decay (DuraiRaj et al., 2014). Such fission can happen naturally in the geological formation due to the availability of physical and chemical conditions that are suitable for such reaction. The existence of this phenomenon was discovered in 1972 at Okloin Gabon, Africa by French physicist Francis Perrin (Smellie, 1995).

2.3.2 TENORM geochemistry and its relationship with oil and gas

The US geological studies dating back to 1944 proved that black shale is a major source of uranium and oil. Some black rocks contain up to a hundred times more uranium than other sedimentary rocks, and they also contain organic substances that will produce oil. The amount of uranium in these rocks is extremely large reckoned in billions of tons of metallic uranium (Swanson, 1960). Furthermore, many scientific works of literature have addressed the presence of NORM in oil and gas formations in several countries.

For example, there have been findings in the United States, Poland, and the Netherlands. Fisher (1995a,b) reported that in the United States between 1959 and 1989, uranium and thorium could be found in sedimentary formations of common shales, black shale, sandstones, orthoquartzites, siltstones, claystone, carbonates, bentonites, carbonate rocks, halite, anhydrite, and phosphate rock. The American Petroleum Institute (API) national NORM survey obtained radioactivity measurements from oil-producing and gas-processing facilities in 123 of the 254 Texas counties and identified geographic regions where above-background radioactivity in oil-producing and gas-processing operations had been recorded (Otto, 1989).

In 1999, the presence of NORM in oil and gas wells in New York State was investigated, particularly in Marcellus shale (black shale), and the Paleontological Research Institution identified different levels of activity concentration of uranium, thorium, potassium, and their daughter products approximately found in all rocks and soil. Their concentrations vary based on the type of the rock. For example, black shale, such as the Marcellus, often contains levels of uranium-238, uranium-235, potassium-40, and thorium-232 in higher concentrations than found in less organic-rich gray shale, sandstone, or limestone.

Many shale formations contain elevated levels of NORMs, such as isotopes of radon and radium (Genereux and Hemond, 1990). Radium (Ra) is a component of Marcellus shale and is produced from the radioactive decay of high concentrations of uranium and thorium found naturally within black shales (Schmoker and James, 1981; Bank et al., 2010). Moreover, the uranium content has been noted to be in the range of 10–100 ppm. The natural radioactive decay of uranium and thorium overtime leads to the formation of other radionuclides such as Ra-226 and Ra-228 (Pennsylvania Department of Conservation and Natural Resources, 2008).

Exploration by the Polish Geological Institute found uranium mineralization in the Ordovician dictonema shales in the Podlasie depression and the lower and middle triassic sediments (sandstones) of the Peribaltic Syneclise. These geological materials are categorized as uranium bearing (Chajduk et al., 2013). The uranium content in various samples taken from the same deposit differ from one another, and dictyonema shales contain the highest uranium content compared with other minerals found, whereas the calculated mean value for uranium content is three times higher than that in dictyonema shales. Similarly, Jonkers et al. (1997) reported findings from the Netherlands that indicated various concentrations of both uranium and thorium in sedimentary rock and geological formations that contain oil and gas such as sandstone, conglomerate, black shale, limestone, and carbonate.

The outcomes of these studies are in line with the geochemistry of both uranium and thorium that are the main sources of TENORM and are found to be abundant in rock reservoirs that contain significant quantities of hydrocarbons. This leads us to a very important preliminary conclusion in deciphering the mystery of the origin of oil and gas through an explanation of the strong positive correlation between the presence of hydrocarbons and radioactive materials in the same formation. Scientifically, it has been proved that, oil is inherent in the shales formations and derived directly from the "lithophiles," which are organism substances that exist within the porous cavities of sedimentary and even broken sedimentary/igneous rocks up to several kilometers deep as a result of the volcanic reactions, whereas most of the uranium is also inherent in the shale formation and from the same organism substances.

The organism substances responsible for both oil and uranium are two types of organic matter; the first type called sapropelic organism substances, which generally yield four or five times more oil than the humic organism substances, which are the second type that create a reducing and acidic environment and responsible for the concentrating and deposition of uranium in the black shales.

This rigorous scientific interpretation may make the world to rethink its old theories related to the origins of oil. Therefore, shale is considered a radioactive formation of different radioactivity concentration. Furthermore, and from geochemistry science point of view, uranium and thorium have different solubility characteristics in the rock matrix and their mobility in aqueous systems is mostly controlled by the pH, alkalinity, the oxidation–reduction potential (ORP), and the type of complexing agents present, such as carbonates, phosphates, vanadates, fluorides, sulfates, and silicates (Kumar et al., 2012). These are very similar to the formation water mineral elements, which explain why TENORM is found more with produced formation water coproduced with oil and gas.

Geochemically, both uranium and thorium are strongly lithophilic elements, and both occur in the 4^{+} oxidation states. However, uranium can also be oxidized to the oxidation state 6^{+} as UO_2^{2+}. This is well within the redox potential range in geological environments (Krauskopt, 1969). Uranium enrichment precipitation occurs more in reducing environments, often of an acidic nature and typically in organic-rich sediment like darker marine shale and carbonate that contains more hydrocarbons, where more radioactivity concentration levels were measured and found with a high content of organic matters (Russell, 1945).

This explains why radioactivity is used as an indication of hydrocarbons presence. It also adsorbs readily onto clays and organic phosphates. Some uranium is found in silt and clay-sized minerals. In essentially all geologic environments, oxidation states 4^+ and 6^+ are the most important oxidation states of uranium, whereas U^{6+} ion is even more soluble than the U^{4+} ion, which also explains why radioactive materials are found more soluble with formation water coproduced during hydrocarbons' production. At the same time, U^{4+} generally precipitates as stable and very insoluble uranous oxides and hydroxides, in the form of uraninite (UO_2(c)), pitchblende (UO_2(am)), schoepite ($UO_2(OH)_2H_2O_2$-(c)), and coffinite ($USiO_4$(c)) (Langmuir, 1978). By oxidation, U^{4+} passes easily to valence U^{6+} as $UO_4{}^{2-}$ or $U_2O_7{}^{2-}$. U^{6+} is typically present as the soluble uranyl ion ($UO_2{}^{2+}$), which can also form stable complexes with a variety of anions, such as phosphates, carbonates, and sulfates.

Furthermore, U^{6+} may form complexes with organics. Depending on their stability, these complexes may affect the Eh value required for the precipitation of UO_2 to occur (Lisitsin, 1971). Therefore, the conversion between uranyl and uraneous ions is highly dependent on Eh and pH conditions [hydrogen ions (pH), and the activity of electrons (Eh)]. Therefore, the following inorganic uranium forms are typical for sedimentary rocks (Jonkers et al., 1997):

- Sandstone UO_2 (uraninite) and $USiO_4$ (coffinite): U contents average of 1.5 ppm or more than that [around 20 μBq (U238/g)].
- Limestone (UO_2) (CO_3): U contents average of 2.5 ppm or more than that [around 30 μBq (U238/g)].

Owing to its solubility, $UO_2{}^{2+}$ is chiefly transported in solutions. However, under reducing conditions $UO_2{}^{2+}$ forms numerous complexes with organic compounds (e.g., humic acids), which facilitates uranium fixation by organic sediments (peat, lignite, and coal) and mineral matter. Localization of uranium in organic shale (up to 20 ppm or 250 μBq or more) (uranium-238/g) is another typical example of this fixation. These organic substances are particularly important in absorption of uranium from water. Thermal diagnosis of organic matter that is responsible to produce hydrocarbons found to contribute in enhancing uranium concentration, as uranium remains with the residual organic matter (Erickson et al., 1954).

On the other hand, thorium can exist only as Th^{4+} in the natural environment owing to its insolubility and is almost wholly transported in suspension. Thus, it concentrates in the silty fraction of shale as thorium minerals or thorium-bearing assessor minerals such as monazite, the major thorium-bearing mineral. Thorium is also found mostly in heavy minerals of silt and clay fraction and in intrusive rocks such as granite, garnierite, and syenite. The following thorium forms are typical for sedimentary rocks (Jonkers et al., 1997):

- Sandstone: ThO_2 (Thorianite) and $ThSiO_2$ (Thorrite) Th content average of 5 ppm [around 20 μBq (Th232/g) or more].
- Limestone: Th content average of 1.1 ppm [around 25 μBq (Th232/g) or more].

Humic substances are also important to the absorption of thorium from the water. Hence, the thorium concentration in groundwater approximated to ±0.007 ppb, corresponding to 0.3 μBq (232Th/g) (Jonkers et al., 1997).

Generally, the mobilization of uranium, thorium, and the radionuclide isotopes leaching from minerals or rocks is governed by various factors including the physical mineral/rock condition, disequilibrium fractionation, polymerization, chemical reactions, the nature of their occurrence in mineral/rock, and the chemical composition of the leaching water (Zukin et al., 1987). Understanding the geochemistry of NORMs and their geological formation is important to predict and prevent their exposure, and to know the source rock of hydrocarbon with high certainty. Significant research has concluded that the main source of NORMs are radionuclides decay from uranium or thorium series, which are found mainly in sedimentary formations of common shales, black shale, sandstones, orthoquartzites, siltstones, claystone, carbonates, bentonites, carbonate rocks, halite, anhydrite, and phosphate rock.

Some of these formations most probably contain oil or gas and are penetrated during drilling activities. Uranium and thorium series and other minerals that exist in these formations usually emit naturally occurring gamma radiations, alpha, and beta particles emissions as their unstable atoms attempt to reach stability by emitting such excess energy. The ratio of natural gamma radiation emitted by thorium compared to uranium in these formation rocks is used as an indicator of the presence of hydrocarbons using a combination of geochemical logs, spectral gamma-ray logs as well as a neutron and resistivity logs that can calculate the total organic carbon content (TOC).

Practically, there are different techniques adopted by the industry to calculate TOC. These include the $\Delta \log R$ technique, the optimal superposition coefficient Δ log R technique, the carbon organic LOG (CARBOLOG) technique. These are mathematically interpreted as:

$$\mathrm{TOC} = \Delta \log R * 10^{(2.297-0.168\mathrm{LOM})} + \Delta\mathrm{TOC} \quad (2.7)$$

where LOM is the amount of level organic metamorphism (Hood et al., 1975) and ΔTOC is the regional background level.

$$\Delta \log R = \log R / R_{\text{baseline}} + 0.0061(\Delta t - \Delta t_{\text{baseline}}) \tag{2.8}$$

where $\Delta \log R$ is the curve separation between porosity log and resistivity log; R is the resistivity measured in Ωm; Δt is the transit time measured in μs/m; and R_{baseline} is the resistivity corresponding to the $\Delta t_{\text{baseline}}$ when the curves are baseline in non-source rocks.

However, selecting a baseline is relatively complicated because of strong subjective factors. In addition, TOC background level is different regionally and not easy to determine. The method is then improved to optimal superposition coefficient $\Delta \log R$ technique, which does not need to determine baseline and calculates TOC directly using fixed superposition coefficient 0.0061. The improved algebraic expression is:

$$\text{TOC} = a \log R + b \Delta t + c \tag{2.9}$$

where a, b, c is constant coefficient.

The CARBOLOG technique.

$$\text{TOC} = a \Delta t + b \Delta t^{-1/2} + c, \tag{2.10}$$

where a, b, c is constant coefficient.

2.4 TENORM production in the oil and gas industry

From geochemical point of view, it can be concluded that there is a strong relationship between uranium/thorium and organic carbon content where hydrocarbon potential can be identified easily, as the same conclusion has been reached by many authors, such as Beers and Goodman (1944), Russell (1945), Swanson (1960), Supernaw et al. (1978), and Zimmerle (1995). It is also concluded that uranium is commonly found in clays of reducing environments, particularly in the presence of carbonaceous material where organic-rich dark shales are highly radioactive and show high gamma-ray log counting rates as well as spectral gamma log responses with high potassium, thorium, and uranium readings. Such readings give very accurate confirmation that shales are ordinarily radioactive and a good source of hydrocarbon and uranium (Swanson, 1960).

They can also be used as an accurate source of information to predict radiation levels associated with hydrocarbon during exploration, extraction, and production activities, where many scholars such as IAOGP (2008), El Afifi and Awwad (2005), Testa et al. (1994), Al-Masri and Aba (2005), and Othman et al. (2005) confirmed that these radioactive materials are found in many types of equipment associated with the various stages of oil and extraction and production processes including but not limited to the following:

- downhole equipment and materials such as electric submersible pump (ESP) pumps, drilling bits, tubular, and casings;
- drilling rig subsurface equipment such as drilling mud systems, wellheads, and waste bits as well as in midstream equipment such as flow lines, separators, and pumps; and
- refining equipment and storage tanks.

Therefore, radiation risk can be mitigated and prevented at a very early stage by using an appropriate safety and risk management system such as the SMART approach that will be discussed in greater detail in Chapter 4.

2.5 TENORM In produced water and wastes generated by the oil and gas industry

As explained earlier from the geochemistry point of view, TENORM are brought to the surface as suspended or dissolved particles with formation water that is produced as the reservoir pressure falls overtime during extraction of oil and gas (Cooper and Malcolm, 2005). The amount of TENORM formed in oil producing fields and incorporated in oil and gas extraction is directly proportional to the volume of produced water generated during the pumping of the oil (Rood et al., 1998; Gazineu et al., 2005). Produced water contaminated with TENORM is considered oil and gas generated waste and the ratio of produced water to oil is approximately 10 to 1. According to the API (1989), more than 18 billion barrels of waste fluids from oil and gas production were being generated annually in the United States vs the total crude oil volume of 2.5 billion barrels (400 million m^3). Total produced water volume constituted 91% of such wastes.

Although researches are being undertaken to determine how to treat produced water to comply with the reuse and discharge limits, the common practice in oil and gas industries is reinjection of contaminated produced water into the geological formation to enhance oil and gas recovery in an economical manner (Veil, 1998). However, this reinjection, in fact, increases formation water salinity deposit of additional radioactive materials that accumulate and react with originally existing NORMs. Therefore, enhances NORM activity concentration and converting them into technologically enhanced naturally occurring nuclear radioactive materials. Unfortunately, this practice is widely used in the oil and gas industry around the world. For example, the enhanced radium-226 activity concentration found is almost like the range of values reported in the waste generated in Australia (Holland, 1998) and the United States (Rood, 2001).

In the 1990s, offshore fields in Europe recorded an annual release of radium-226 and radium-228 with produced water at around 5 TBq (1 TBq = 10^{12} Bq) per year and 2.5 TBq per year, respectively. This explains why reinjection of produced water is considered one of the reasons behind NORM's activity concentration enhancement. As a result, the enhanced radioactive radionuclides in this waste are classified as TENORM (IAEA, 2002). In this context, El Afifi and Awwad (2005) have concluded from their study that:

- There is an enhancement in the radium-226 concentrations in the TENORM waste generated during the oil and gas production.
- TENORM waste contains mainly radionuclides of uranium-238, uranium-235, and thorium-232 series.
- TENORM waste contains major elements of Si, Fe, Al, Na, Mg, Ca, Sr, Ba as well as trace amounts of heavy metals Mn, Fe, Zn, Cu, and Pb.

It has also been reported in the IAEA basic safety standards-1994 that the activity concentrations of the uranium-238 and thorium-232 series in the bulk waste samples coproduced with formation water are higher than the exemption activity levels for the NORMs. Consequently, this gives rise to a serious health hazard for workers in this industry.

2.6 Common forms of TENORM wastes

TENORM wastes result from uranium-238 and thorium-232 series and their decay products are brought to the surfaces in different forms through the produced water (Cooper and Malcolm, 2005) or as a drilling cuttings with drilling fluids and may contain levels of radioactivity above the surface background (API, 1992; Rood et al., 1998; Rood, 2001; Shawky et al., 2001; Matta et al., 2002; Al-Masri and Suman, 2003; Godoy and da Cruz, 2003; Hamlat et al., 2003; Mohamad Puad and Muhd Noor, 2004; Omar et al., 2004; El Afifi and Awwad, 2005; Gazineu et al., 2005). Some uranium and thorium decay products and their progenies are soluble in the produced water such as radium isotopes or insoluble and become suspended in the produced water. As a result, these products may remain in the solution even in the final product or settle to form sludge, mineral scales, or a thin film, the latter being common in gas processing activities.

Sludge usually is composed of dissolved solids. A mixture of hydrocarbon, mud, natural or technologically enhanced radionuclides, sediments, bacterial growth, corrosion particles, and scale debris precipitate from produced water due to temperature and pressure change (Omar et al., 2004). The main radionuclides of interest in sludge are radium-226, radium-228, polonium-210, lead-210, and radium-228 according to the IAEA-TECDOC-1712 (IAEA, 2013).

Radioisotopes of radium-226 and radium-228 are not only incorporated into sludge but also can be found in scale, produced sands and produced water associated with oil and gas production. In fact, radium isotopes and their progenies are strong gamma emitters; therefore, the external radiation dose near separation tanks, flow lines, for example, increases as sludge builds up. Other radionuclides such as lead-210 (beta and gamma emitter) and polonium-210 (alpha emitter) can also be found in a drilling rig's waste pits, evaporation ponds, mud tanks, mud pumps, drill pipes as well as in downstream equipment such as pipelines, tank bottoms, gas/oil/water separators, dehydration vessels, liquid natural gas (LNG) storage tanks, and slops tanks of oil production facilities (IAOGP, 2008). The API (1987) has determined that most sludge settles out of the production stream and remains in the oil stock and water storage tanks.

Scales are another form of TENORM wastes that are generally formed in the downhole tools such as completion tools, packers, casings, liners, ESPs, bottom hole assemblies as well as in completion tubing and piping (AP1, 1989). Moreover, downhole equipment used in oil wells such as casing and tubing also found to be highly contaminated with TENORM scale from outside and according to the Michigan survey (Minnaar, 1994), it has reported of high contamination of (5300 R/h) on outside downhole equipment. They can also be found in well heads, injection station equipment, and upstream flow lines and refinery equipment (Testaet al., 1994; Al-Masri and Aba, 2005; Othman et al., 2005); while its brittle nature can cause it to dislodge from the pipe walls and migrate to the oil–water separation tanks or any other associated equipment.

Unfortunately, personnel working on drilling rigs and work-over units, flow line construction and maintenance, production/gathering stations, and refinery are highly exposed to radiation from these scales because they are in direct contact with bottomed hole assemblies, retrieved casing, liners, completion tools, well heads, production equipment, flow lines, separation tanks, and pumps that are contaminated with TENORM.

As mentioned earlier, scale precipitates from the produced water or formation water due to changes in temperature and pressure. The sudden change in pressure and temperature increases the scaling tendency of TENORM as it is brought to the surface. Under high-temperature and pressure conditions in an oil reservoir, different concentrations of barium, strontium, calcium, and radium are leached out from reservoir sand and are present in a soluble form in the formation water that contains sulfates, carbonates calcium, barium, strontium, acids, and other ions.

The chemical characteristics of radium catalyze its reaction with Ba, Sr, and Ca compounds, and as a result radium precipitates with Sr, Ba, and/or Ca scale forming radium sulfate, radium carbonate, and in some cases radium silicate that develops in the tubular and other areas of the oil and gas extraction rigs (Wilson and Scott, 1992; Hamlat et al., 2001; Godoy and da Cruz, 2003; Al-Masri and Aba, 2005). Moreover, TENORM scales encountered in oil and gas facilities can also be incorporated into sulfate scale such as $BaSO_4$, $SrSO_4$, and carbonate scale such as $CaCO_3$.

According to the US EPA (1993) and Smith et al. (1996), it has been estimated that between 25,000 and 225,000 tons of NORM contaminated scale and sludge wastes are generated each year from the US petroleum industry. The available data indicate that total radium in scale and sludge varies greatly from undetectable levels to 15,170 Bq/g in scale and 25,900 Bq/g in sludge and even to higher levels. Drilling cuttings is another potential radioactive hazard. Since uranium and thorium have different ranges of solubility in the formation water in sediment or rocks that contain oil and gas, there is a reasonable probability that these materials will appear on the surface as cuttings that are generated as the rocks are broken by the drill bit penetrating through the rock or soil.

These cuttings are usually carried to the surface by a drilling fluid called drilling mud circulating up from the drill bit. Drill cuttings can be separated from liquid drilling fluid by shale shakers or by centrifuges. Unfortunately, these cuttings are dumped into waste pits or disposed of via land-spreading farms or directly into the seabed. Such practices pose serious radiological health and environmental risks as these cuttings may contain gamma radiations coming from the radium-226 radionuclide and its progenies: lead-214 and bismuth-214. IAEA (2008) reported that "γ radiations carry energies that range from ten thousand to ten million electron volts and depending on their initial energy can travel up to a hundred meters in the air." Thus, it can easily penetrate through most of the materials around the drilling rig site/platform or disposal area.

Subsequently, crew members involved in drilling activities, disposal farms, and the mud system and geologists [who examine the drill cuttings to make a record (a well/mud log) of the formation] all are at high radiation risk, which naturally poses a significant health risk. In this regard, the Paleontological Research Institution (1999) found that all radioactive elements present in Marcellus shale can potentially pose a threat of direct radiation exposure during gas well drilling operations that can bring rock cuttings with TENORM to the surface. Furthermore, the US Department of Energy (2013) reported the concentrations of NORM present in black shale drill cuttings and drilling mud may be greater than background environmental levels.

The last form of TENORM waste types is a gas film. Radon presents in varying degrees in natural gas and dissolves in the (light) hydrocarbon and the aqueous phase. When produced with oil and gas, radon will usually follow the gas stream. If the natural gas is fractionated, a disproportionately high percentage of radon can concentrate in the propane streams and to a lesser degree in the ethane streams. Through natural decay, radon-222 produces several radioactive nuclides (also known as radon progeny) which may result in forming thin radioactive films containing relatively high levels of isotopes of lead-210 on the inner surfaces of gas processing equipment such as scrubbers, compressors, reflux pumps, control valves, and product lines. Approximately 64% of the gas producing equipment and 57% of the oil production equipment showed radioactivity above or near background levels (API, 1990). TENORM radioactivity levels tend to be the highest in water handling equipment. Average exposure levels for this equipment were found between 30 and 40 μR/h, which is about five times background (Abdel-Sabour, 2014).

2.7 Modes of radiation exposures in the oil and gas industry

When an organism is exposed to nuclear radiation such as alpha or beta or gamma, ionization of atoms that form the molecules of the human body lead to the destruction of tissues and cells. The degree of risk resulting from these radiations depends on several factors, including type of the radiation, radiation quality, exposure duration, amount of energy produced from the radiation, radiation accumulation, the age, medical history, type of living cell and its ability to respond, which differs from cell to cell in the same body or from one body to another, and many other factors.

Ionized radiation comes from various sources and affects living organisms from humans, animals, plants, and microorganisms. Ionized radiation emits high-energy particles in the form of electrons, protons, helium atoms, and photons so that a change in the order of amino acids in the genetic and enzymatic material results in genetic damage transmitted to future generations or physical damage affecting the living organism.

The time between exposure of the living organisms to radiation and the occurrence of damage varies from several hours to several decades. The interaction of radiation with the human body arises from two sources either from an external source of the body and from an internal contamination of radioactive substances (Fig. 2.5) resulting from ingestion or inhalation, both of which lead to biotic effects that may subsequently emerge as pathological symptoms.

The nature and intensity of these symptoms can be divided into two parts: (1) the physical effects. Here, the symptoms appear on the same person in form of the skin cancer, or blood cancer, or lung cancer, or bone cancer, or white eyes injury and sterility or (2) genetic effects that appear on the descendants of the person exposed to the radiation. This is clearly shown on the Japanese after the atomic bombs were dropped on Hiroshima and Nagasaki in September 1945.

2.8 Biological and health effects of radiation exposure

2.8.1 Radiation reaction with cells

The fundamental difference between nuclear radiation and the rest of the radiation we encounter daily, such as heat and light, is that nuclear radiation has enough energy to cause ionization of the living cell. As mentioned earlier, the water molecules make up most of the living cell in the body, and when ionized by radiation this causes molecular changes that give rise to different groups of chromosomes in form of mutations that may develop later into cancer.

The processes that cause biological effects are quite complex and often take four stages:

1. The physical phase
2. The physicochemical phase
3. The chemical phase, and
4. The biological phase

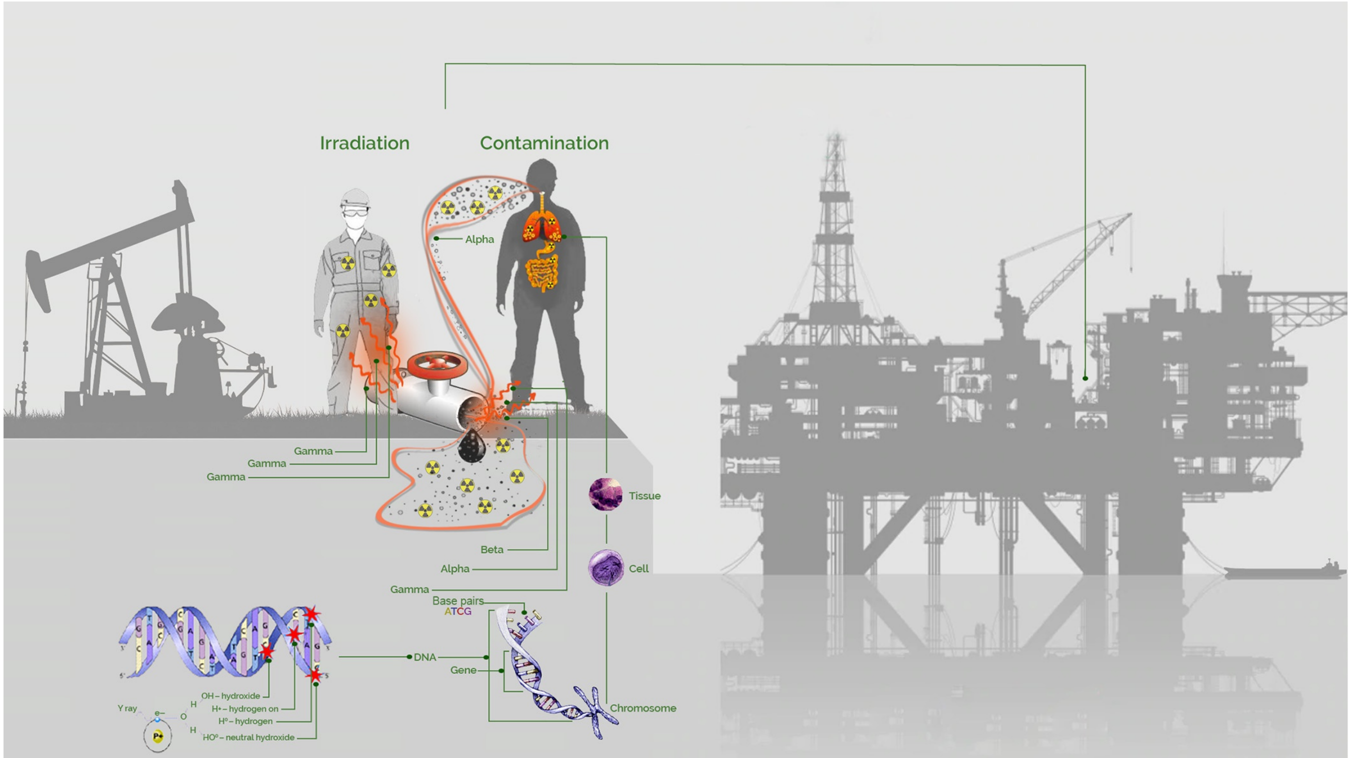


Fig. 2.5 Modes of radiation exposure and its biological effects.

The physical phase

At this phase, the time it takes for the radiation to enter the living cells is about 10^{-16} s. When the energy of a certain type of radiation moves in water molecules in living cells, ionization reactions occur, this reaction can be explained by.

$$\text{Photon or particle} + H_2O \rightarrow H_2O^+ + e^- \tag{2.11}$$

where H_2O^+ is the positive water ion and e^- is the negative electron.

The physicochemical phase

This phase also takes a very short time about 10^{-6} s after ionization has occurred in the previous phase. At this stage, a reaction between the positive and negative ions with the water molecules occurs, where different compounds will result from this reaction, for example, the positive water ion can be decomposed into a diatomic anion called hydroxide according to the following equation:

$$H_2O^+ \rightarrow OH + e^- \tag{2.12}$$

The hydroxide will react with other produced hydroxide and will finally decompose into hydrogen peroxide as shown by.

$$OH + OH \rightarrow H_2O_2 \tag{2.13}$$

while the negative electron produced from reaction shown by Eq. (2.11) can also combine with water molecules and will decompose into a negative water ion as shown by.

$$e^- + H_2O \rightarrow H_2O^- \tag{2.14}$$

Furthermore, the negative water ion may decompose into hydrogen and the negative hydroxide ion as shown by

$$H_2O^- \rightarrow H + OH^- \tag{2.15}$$

Chemical phase

This phase takes a few seconds after the physicochemical phase. And at this phase, the final products of the previous reactions of the physicochemical phase, which are H, OH, and H_2O_2, will react on a very large scale with millions of living cells that are made up of chromosomes and will combine, eventually, these reactions will result in breaking the chromosomes chains causing mutation or cell damage. This type of radiation reactions called the indirect action of radiation, which is more dangerous than the direct action of radiation due to the fact of cluster reactions resulting in a cluster attack of living cells and thus multi-biological damage.

In this regard, Fan (1992) argued that double-strand breaking and DNA-protein cross-links breaking are "relevant" to DNA damages, which has a great potential to contribute to biological effects and cell death (the deterministic effects). Furthermore, Ward (1988) argued that it has been measured that numbers of damaged per cell per Gy are as following:

- 1000 base damage,
- 1000 single-strand breaking,
- 40 double-strand breaking, and
- 150 DNA-protein cross-links.

While a recent laboratory study conducted by Caron et al. (2008) argues that even low-energy electrons can cause a serious DNA damage and if electron's energy is above the ionization threshold which is about 10 eV then that is enough to ionize the living cell and cause a DNA damage and biological effect.

The biological phase

This phase can take from a few minutes to several years. At this phase, the chemical changes that occur in the living cell begin to appear in the form of a biological effect, which will take one of the following roots if it fails to repair itself:

1. transformation, mutation, chromosome aberration, or cells dead (deterministic effects),
2. prevent, delay, or increase the division of living cells, and.
3. constant changes in the cell are transmitted genetically to nascent cells.

Therefore, workers involved in oil and gas extraction and production activities including upstream, midstream, and downstream are at high risk of being exposed to different levels of radiation exposure as shown in Fig. 2.5.

This could be attributed to the fact that TENORM is produced with oil and gas production and can be found in different forms in different streams. Accordingly, these workers can be exposed to the ionizing radiation in two exposure pathways explained below.

External radiation paths

Gamma, beta, and neutron radiation are the dominant external radiation pathways. External radiation is responsible for emitting radiation that would hit the human body and cause the ionization of cells. Therefore, workers involved in drilling operations including mud loggers, mud testers, work over crewmembers, and flow line maintenance crewmembers are highly expected to be exposed to external radiation because of the gamma radiations emission from soluble and insoluble radioactive materials that can be found in form of scales, sludges, and drilling cuttings.

Internal radiation exposure pathway

The route of exposure to internal radiation can be through the inhalation routes or through the ingestion routes.

Inhalation routes

Inhalation exposure results from the inhalation of alpha particles and mainly from radon decay products and contaminated dust. Radon-222 is a radioactive by-product of radium, which is part of the series of radioactive decay that begins from uranium-238 and decays by emitting alpha particles to polonium, bismuth, and lead in successive steps. The only possible route for inhaling radioactive materials is through an airborne exposure route connecting the source in the contaminated area. The airborne exposure route is expected more in the drilling sites, gathering, and production stations where oil and gas are separated from formation fluid and other contaminated scales and sludges, as well as in the refineries.

Ingestion routes

When it comes to ingestion pathways, contaminated drinking water, and food pathways can be considered as the primary sources. People consume many different types of foods, which include aquatic foods, milk-based foods, meat, and plant-based foods. All these food types can result in the ingestion pathways.

It is possible to subdivide the plant-based food pathway into four different categories. They include:

1. Root uptake of the foods that are cultivated in a contaminated source.
2. Foliar uptake of the foods that are subjected to the deposition of dust on foliage.
3. Root uptake of the foods, which are contaminated with irrigation water.
4. Foliar uptake of the foods that are contaminated with irrigation water.

They can, directly and indirectly, affect humans through drinking contaminated water or eating food or livestock that eat contaminated food, respectively. Therefore, this can be considered as the fifth subcategory as well. A good example to explain the fifth subcategory is the camels that graze in the oilfield. This has become prominent in the Middle East countries where most of the oilfields are in the deserts. Usually, these deserts are inhabited by Bedwen people and their livestock that usually graze and seek for water in nearby oilfields, where radioactive waste materials are being disposed of within the unfenced pits. It has been reported many times that these camels are drinking or even sometimes falling in unfenced oilfield waste pits (Fig. 2.6), drilling fluid pits, and eating from the contaminated grass and plants that are growing nearby radioactive waste disposal land farms. Then, Bedwen people will consume the camels' milk and their meats and will indirectly be exposed to the radiation that may develop into cancer.

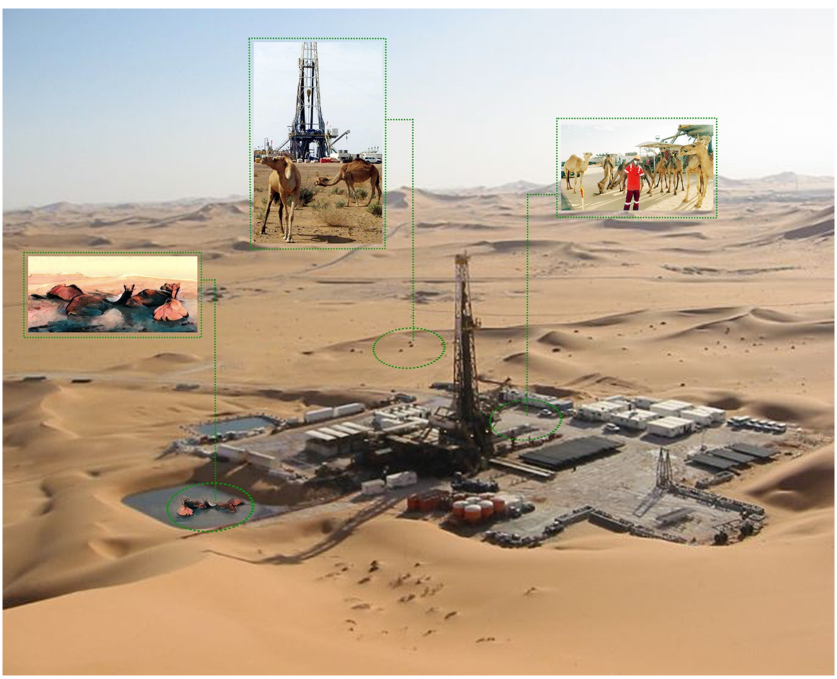


Fig. 2.6 The risk of the oil and gas industry on camels.

2.9 Knowledge and technical gaps

The presence of TENORM in the oil and gas industry has been known for over a century, but its impacts on health, safety, and the environment have not been closely assessed. Despite several decades of extensive research and studies addressing qualitatively the presence of TENORM in the oil and gas industry, many knowledge and technological gaps remain in addressing scientifically the potential health, safety, and environmental concerns of how to safely manage their exposure. Therefore, this section attempts to outline the main knowledge and technical gaps that have not yet been explored or fully addressed in the available literature with respect to TENORM issues in oil and gas.

2.9.1 Knowledge gaps

Lack of scientific knowledge about the fundamental concepts and theories of TENORM in the oil and gas industry

Some of the available studies and researches are unable to scientifically distinguish between NORM and TENORM. While the radiological properties of the naturally occurring, radioactive materials are coproduced during the oil and gas extraction and production processes found to be technologically enhanced through anthropogenic processes. Unfortunately, the fundamental theories and concepts related to TENORM issues in the oil and gas industry were absent in many of the available studies and literature. This lack of scientific knowledge certainty dictates that precautions should be taken to ensure the quality and integrity of research.

The Absence of legislation and the lack of consistency of safety standards related to radiological risks posed by TENORM in the oil and gas industry

The current regulatory and legislative status of TENORM has not been well established, particularly in relation to the issues that affect and threaten the human welfare and the environment. Occupational radiological exposure or radiological pollutions from huge volumes of TENORM waste are generated daily from oil and gas production and their direct disposal processes into the environment. Therefore, risks posed by TENORM produced from oil and gas production are significant enough to warrant immediate action to develop state regulatory controls and to standardize international guidelines for TENORM safety management in the oil and gas industries.

For example, this issue is an important concern in the United States because, in the absence of federal regulations, many states have begun to develop regulatory programs to control TENORM in oil and gas that may contradict with others. However, there remains the challenge of obtaining adequate information and understanding to devise appropriate regulations that can mitigate or eliminate TENORM risks.

There is a significant knowledge gap also in many TENORM guidelines that are appropriate for the handling and storage of TENORM wastes but fail to adequately outline considerations regarding the long-term assessment, monitoring, and management of disposed TENORM wastes in a safe and environmentally friendly manner, and the implications of such disposal options on environment and human health. In addition, many guidelines fail to standardize the correct safest allowable exposure limits of TENORM to be followed in the oil and gas industry, which is still a controversial issue within the scientific community. Furthermore, many of the available guidelines and regulations are designed to regulate nuclear safety in general and are not specifically designed for TENORM safety in the oil and gas industry, which in turn have similar nuclear, chemical, and physical properties. For example, neither the US EPA nor the Nuclear Regulatory Commission has specific regulations designed for safe TENORM exposure and management in the oil and gas industry (Smith, 1992).

Historical database of TENORM

A knowledge gap also exists in maintaining an accurate database of TENORM production from the oil and gas industry in the past and present. For example, knowledge of TENORM waste inventory is important to assess the long-term consequences of TENORM exposure, exposure pathways, and the fate of radioactive waste in the last 60 years. It is also needed to determine waste disposal options through an assessment of the relative amount of waste that is being produced, the amount of waste currently on production sites in need of safe disposal, and likely future production of this waste.

Considering that some of these TENORM radionuclides in such waste have a long-term effect that can exceed thousands of years. It becomes very important to have accurate inventory records to know what types of radioactive materials were produced so that future generations know the exact amount of the radioactive waste, their radiological risks, where they have been disposed of, and how so they are able to avoid living with such waste.

2.9.2 Technical gaps

Technical evaluation of TENORM geochemistry

Characterization of the varying geochemical and physical forms of TENORM in geological formations will help to predict and mitigate radiological risks at a very early stage during oil and gas extraction and production activities. Bridging this gap will give a better understanding of risks associated with TENORM exposure in each phase of production and therefore, provide the scientific basis for TENORM risk management in the oil and gas industry.

Consideration of consequences of hazardous chemical agents

Another significant technical gap is the failure to consider the consequences of the hazardous chemical agents commonly found in combination with TENORM. The risks posed by mixed hazardous chemicals and radioactive wastes raise complex issues during dynamic quantitative risk assessment that need to combine both radiological and toxic risks assessment simultaneously.

Dynamic accident modeling and quantitative risk assessment and management

Understanding the conceptual models for TENORM system behavior will bridge the primary technical gaps in developing new approaches of dynamic accident modeling and quantitative risk assessment management. This strategy will help to predict, prevent, and manage TENORM exposure risk at very early stages. The development of safety barriers and other safety precautions will make it possible to prevent, mitigate, and control the unwanted/undesirable events resulting from radiation pollution or radiation exposure. Radiation in the oil and gas industry can be predicted from available data used to confirm the presence of hydrocarbons that can be obtained from well and field correlation logs. This data are a valuable source of information that can be used to characterize the geological distribution of uranium/thorium sources (TENORM) due to the strong correlation relationship between radioactive materials and the presence of hydrocarbon. The findings of this study show the potential for further research areas and methodologies to be explored and developed, including but not limited to the following:

- Comprehensive TENORM exposure pathways survey in all oil and gas drilling, production, processing, and refining, filling stations facilities, workshops, and equipment, as many of them were neither surveyed nor assessed yet.

- Engineering dynamic and quantitative risk assessment coupled with medical recommendations of TENORM waste management practices including handling, disposal options, and risk values.
- Laboratory investigation of the consequences and impacts of TENORM exposure on public health and the environment.

Current TENORM waste disposal methods used by the oil and gas industry

Current practices for managing and disposing of such wastes are short term in nature and are not necessarily based on the scientific evaluations or radiological risk assessments from both engineering and biological perspectives. These practices include disposal in land farms or injection into geological formations, or directly into the seabed. All are designed only to temporarily prevent the direct exposure of workers and the public to radiation. Moreover, they have created additional problems and unforeseen hazards for both environment and future generations.

Lack of scientific-based TENORM waste disposal and management solutions

The oil and gas industry, as well as governments, shall soon be confronted with the task of developing safer, longer term, and more cost-effective methods to minimize, process, and dispose of TENORM wastes to adequately protect workers, the public, and the environment. One option is the development of process plants that can safely manage huge volumes of daily produced TENORM waste and then use this wasted energy to generate energy that will contribute positively to the sustainable economies development of oil and gas producing countries. In principle, these process plants shall be like the Thermo-chemi-nuclear Conversion Plant (TCP) invented and proposed at the end of this book in the chapter that outlines recommendations for future projects.

Utilization and recycling of TENORM wastes to generate energy

Results from TENORM surveys indicate that radionuclide concentration can vary in range from undetectable to extremely high levels. For example, offshore fields in Europe recorded an annual release of radium-226 and radium-228 with produced water at around 5 TBq (1 TBq = 1012 Bq) per year and 2.5 TBq per year. Furthermore, US EPA (1993) and Smith et al. (1996) estimated that between 25,000 and 225,000 tons of NORM contaminated scale and sludge wastes are generated each year from the US petroleum industry. The available data indicate that total radium in scale and sludge varies greatly from undetectable levels to 15,170 Bq/g in scale and 25,900 Bq/g in sludge and even to higher levels. Moreover, extremely high radium concentration was measured in produced water as high as 159,000 pCi/L in sludge according to the Michigan survey (Michigan Department of Public Health, 1992); therefore, the potential of energy optimization produced from enhanced radioactive nuclides coproduced with oil and gas production may provide an area for future research consideration especially that scientifically, it has been found that rocks contain hydrocarbons are also the good source for uranium.

Energy generated by TENORM waste could be assessed directly, or by investigating data collected from well and correlation data. These data are capable of quantifying with more accuracy the content of radioactive material, abundances, rock source types, energy emission strength, and radionuclide half-lives (energy life). Furthermore, researching this area will provide valuable insight into how to manage, recycle, or dispose of waste in a safe and efficient manner as compared to current practices.

Moreover, oil and gas industries can produce uranium ore beside oil and gas production. Swanson (1960) argues that some black shales are referred to be a good potential source of both oil and uranium as they contain up to 100 times more uranium than other common sedimentary rocks as well as contain organic responsible for both of oil and uranium. Thus, produced formation water can be treated using in situ recovery technique, which can be incorporated in TCP. In situ recovery process is a lixiviant solution injection process that is exactly like enhanced oil recovery technology (EORT) currently used to enhance oil recovery. In this process, a liquid medium such as sulfuric acid or water mixed with oxygen and sodium bicarbonate is used to extract the desired metal, which are in this case U238 or U235 from the ore. This process is known by the hydrometallurgical extraction process.

TENORM exposure pathways and health impacts

It is not only workers involved in drilling, production processing, and refining activities of oil and gas production who are at risk of being exposed to TENORM radiation, but also the public can be at the risk of being exposed to radiation through different exposure pathways. The pathways of concern are internal inhalation (e.g., TENORM suspended particle in the dust, radon inhalation), ingestion (drinking contaminated water, food, or skin beta exposure), and external exposure (exposure to gamma rays). Exposure to any of these pathways in the absence of safety measures may lead to cancerouseq chronic and fatal diseases, such as leukemia; cancers of the lung, stomach, esophagus, bone, thyroid, and the brain; harm to the nervous system; and genetic abnormalities and sterility. These pathways and the effects of exposure to them require further investigation.

References

Abdel-Sabour, M.F., 2014. NORM in waste derived from oil and gas production, http://www.researchgate.net/profile/MamdouhAbdelSabour/publication/264722815 NORM in waste derived from oil and gas production.pdf (retrieved 17.02.15).

AEC, 1972. Grand junction remedial action criteria. 10 CFR 12. Atomic Energy Commission, Washington, DC.

Al-Farsi, A., 2008. Radiological aspects of petroleum exploration and production in the Sultanate of Oman, Doctoral thesis. Available from QUT database (Document ID 29817/1) http://eprints.qut.edu.au/29817/1/Afkar Al-Farsi Thesis.pdf (retrieved 11.02.15).

Al-Masri, M.S., Aba, A., 2005. Distribution of scale containing NORM in different oilfields equipment. Appl. Radiat. Isot. 63, 457–463.

Al-Masri, M.S., Suman, H., 2003. NORM waste in the oil and gas industry: the Syrian experience. J. Radioanal. Nucl. Chem. 256 (3), 159–162.

AP1, 1989. A national survey on naturally occurring radioactive materials (NORM) in petroleum producing and gas processing facilities. API, Dallas, TX.

API, 1987. Measurement Protocol for the Occurrence of LSA Material. API, Dallas, TX.

API, 1990. Management and disposal alternatives for NORM wastes in oil production and gas plant equipment, Report submitted to API: RAE-8837/2-2, prepared by Rogers and Associates Engineering Corporation. API, Dallas, TX.

API, (Ed.), 1992. Bulletin on management of naturally occurring radioactive materials (NORM) in oil and gas production, first ed. API, Dallas, TX. API Bulletin E2 (BULE2).

Avwiri, G.O., Ononugbo, C.P., 2011. Assessment of the Naturally Occurring Radioactive Material (NORM) content of hydrocarbon exploration and production activities in Ogba/Egbema/Ndoni Oil/Gas Field, Rivers State, Nigeria. In: Proceedings of the 1st International Technology, Education and Environment Conference (c) African Society for Scientific Research (ASSR). Co-Published By: Human Resource Management Academic Research Society, pp. 572–580. Available from: http://hrmars.com/admin/pics/262.pdf.

Bank, T., Malizia, T., Andresky, L., 2010. Uranium geochemistry in the Marcellus shale: effects on metal mobilization. Geol. Soc. Am. Abstr Programs 42, 502.

Beers, R.F., Goodman, C., 1944. Distribution of radioactivity in ancient sediments. Bull. Geol. Soc. Am. 55, 110–118.

Bou-Rabee, F., Al-Zamel, A., Al-Fares, R., 2009. Technologically enhanced naturally occurring radioactive materials in the oil industry (TENORM): a review. Nukleonika 54 (1), 3–9.

Bourdon, B., Turner, S., Henderson, G., Lundstrom, C., 2015. Introduction to U-series geochemistry. http://www.earth.ox.ac.uk/ gideonh/pdffiles/Intro.pdf (retrieved 25.03.15).

Bradley, F.J., 2003. Risk-based classification of radioactive and hazardous chemical wastes. Health Phys. 85 (6), 759–760. NCRP Report No. 139.

Burton, E.F., 1904. Petroleum radioactive gas. Phys. Z 5, 511–516.

Caron, L., Tonzani, S., Greene, C., Leon Sanche, L., 2008. Diffraction in low-energy electron scattering from DNA: bridging gas phase and solid-state theory. Phys. Rev. A 78, 1–42.

Chajduk, E., Bartosiewicz, I., Pyszynska, M., Chwastowska, J., Polkowska-Motrenko, H., 2013. Determination of uranium and selected elements in Polish dictyonema shales and sandstones by ICP-MS. J. Radioanal. Nucl. Chem. 295, 1913–1919. https://doi.org/10.1007/s10967-012-2330-9.

Charlie Ma, C.-M., Lomax, T., 2012. Proton and Carbon Ion Therapy Imaging in Medical Diagnosis and Therapy. CRC Press, pp. 1–256.

CNSC, 2014. Fact sheet naturally occurring radioactive material, (http://www.nuclearsafety.gc.ca/pubscatalogue/uploads/NORM-factsheet-eng.pdf (retrieved 27.02.15)).

Cooper and Malcolm, B., 2005. Naturally occurring radioactive materials (NORM) in Australian industries—Review of current inventories and future generation. Australian Radiation Laboratory. Radiation Health and Safety Advisory Council ERS-006, September.

Cullen, T.L., Franca, P.E., 1977. Proceedings of International Symposium on High Natural Radioactivity, Pocos de Caldas, Brazil, June 16–20.

Dresel, P.E., and Rose, A.W., 2010. Chemistry and origin of oil and gas well brines in Western Pennsylvania. Pennsylvania Geological Survey, Fourth Series Harrisburg. (Open-File Report OFOG 10-01.0), 48 pp. http://www.marcellus.psu.edu/resources/PDFs/brines.pdf (retrieved 17.03.15).

DuraiRaj, P., Thamilarasu, P., Krishnadas, K., 2014. Gamma rays from nuclear propulsion annihilation of matter. IJMRD 1 (7), 292–295. Retrieved from, http://allsubjectjournal.com/vol1/issue7/PartG/pdf/47.1.pdf.

Edmonson, R.M., Jeliffe, M.R., Holwand, K.N., 1998. Chapter 2. Naturally Occurring Radioactive Material (NORM). Jackson, Mississippi.

El Afifi, E.M., Awwad, N.S., 2005. Characterization of the TE-NORM waste associated with oil and natural gas production in Abu Rudeis. Egypt. J. Environ. Radioact. 82, 7–19.

Elster, J., Geitel, H., 1904. Über die radioaktive Substanz, deren Emanation in der Bodenluft und der Atmosphäre enthaltenist. Phys. Z. 5 (1), 11–20.

Erickson, R.L., Myers, A.T., Horr, C.A., 1954. Association of uranium and other metals with crude oil, asphalt, and petroliferous rock. Am. Assoc. Pet. Geol. Bull. 38, 2200–2218.

Fan, S., 1992. DNA strand breaks induced by gamma ray irradiation, Doctoral thesis. University of Leicester.

Farooqui, M.Y., Hou, H., Li, G., Machin, N., Neville, T., Pal, A.,Wang, Y., Shirivastva, C., Yang, F., Yin, C., Zhao, J., Tang, X., 2009. Evaluating volcanic reservoirs. Oilfield Review 21, https://www.slb.com/media/Files/resources/oilfield review/ors09/spr09/evaluating volcanic reservoirs.pdf (retrieved 3.03.15).

Fisher, R.S., 1995a. Naturally occurring radioactive materials (NORM) in produced water and scale from Texas Oil, Gas and Geothermal Wells: Geographic, Geologic and Geochemical controls. Bureau of Economic Geology. 43 pp.

Fisher, R.S., 1995b. Geologic and Geochemical Controls on Naturally Occurring Radioactive Materials (NORM) in Produced Water from Oil, Gas and Geothermal Operations. The University of Texas at Austin, Austin, TX.

Gazineu, M.H.P., Araujo, A.A., Brandao, Y.B., Hazin, C.A., Godoy, J.M.D.O., 2005. Radioactivity concentration in liquid and solid phases of scale and sludge generated in the petroleum industry. J. Environ. Radioact. 81, 47–54.

Genereux, Hemond, 1990. Naturally occurring radon 222 as a tracer for stream flow generation: steady state methodology and field sample. Water Resour. Res. 26, 3065–3075.

Godoy, J.M., da Cruz, P., 2003. 226Ra and 228Ra in scale and sludge samples and their correlation with the chemical composition. J. Environ. Radioact. 70, 199–206.

Gopalakrishnan, R.K., 1998. Basic nuclear physics (radioactivity). 31–41. http://gnssn.iaea.org/RTWS/general/Shared%20Documents/Standards%20Application/Education%

20and%20Training/Task%20McDonnell/PGEC%202002%20-%20Syllabus%20and%20Lectures%20Notes/Lecture%20notes/Part%20I II/Chapter%204 5.pdf.
Hamlat, M.S., Djeffal, S., Kadi, H., 2001. Assessment of radiation exposures from naturally occurring radioactive materials in the oil and gas industry. Appl. Radiat. Isot. 55, 141–146.
Hamlat, M.S., Kadi, H., Fellag, H., 2003. Precipitate containing norm in the oil industry: modeling and laboratory experiments. Appl. Radiat. Isot. 59, 95–99.
Himstedt, F., 1904. Radioactive emanation. Phys. Z. 55, 210–213.
Holland, B., 1998. Experience with operations involving NORM in the UK and some other regions. Australian Nuclear Science and Technology Organization, Sydney, pp. 16–20.
Hood, A., Gutjahr, C., Heacock, R., 1975. Organic metamorphism and the generation of petroleum. AAPG Bull. 59, 989–996.
IAEA, 2002. Technologically enhanced natural radiation (TENRII). Vienna.
IAEA, 2003a. Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry. Safety Series, vol. 34. ISBN 92-0-114003-7.
IAEA, 2003b. Extent of environmental contamination by naturally occurring radioactive material (NORM) and technological options for mitigation. Technical Reports Series no. 419, ISBN 92-0-112503-8.
IAEA, 2008. Radiotracer residence time distribution method for industrial and environmental applications. Vienna.
IAEA, 2013. Management of NORM residues. TECDOC 1712, Vienna.
IAOGP, 2008. Guidelines for The management of naturally occurring radioactive material (NORM). The Oil & Gas Industry Report No. 412.
Jonkers, G., Hartog, F.A., Knaepen, W.A.I., 1997. Characterization of NORM in the oil and gas production (E&P) industry. In: Proceedings of International Symposium on Radiological Problems with Natural Radioactivity in the Non-Nuclear Industry, September 8–10, 1997. Shell Research & Technology, Netherlands, Amsterdam. 23–47 Available from: http://i.iv.7.eu-norm.org/index.pdf (retrieved 09.03.15).
Knaepen, W.A.I., Bergwerf, W., Lancée, P.J.F., Dijk, V.W., Jansen, J.F.W., Jannssen, R.G.C., Kietzenberg, W.H.T., Sluijs, V.R., Tijsmans, M.H., Voljers, K.J., Voors, P.I., 1995. State-of-the-art of NORM nuclide determination in samples from oil and gas production: validation of potential standardization methods through an interlaboratory test program. J. Radioanal. Nucl.Chem. 198 (2), 323–341.
Kolb, W.A., Wajcik, M., 1985. Enhanced radioactivity due to natural oil and gas production and related radiological problems. Sci. Total. Environ. 45, 77–84.
Krane, K.S., 1978. Introductory Nuclear Physics. Oregon State University.
Krauskopt, 1969. Introduction to Geochemistry. McGraw-Hill, New York.
Kumar, A., Dangi, V., 2016. Electromagnetic spectrum and its impact on human life. Int. J. All Res. Educ. Sci. Methods 4 (8), 67–72.
Kumar, A., Singhal, R.K., Rout, S., Narayanan, U., Karpe, R., Ravi, P.M., 2012. Adsorption and kinetic behavior of uranium and thorium in seawater-sediment system. J. Radioanal. Nucl. Chem. 295, 649–656.
Langmuir, D., 1978. Uranium solution mineral equilibria at low temperatures with applications to sedimentary ore deposits. Geochim. Cosmochim. Acta 42, 547–568.
L'Annunziata, M., 2012. Handbook of Radioactivity Analysis. 3, Elsevier Science, pp. 1–1418.
L'Annunziata, M., 2016. Radioactivity: Introduction and History, From the Quantum to Quarks. 2, Elsevier, pp. 1–932.
Leopold, K., (2007). Chemical types of bounding of natural radionuclides in TENORM, Doctoral thesis. University Duisburg-Essen, Germany.
Lisitsin, A.K., 1971. Ratio of the redox equilibria of uranium and iron in stratiform aquifers. Geol. Rev. 13 (5), 744–751.

Matta, L.E., Godoy, J.M., Reis, M.C., 2002. 226Ra, 228Ra, and 282Th in scale and sludge samples from the campus basin oilfield E&P activities. Radiat. Prot. Dosim. 102, 175–178.
Michigan Department of Public Health, 1992. Interim standards for the control of NORM associated with oil and gas industry in Michigan, Lansing, MI.13.
Minnaar, D., 1994. Personal communication from Minnaar (Division of Radiological Health, Michigan Department of Public Health, Lansing, MI) to K.P. Smith (Argonne National Laboratory, Lakewood, CO), Aug. 30.
Mohamad Puad, H.A., Muhd Noor, M.Y., 2004. Behaviors of 226Ra 228Ra, 238U, 232Th on combustion of crude oil terminal sludge. J. Environ. Radioact. 73, 289–305.
Omar, M., Ali, H.M., Abu, M.P., Kontol, K.M., Ahmad, Z., Ahmad, S.H.S.S., Sulaiman, I., Hamzah, R., 2004. Distribution of radium in oil and gas industry wastes from Malaysia. Appl. Radiat. Isot. 60, 779–782.
Organo, C., Fenton, D., 2008. Radiological assessment of NORM industries in Ireland—radiation doses to workers and members of the public. https://www.epa.ie/pubs/reports/radiation/RPII NORM Report 08.pdf (retrieved 17.03.15).
Othman, I., AL-Masri, M.S., Suman, H., 2005. Public and regulatory acceptability of NORM contaminated soil disposal: the Syrian experience. In: E&P NORM Workshop, Sultanate of Oman, Muscat.
Otto, G.H., 1989. A national survey on naturally occurring radioactive materials (NORM) in petroleum producing and gas processing facilities, 265, Report to the American Petroleum Institute.
Paleontological Research Institution, 1999. New York state department of environmental conservation. An investigation of naturally occurring radioactive materials (NORM) in Oil and Gas Wells in New York State.
Paschoa, A.S., Godoy, J.M., 2002. The areas of high natural radioactivity and TENORM wastes. Int. Congr. Ser. 1225, 3–8.
Pennsylvania Department of Conservation and Natural Resources (PaDCNR), 2008. Spring Pennsylvania Geology. 38, p. 1.http://www.dcnr.state.pa.us/topogeo/pub/pageolmag/pageolonline.aspx.
Ray and Hiebert, R. 1970. Atomic pioneers: from Ancient Greece to the 19th century. United States Atomic Energy Commission, Division of Technical Information.
Rood, A.D., White, G.J., Kendrick, D.T., 1998. Measurement of Rn-222 flux, Rn-222 emanation and R-226 Ra-228 concentration from injection well pipe scale. Health Phys. 75, 187–192.
Rood, G.W.A.S., 2001. Radon emanation from NORM contaminated pipe scale and soil at petroleum industry sites. J. Environ. Radioact. 54, 401–413.
Russell, W.L., 1945. Relation of radioactivity organic content and sedimentation. Bull. Am. Assoc. Pet. Geol. 29(10).
Schmoker, James, W., 1981. Determination of organic-matter content of appalachian devonian shales from gamma-ray logs. AAPG Bull. 65 (7), 1285–1298.
Shawky, S., Amer, H., Nada, A.A., Abd El-Maksoud, T.R., Ibrahim, N.M., 2001. Characteristics of NORM in the oil industry from eastern and western desert of Egypt. Appl. Radiat. Isot. 55, 133–135.
Smellie, J., March 1995. The fossil nuclear reactors of Oklo, Gabon. Radwaste Magazine, Special Series on Natural Analogs. 21.
Smith, A.L., 1987. Radioactive scale formation. J. Petrol. Technol, 697–706.
Smith, K.P., 1992. An overview of naturally occurring radioactive materials (NORM) in the petroleum industry. United States Department of Energy.
Smith, K.P., Blunt, D.L., Williams, G.P., Tebes, C.L., 1996. Radiological dose assessment related to management of naturally occurring radioactive materials generated by the

petroleum industry. ANL/EAD-2, Argonne National Laboratory. Available from: http://www.netl.doe.gov/kmd/cds/disk23/G-Soil%20Projects/NORM%5CANL-EAD-2.pdf (retrieved 13.03.15).

StrSchV, 2001. Verordnung über den Schutz vor Schäden durchionisierende Strahlen (Strahlenschutzverordnung).—Artikel 1der Verordnung für die Umsetzung von EURATOM-Richtlinien zum Strahlenschutz vom 26. Juli 2001. BGBl. I, Nr. 38, 1714 S., Bonn.

Supernaw, I.R., McCoy, A.D., Link, A.J., 1978. Method for in-situ evaluation of the source rock potential of each formation. US Patent 4,071,744, Jan 31.

Swanson, V., 1960. Oil yield and uranium content of black shales: uranium in carbonaceous rocks. Geological Survey Professional Paper 356-A. The US Atomic Energy Commission.

Testa, C., Desideri, D., Meli, M.A., Roselli, C., Bassignani, A., Colombo, G., Fantoni, F.R., 1994. Radiation protection and radiation scale in oil and gas production. Health Phys. 67, 34–38.

Underhill, P., 1996. Naturally Occurring Radioactive Materials: Principles and Practice. Taylor & Francis, pp. 1–160.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1993. Exposures from natural sources of radiation. United Nations, New York, Annex A, A/Ac., 82/R.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000. Sources, effects and risks of ionizing radiation. United Nations, New York.

US Department of Energy, 2013. US Department of the Interior, Geological Survey, Open-File Report 2013-1137.

US Environmental Protection Agency, 1993. DRAFT diffuse NORM waste characterization and preliminary risk assessment. Office of Radiation and Indoor Air, Washingto, DC.

US Environmental Protection Agency, 2008. Technical Report on technologically enhanced naturally occurring radioactive materials from uranium mining. EPA 402-R-08-005 (1), Washington, DC. Available from: http://www.epa.gov/radiation/docs/tenorm/402-r-08-005-voli/402-r-08-005-v1.pdf (retrieved 13.02.15).

Vandenhove, H., 2002. European sites contaminated by residues from ore-extracting and -processing industries. Inter. Congr. Ser. 1225, 307–315.

Veil, J.A., 1998. Options and cost for disposal of NORM waste. In: 5th International Petroleum Environmental Conference, October 20–23, 1998, Albuquerque, NM.

Ward, J.F., 1988. DNA damage produced by ionizing radiation in mammalian cells: identities, mechanisms of formation, and reparability. Prog. Nucleic Acid Res. Mol. Biol. 35, 96–125.

Wilson, A.J., Scott, L.M., 1992. Characterization of radioactive petroluem piping scale with an evaluation subsequent land contamination. Health Phys. 63, 681–685.

Zimmerle, W., 1995. Petroleum Sedimentology. Kluwer, Dordrecht. 413 pp.

Zukin, J.G., Hammond, D.E., Teh-Lung, K., Elders, W.A., 1987. Uranium–thorium series radionuclides in brines and reservoir rocks from two deep geothermal boreholes in the salton sea geothermal field, southeastern California. Geochim. Cosmochim. Acta 51, 2719–2731.

Further reading

Nobel Koran, 2018a. Surah Az-Zalzalah, verse 7.

Nobel Koran, 2018b. Surah Yunus, verse 61.

CHAPTER THREE

Risk assessment and management of TENORM waste disposal options in the oil and gas industry

Chapter Outline

3.1 Introduction

This chapter presents scenario-based risk assessments of disposal methods commonly used for technologically enhanced naturally occurring nuclear radioactive materials (TENORM) wastes in the oil and gas industry. These wastes fall into four main categories: hard scales, sludge, drilling

Nuclear Radioactive Materials in the Oil and Gas Industry
https://doi.org/10.1016/B978-0-12-816825-7.00003-0

cuttings, and contaminated produced water which contains different levels of soluble radioactive materials ranging from low- to high-level radioactive isotopes and also reported in form of radioactive gases such as radon. As mentioned earlier, the wastes from radioactive isotopes decay mainly from Uranium-238 and Thorium-232 series that are likely to be enhanced technologically as a consequence of physical and chemical processes associated with enhanced oil and gas recovery technologies (Kolb and Wajcik, 1985; Baried et al., 1996; Jonkers et al., 1997; O'Brien and Cooper, 1998). If the disposal of these wastes is not regulated, the resulting environmental pollution may lead to radiation exposure for people directly involved in oil and gas operations, the general public, animals, soil, water, and plants. In this context, the E&P Forum (1988) examined the disposal of scale and reported that in 62% of cases, it was discharged into the sea at the platform location; in 29% of cases, it was disposed of on land (disposal in a dedicated NORM disposal facility, and deep well disposal), and in the remaining cases, scale and contaminated equipment were stockpiled within a controlled area, also on land. According to the US Environmental Protection Agency (US EPA), the total amount of radioactive waste generated annually by the oil and gas industry in the United States was expected to be 100 tons of scale per oil well. It was also estimated that between 25,000 and 225,000 tons of contaminated scale and sludge, respectively, were generated each year from the US petroleum industry in the mid-1990s (US EPA, 1993a,b; Smith et al., 1995; Bou-Rabee et al., 2009). However, the major concern is the amount of produced water contaminated with TENORM wastes that is coproduced during the oil and gas extraction and production processes. This amount is directly proportional to the volume of produced water generated during the pumping of the oil (Rood et al., 1998; Paranhos Gazineu et al., 2005). The ratio of produced water to oil is approximately 10:1, and according to the American Petroleum Institute, API (1989) and Al-Farsi (2008), 18–25 billion barrels of waste fluids from oil and gas production were being generated annually in the United States alone, versus the total crude oil volume of 2.5 billion barrels (400 million m^3). In 2007, about 22,000 m^3/day of this produced water was reinjected for enhanced recovery or disposal, and about 234,000 m^3/day was treated and discharged to the ocean (Clark and Veil, 2009). In the same context, Chevron claimed that it has safely disposed of more than 1 million barrels of NORM and other oilfield wastes in Louisiana through slurry fracture injection (SFI) technique that were injected into a high permeability sandstone formation at depths from

4400 to 5000 ft in a single well during 2 years of injection operation, which was concluded in March 2000 (Reed et al., 2001). This leads to an important conclusion, which is these figures have increased dramatically as a result of the increase in the oil production satisfy growing demands worldwide for energy, thereby increasing the volume of generated TENORM wastes. Accordingly, this raising a serious concern and an important question whether the oil and gas industry are disposing of radioactive waste safely based on scientific evaluation or not?

3.2 An overview of TENORM waste disposal options in the oil and gas industry

3.2.1 The suggested TENORM waste disposal options in the oil and gas industry

With the increased concentration of TENORM wastes produced along with oil and gas production, an urgent need arose for finding appropriate ways to safely and economically manage and dispose of such huge wastes. Different waste disposal options were suggested by oil and gas organizations such as the Oil Industry International Exploration and Production Forum and the American Petroleum Institute. Fig. 3.1 summarizes different disposal alternatives proposed according to concentration limits of radioactive materials, the degrees of isolation from the public, and cost associated with the technology used and future remediation plans. For example, theoretically the disposal in the deeper geological formations seen to be more expensive in short and long term as a result of high well-drilling cost, maintenance cost, well-integrity cost, and well-monitoring cost. While some oil and gas companies may have different opinion in this regard and claim that it is more economical alternative because they dispose of radioactive wastes either in abandoned wells (dry exploration or production or injection wells) or use radioactive waste as a good mixture in forming hydraulic fracturing slurry that is used for hydraulic fracturing purposes, which will eventually settle in the deep geological formations or will flow back. This alternative, for example, seems to be a more economical and safer option from oil and gas companies' perspective. While, the fact is that, it has not yet been scientifically proven with conclusive evidence the success of this method or its effectiveness due to the lack of risk assessments, scientific evaluation studies, and the increasing of uncertainty levels associated in the deeper geological formations.

Furthermore, Strand (1999) categorized TENORM waste disposal options into four disposal options with 14 alternatives, which include:

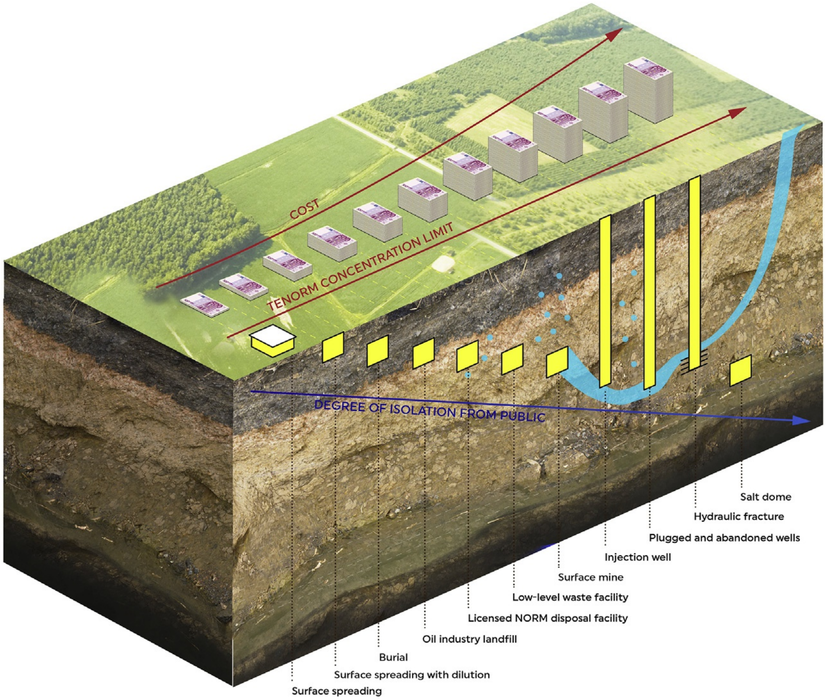


Fig. 3.1 Suggested disposal alternatives for NORM/TENORM wastes.

- injection/reinjection of waste together with cuttings and other types of nonradioactive production wastes:
  (1) well injection/reinjection into the reservoir;
  (2) well injection by hydraulic fracturing or what known by SFI; and
  (3) injection into the well during plugging and abandonment operations.
- sea disposal of waste or dumping of equipment with or without encapsulation:
  (4) disposal of solid waste into the sea;
  (5) dissolution of solid waste by use of chemicals followed by disposal into the sea;
  (6) encapsulation of the waste in drums followed by dumping or burial in the sea bed; and
  (7) sealing of tubulars and other types equipment without removal of NORM, followed by dumping.
- land disposal of waste or equipment with or without encapsulation:
  (8) depository in an abandoned mine, tunnel, or other types of underground facility;

(9) burial of waste with encapsulation or surrounded by a concrete barrier;
(10) burial of waste or sealed equipment without encapsulation;
(11) land spreading of solid waste with or without dilution;
(12) at approved depositories for inorganic waste or depositories for other types of waste from the oil industry; and
(13) volume reduction (of waste) followed by deposition at national depositories for radioactive waste.

- Scrap metal recycling of contaminated equipment:

(14) equipment smelting without decontamination followed by recycling of the metal and disposal of the slag.

Sharkey and Burton (2008) proposed two additional methods, which focused on the remediation of hazardous materials with a particular emphasis on TENORM. These methods are:

(15) minimization techniques including recent technologies such as gasification, oxidation-reduction reaction chemicals, and solids/fluids separation and bioreactor cell; and
(16) salt dome disposal where nuclear radioactive including NORM and TENORM wastes are injected and placed into old abandoned underground salt domes formations.

3.2.2 Commonly used TENORM waste disposal options in the oil and gas industry

Many of the suggested nuclear radioactive waste disposal categories and alternatives are not necessarily based on scientific evaluations or radiological risk assessments from both engineering and medical perspectives. However, some of them are still widely used by many onshore and offshore oil and gas companies. The infographic sketch (Fig. 3.2) demonstrates the most common TENORM waste disposal methods used in the oil and gas industry.

3.2.3 Some real models of common radioactive waste disposal methods used by the oil and gas industry and their health, environmental, and political aftermaths

Chevron disposes of one million barrels of radioactive waste in Louisiana through slurry fracture injection (Reed et al., 2001)

The Bay Marchand oil field in Louisiana has been operated by Chevron and began its production in 1949. Chevron processed oil through a series of pits to separate water and other materials from the oil. Over the time these pits contaminated with the accumulated separated substance that mostly

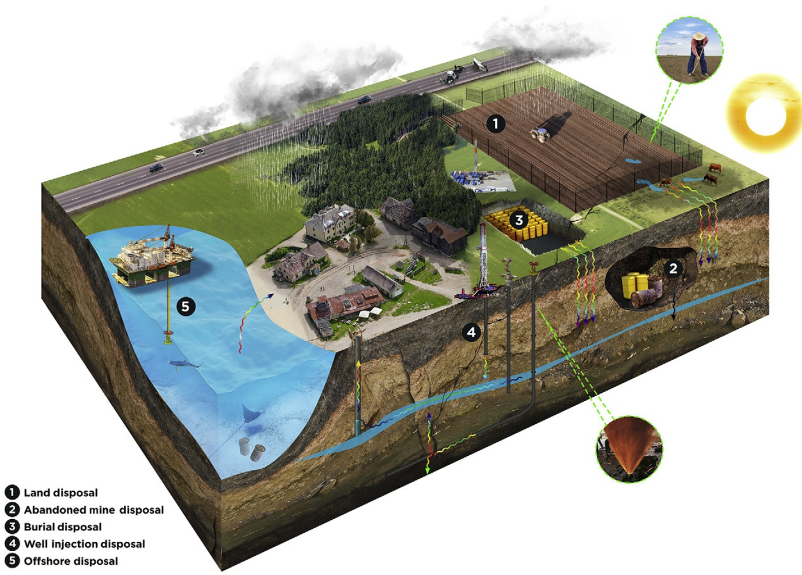


Fig. 3.2 Common TENORM waste disposal options used in the oil and gas industry.

included drill cuttings, drilling mud, produced sand, salt water, pipe scale, crude oils, and precipitates, all of these materials contained amounts of technologically enhanced nuclear radioactive materials. Chevron is aware of the fact that these contaminated materials contain uranium-238, thorium-234, and radium-228 that are serious threats to the environment and public health. The company used three processing pits that are hydraulically isolated to prevent any radioactive materials from seepage into the adjacent canal, particularly radium that is very soluble in salt water. The Dead End Canal to the southeast also contained extensive amounts of technologically enhanced nuclear radioactive materials and other drilling wastes that are classified by the company as nonhazardous oilfield waste, which are mixed into canal bottom soils. The company argues that at the material handling facility located adjacent to the canal, this contamination was primarily due to spill over from discharge and processing pits. Chevron feared that this disposal method might pose a direct threat to the environment; thus, it decided to utilize an immediate remedy to collect all waste from the three disposal pits and reinject it into a geological formation. The company asserts that the remediation project was composed of two phases, which are (1) excavate and backfill the Bay Marchand pits, and remediate the bottom of the dead end canal; (2) Disposed radioactive waste using the SFI process in deep well injection where the company claimed that this method is more safer and environment friendly. Chevron insisted that deep injection disposal alternative compared to the surface pit or landfill disposal alternative will provide a better environmental and economic solution because it is much cheaper compared to the off-site transport cost and other associated risks. The company stated that during 2 years of injection, concluding in March 2000 more than 1 million barrels of contaminated soil and canal bottoms were safely disposed into the deep geological formation. At depths from 4400 to 5000 ft, contaminated waste was mixed with water to create slurry and then it is injected down-hole above formation parting pressure into a weakly consolidated and permeable sandstone formation. The total volume of the oilfield wastes was 20,970 bbl of liquids and 6120 bbl of solids. The total volume of solids disposed over the course of the project was 1,000,800 bbl, contained in 2,949,700 bbl of the slurry.

Chevron has claimed that it has designed the project and suggested some good monitoring techniques to extensively monitor it to trace any expected pollution and to verify containment within the permitted interval. However, this claim is considered scientifically unreliable and represents a controversial scientific issue particularly in the absence of scientific evidence, reliable risk assessment studies, and the presence high uncertainty levels to evaluate the situation at such depth due to many factors including but not limited to: extension of out-of-zone fracturing; field nature; well integrity; and work over (Chevron reported: the casing was found damaged at 4614 ft. due to sand pressuring up and shearing. Casing damages provide a good chance for formations channeling); formations connections; natural forces; and many other geographical, geological, and environmental factors, which are difficult to be monitored or predicted at high accuracy according to the monitoring process suggested by Chevron such as continue pressure monitoring and well logging. In addition to that, there is a high probability of particles migration especially that Chevron has injected the contaminated waste into a soft formation with high permeability, relatively thick fracture, and dilation zone. Furthermore, Reed et al. (2001) stated, "the use of deep well disposal injection has expanded significantly in recent years. For example, large-scale E&P waste injection operations have taken place in Canada, Alaska, California, and in the North Sea. High volume injection projects often involve annual injection exceeding several hundred thousand barrels of waste for several years." Accordingly, this is a serious matter that raises the alarm. Therefore, there is an urgent need to evaluate dynamically with a high level of accuracy, the effectiveness, and the associated risks with this type of waste disposal methods since annually millions of nuclear radioactive and hazardous waste are injected into the geological formations that will eventually pose serious threat to the environment.

Louisiana pollution case (Silverstein, 2014)

Post-1930, the oil industry has developed a new drilling waste disposal method in the form of surface unlined pit disposal that later developed into an underground disposal well and claims they are safer disposal methods. Scientifically, this claim is also considered unreliable and controversial due to the absence of scientific evidence and not based on scientific evaluation. In 1933, in Louisiana, the first suchlike well was launched. After this launch, these types of wells became the role model for the oil industry to dump brine and other drilling waste that may contain nuclear radioactive materials and rapidly this became the principal method of drilling waste disposal. Nevertheless, it turned into a common practice of the oil and gas industry to use unlined pits to store brine and other drilling waste that may contain nuclear radioactive materials until the late 1980s. Finally, in the late 1980s, Louisiana banned the use of unlined pits to store brine and other drilling waste that may contain nuclear radioactive materials, thus, this ban in some way had given consent to the oil companies to discard brine and other drilling waste that may contain nuclear radioactive materials into marshlands and coastal waters. Moreover, oil companies had not been provided with an alternative method to get rid of drilling waste safely and under certain circumstances, this means that the state regulators permitted the oil and gas companies to become self-regulators. Consequently, they had become the key factor of spreading the environmental pollution. Since oil companies are well-known to be profit-driven companies and always seeking cost-cutting technics. Accordingly, oil companies considered the ban a great opportunity to save their resources and money because this prohibition allowed them to use such a method of waste dumping that was cheap and effortless. Therefore, the oil companies without bothering to seek authorization or notification from the state regulators usually dumped brine and other drilling waste that may contain nuclear radioactive materials unsafely into the environment using methods that are not necessary based on scientific evaluation, this very act of the state posed serious threats to the land, environment, human beings, and other species. In Louisiana, for example, a massive quantity of brines, which contain technologically enhanced nuclear radioactive materials such as uranium-238, thorium-232, and radium-228 that are very soluble in salt water and are discharged for decades directly into the environment, while authorities and government had not taken any constructive or serious action to prevent this practice. This slackness could be attributed to several reasons such as lack of knowledge or due to political and economical reasons.

In this context, Silverstein (2014) argues that the oil and gas industry became more politicized, as it is the main source of the countries' economy. Thus, the oil and gas industry blamed the trial lawyers in regard to Louisiana pollution case. In Mississippi, another major Gulf Coast Petro-state, the companies previously got legislature pass bills that kept these cases out of the court. They wanted any related oil and gas cases to be heard by a state regulatory agency, the Oil and Gas Board, over which the industry exerts huge leverage in what known these days by arbitrations process. Moreover, in 1989, the US Minerals Management Service report claimed that oil companies were dumping approximately 82 million gallons of contaminated brine daily (Silverstein, 2014). This brine according to the new studies may contain nuclear radioactive materials of different levels of activity concentrations that are disposed of directly into the ground. This practice makes the risk invisible and for many decades. Sooner or later, this issue will become evident to the public either by means of in-depth scientific investigation or naturally after some years. In this context, Silverstein (2014) pointed out that about a decade ago, in legacy lawsuits and related cases, Louisiana landowners began winning huge judgments against Exxon, Chevron, Shell, and BP, as well as smaller independents that contributed in a massive environmental pollution. ExxonMobil, in one case, for example, was fined for polluting a 33-acre site near New Orleans. At first, a jury awarded the company the heavy fine of $1 billion but later it is reduced to only a few million. On one hand, Louisiana appealed court and said that Oil Company had acted with a callous apathy toward plaintiffs and their properties. For Exxon, the decision was chiefly awkward because the property it had polluted was owned by a state judge, Joseph Grefer. In short, the company could have escaped the penalty if the polluted land did not belong to the state judge or some other influential person. Through the discovery process corporate documents obtained by trial lawyers, the remarks illustrated that the companies were aware of the fact that their storage techniques are hazardous and are not based on scientific evaluation and for 50 years, they continued the use of unlined pits because it was more lucrative and cost effective, subsequently, they pay no heed to the problem (Silverstein, 2014). The company cold-bloodedly ignored the problem because of its material gains and not bothered by the damage it had been doing to the environment. In this context, for example, a 1986 Texaco memo accredited that at a site named Fordoche Field, the waste leakage from the company's unlined pits had been the root cause of severe groundwater contamination. The memo propounded that the remedial measures will take more than a century to clean up the harms it has done. Moreover, the fastest remediation process would be to remove the soil and eradicate the source of contamination. Nevertheless, this technique is not cost effective because the approximate cost of this process is between 5 and 10 million dollars. It also suggested that other remedial techniques or measures could be used to speed up the dilution process; hence, more funds will be needed. In other words, other remediation techniques are very costly and there is less likelihood of using them. In short, there is an urgent need for a further scientific investigation of the effectiveness of the disposal methods currently used by the oil and gas industry in order to avoid unexpected environmental crises as a result to what oil and gas companies claiming decades of using the most safer disposal methods. While the fact is that oil and gas companies are using the cheaper methods and the underground waste disposal methods currently used by the oil and gas industry are nothing but an environmental time bomb.

In order to demonstrate the potential risk of radiation exposure for workers, the general public, and the environment resulting from the most common TENORM waste disposal methods. This study presents a scenario-based approach that can be used as a guideline for the risk assessment of TENORM wastes disposal methods considering various fate and transport exposure pathways. The infographic sketch (Fig. 3.2) also illustrates the adverse effects of radiological pollution from TENORM wastes disposal methods and potential sources of exposure for workers, the public, food, soil, water resources, and the environment. Accordingly, this study simulates a real scenario of TENORM waste disposal in evaporation pond using the RESRAD 6.5 modeling system (http://web.ead.anl.gov/resrad/documents) to measure doses and excess carcinogenic risks through different pathways of exposure using real input data that are updated dynamically. These results are used as the basis of comparison with results obtained from risk assessments of other similar TENORM waste disposal options found in other literature reviews. The comparison helps to better understand how real data that are dynamically updated and related assumptions affect the results and degree of confidence. Finally, this study attempts to fill the current knowledge gap on radiological risk assessment of TENORM exposure and leads to an important conclusion that it might not be appropriate to evaluate the safety performance of TENORM waste disposal methods based only on the risks obtained from radiological risk assessments, and draw conclusions exclusively based on the risk value itself without any considerations from the medical and environmental perspectives. Indeed from the standpoint of public health and safety, medical, and environmental opinion is the most accurate way to determine safe exposure to radiological risk.

3.3 Risk assessment of TENORM waste disposal options

Fig. 3.3 describes an integrated conceptual model of fate and transport pathway assessment for TENORM waste disposal options that are incorporated into RESRAD (Version 6.5) for doses and carcinogenic risks assessment on different exposure pathways of TENORM.

The model investigates all possible fate and transport pathways of radionuclides disposed in the evaporation pond. It assumes usage of contaminated water in the biosphere at the interface with the aquifer after migration of the radionuclides through the vadose zones as a major concern. In the interface between the geosphere and the biosphere, a well intercepts the radioactive plume at an off-site location where the concentration is highest. The biosphere therefore may consist of a residential, industrial, or farming system where a well provides water for drinking and irrigation purposes. When used for irrigation, the contaminated water can expose the public to radiation in a number of ways, including direct external gamma radiation exposure, accidental ingestion of the contaminated water and skin contact. Exposure risks for members of the public working or residing within 100 m of a disposal site are found to be similar to those for disposal workers (Efendi and Jennings, 1994). These risks include the following: direct gamma radiation; inhalation of contaminated dust during contaminated soil removal; skin contact; inhalation of radon; and other radionuclides during soil mixing or evaporation (Vandenhove et al., 1999). Moreover, radiological surveys conducted by US EPA (1993a,b) have also indicated that TENORM contamination in some scrap pipes stored in disposal sites or that used in evaporation ponds may have contaminated the surrounding environment. These surveys found that some equipment and disposal locations exhibited external radiation levels above 2 mR/h and radium-226 soil contamination above 37 Bq/g (Abdel-Sabour, 2014). At one site, contamination spread to a nearby pond, a drainage ditch, and an agricultural field, the latter resulting in subsequent uptake of radium by vegetation.

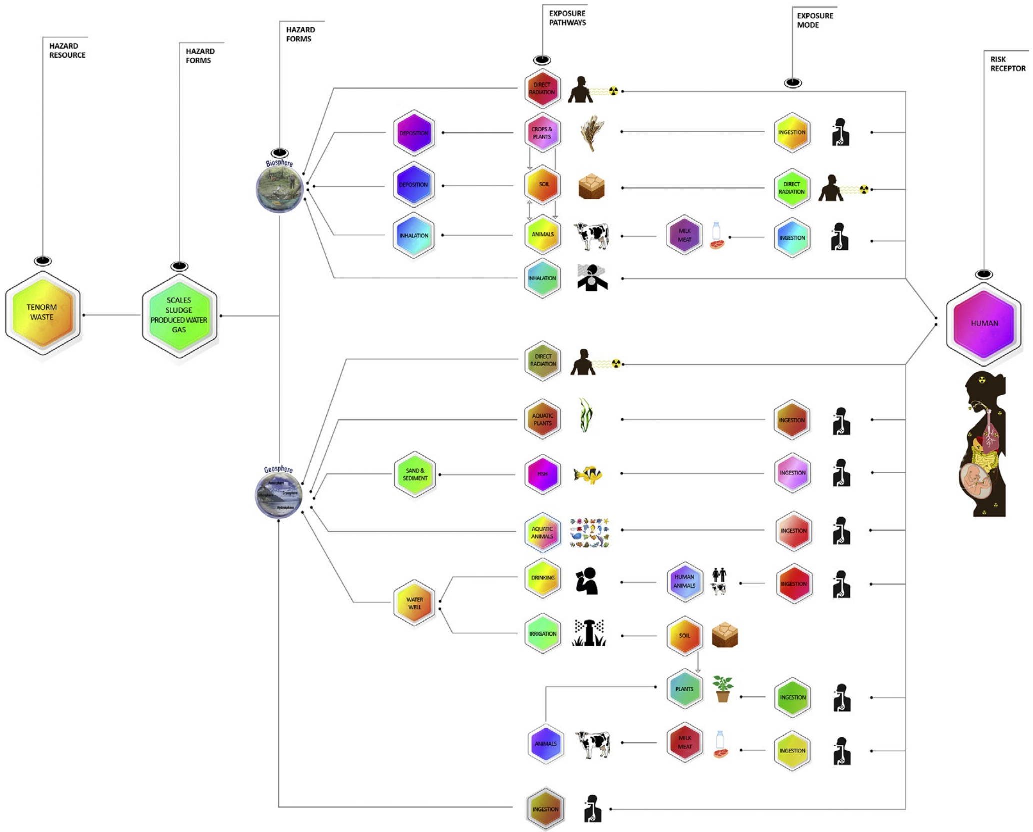


Fig. 3.3 Fate and transport model.

3.3.1 Case study #1: Risk assessment of TENORM waste disposed of in an evaporation pond (a real-scenario simulation)

Unfortunately, TENORM waste disposal in evaporation ponds is claimed an economical alternative for many onshore oil and gas companies for the disposal of huge quantities of contaminated formation water coproduced during oil and gas production. With this method, a pond is usually excavated and lined with high-density polyethylene (HDPE) liners of a certain thickness to prevent any leakage (but a potential for leakage remains). While some oil and gas companies used unlined pits to dispose of radioactive waste and other oilfield wastes such as the case of Louisiana pollution discussed earlier. Coproduced water contaminated with TENORM is then dumped into the pond. In order to evaluate the performance of this disposal method, RESRAD 6.5 for doses assessment has been used to assess the health risk of TENORM exposure from these ponds for workers and others, including workers located in production stations that may be as far away as 1000 m. The assessment considers different exposure pathways based on fate and transport model tailored for the assigned scenario as shown in Fig. 3.4.

The analysis presented in this section aims to demonstrate:

- How real inputs that are dynamically updated improve the accuracy of results of radiological doses and carcinogenic risk values compared with the results reported in other literatures, which are presented in case studies 2 and 3 discussed in the following section. The differences are mainly attributed to data and model uncertainties.

The urgent need for further research and investigation to fill an important knowledge gap related to the role of medical opinion in engineering radiological risk assessments. To the author's knowledge, the question of how exposure to low radiological doses in the oil and gas industry may increase cancer risk has not yet been thoroughly addressed from a joint medical and engineering perspective. Moreover, some sophisticated scientific studies and epidemiological reports confirmed that even exposure to low radiological doses is still unsafe and may increase the chance of carcinogenic risks.

Scenario description

The fate and transport model of this risk assessment involves six main analyses:

(1) *Hazard source*: TENORM waste.

(2) *Hazard forms*: Coproduced water contaminated with TENORM waste from oil and gas production with a potential mixture of sludge, scales,

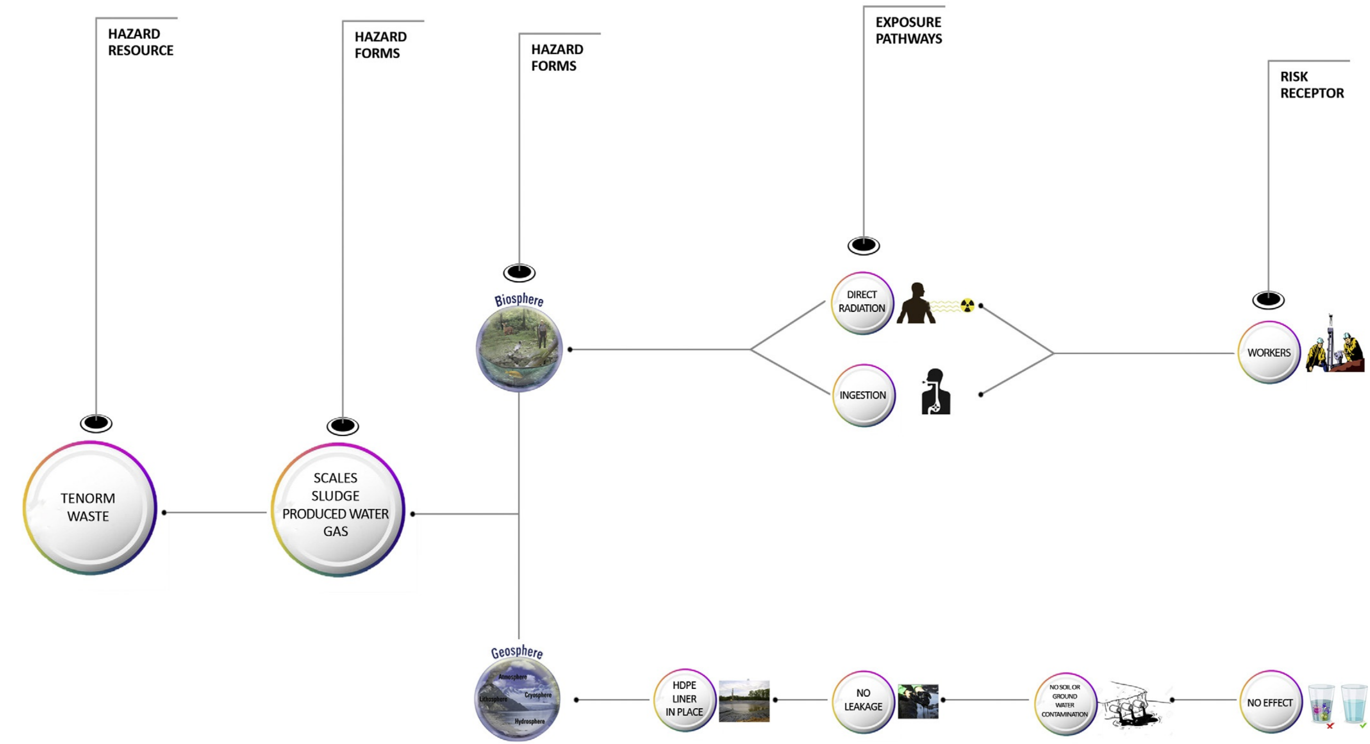


Fig. 3.4 Different exposure pathways of TENORM waste disposed in an evaporation pond based on fate and transport model.

and gases. This rate is modeled as a function of the geometry of the contaminated zone and the decay of the radionuclides.

(3) *Pathway model analysis*: This analysis addresses external radiation and internal radiation (combination of inhalation and ingestion) pathways by which the radionuclides may migrate from the source to other areas into the environment, posing serious health, and environmental risks.

(4) *Doses/exposure model analysis*: This addresses the problem of deriving doses conversion factors for the radiation doses that will be incurred by exposure to TENORM radiation.

(5) *People exposed to radiological risk*: This scenario model considers workers operating TENORM waste disposal evaporation pond, nearby sites, and operating contractors such as crew members of drilling rigs, crew members of work over units, flow line maintenance construction teams, production station workers, road construction teams, other service contractors, visitors, and waste treatment crew members. All may potentially be exposed to TENORM from a contaminated evaporation pond and from the future potential use of contaminated land for industrial or housing or farming purposes.

(6) *Mode of **e**xposure **p**athways*: The scenario modeling was conducted for evaporation ponds located in a desert, therefore the only external radiation sources considered were radiation from the ground, inhalation, and ingestion of the dust and vapors contaminated with radium isotopes, and other radionuclides. Since the scenario assumes that no agricultural activities are being undertaken near the evaporation ponds and that there is no vegetation, pathways through food ingestion were excluded. As well, since the evaluated ponds are lined with HDPE sheets, the scenario also excludes any geosphere contamination such as contaminated ground water or soil as a pathway for exposure.

Model inputs

The following parameters were used as inputs for scenario modeling using RESRAD (Version 6.5):

- Three samples of TENORM waste of radionuclides U238 and Th232 (^{226}Ra and ^{228}Ra) were used for this simulation with an average activity concentration as a function of time during the study (0.603, 1.12, and 1.65 Bq/g).
- Activity concentrations of above three samples were assumed homogenously distributed according to collected sample.

- Secular equilibrium between radioactive parent and daughters at time of the study.
- The pond is lined with HDPE liner.
- TENORM waste thickness is 100 cm.
- Total area of the pond is 40,000 m^2.
- Exposure duration: 4 h per day × 365 days a year × 30 years. (TENORM waste disposal facilities are operating for 365 days per year due to continual oil and gas extraction and production operations. Therefore, workers who are operating these facilities are exposed to TENORM radiations for minimal continuous exposure of no less than 4 h per day during their maximum working life of 30 years.)
- Pond is located in the desert. (Average wind speed is 6 m/s; average temperature is 45°C; Average relative humidity is 9%.)

Model theory

An analytical model using decay chain series was used to simulate fate and transport of TENORM in the biosphere. The fate and transport of TENORM in the geosphere were not considered in this case because the HDEP liner is in place to prevent leakage. RESRAD (Version 6.5) was used to simulate the defined scenario and to calculate the time-integrated annual total effective doses equivalent and excess lifetime cancer risk that industrial workers are exposed to. Two main exposure pathways of U-238 and Th-232 radionuclides were identified from the evaporation pond or nearby areas: Internal radiation exposure including both inhalation and ingestion pathway (ingestion pathway of contaminated airborne dust was combined with this inhalation path as it was found to be very minor in this study) and external radiation exposure. Three samples with different radionuclides concentrations of U-238 and Th-232 that dissolved in produced water in evaporation ponds were used and projected over a 1000-year period. The total intake doses contribution and excess cancer risk from identified radiation exposure pathways (external gamma radiation and inhalation) were calculated based on current radiation risk science and recommendations of the US EPA, ICRP, NAS, and the US Department of Energy. RESRAD Version 6.5 was used in this study to calculate the total intake doses contribution and excess cancer risk because of its accuracy, reliability, and ability to calculate low doses. A better estimate of the radiation risk can be calculated using US EPA risk coefficients with the exposure rate (for the external radiation exposure pathways) or the total intake quantity (for internal exposure pathways through inhalation and ingestion). The US

EPA risk coefficients are estimates of risk per unit of eternal exposure to radiation or intake of radionuclides via inhalation in this case study based on age- and gender-specific coefficients for individual organs, along with organ-specific DCFs. The US EPA risk coefficients are categorized as best estimate values of the lifetime excess cancer risk or cancer mortality risk per unit of intake or exposure for the radionuclide of concern. More details on the derivation of US EPA risk coefficients and their application can be found in US EPA documents and risk assessment guidance (US EPA, 1997). Intake rates for inhalation and ingestion pathways are computed first for all of the primary radionuclides and then multiplied by the risk coefficients to estimate cancer risks. For example, for inhalation and soil ingestion exposure pathways denoted by ($p = 2$ and 8, respectively), the intake rates (Bq/year or pCi/year) can be computed by using the following equation:

$$(\text{Intake contributing doses})_{j,p}(t) = \sum_{i=1}^{M} \text{ETF}_{j,p}(t) \times \text{SF}_{ij}(t) \times \text{S}_i(0) \times \text{BRF}_{i,j} \tag{3.1}$$

where

$(\text{Intake contributing doses})_{j,p}(t)$ = intake rate of radionuclide j at time t (Bq/year or pCi/year),

M = the number of initially existent radionuclides,

$\text{ETF}_{j,p}(t)$ = environmental transport factor for radionuclide j at time t (g/year),

p = primary index of pathway,

$\text{SF}_{ij}(t)$ = source factor,

i,j = index of radionuclide (i for the initially existent radionuclide and j for the radionuclides in the decay chain of radionuclide i),

$S_i(0)$ = initial contaminated zone concentration of radionuclide i at time 0, and

BRF_{ij} = a branching factor that is the fraction of the total decay of radionuclide i that results in the ingrowth of radionuclide j.

The cancer risk at a certain time point from external exposure can be estimated directly by using the risk coefficients, which are the excess cancer risks per year of exposure per unit of contaminated zone concentration, and the environmental transport and exposure duration, as per the following equation:

$$(\text{Excess cancer risk})_{j,p}(t) = \sum_{i=1}^{M} \text{ETF}_{j,p}(t) \times \text{SF}_{ij}(t) \times S_i(0) \times \text{BRF}_{i,j} \times \text{RC}_{j,p} \times \text{ED} \quad (3.2)$$

where

$\text{RC}_{j,p}$ = risk coefficient for environmental pathways exposure (risk/year)/(pCi/g) [risk coefficients for external and internal (inhalation and ingestion) exposure are listed in Appendix A and B],

ED = exposure duration (year).

Calculation of: $\text{ETF}_{j,p}$, SF_{ij}, $S_i(0)$ $\text{BRF}_{i,j}$

- The environmental transport factor ($ETF_{j1,2}$) which is the time-dependent ratio is calculated as per the following equation:

$$\text{ETF}_{ij,pq}(t) = E_{ij,pq}(t) / \left[S_i(0) \times \text{SF}'_{ij},_{pq}(t)\right], \quad (3.3)$$

where

$E_{ij,\ pq}(t)$ = exposure parameter value at time t for the jth principal radionuclide (or radiation therefrom) transported through the pqth environmental pathway as a result of the decay of the initially existent radionuclide i in the contaminated zone (Bq/g, Bq/mL) [pCi/g, pCi/mL] for external radiation from the contaminated zone; (Bq/year) [pCi/year] for internal radiation.

p = index label for environmental pathways.

q = index label for the component of the environmental pathway p.

$S_i(0)$ = average concentration of the ith principal radionuclide in a uniformly contaminated zone at time 0 (Bq/g, Bq/mL) [pCi/g, pCi/mL].

$\text{SF}'_{ij,pq}(t)$ = an adjusting factor to modify the contaminated zone concentration.

- Branching factor (BRF_{ij}) is the fraction of the total decay of radionuclide i that results in the ingrowth of radionuclide j.
- Source factor (SF_{ij}) from each decay product (j) of the principal radionuclide (i) (which is the time-dependent ratio calculated using the following equation:

$$\text{SF}_{ij}(t) = S_{ij}(t)/S_i(0), \quad (3.4)$$

where

$S_{ij}(t)$ = concentration at time t of the jth principal radionuclide remaining in the contaminated zone after leaching and ingrowth from the ith principal radionuclide (Bq/g, Bq/mL) [pCi/g, pCi/mL]; and

$S_i(0)$ = initial concentration of the *i*th principal radionuclide in the contaminated zone (Bq/g, Bq/mL) [pCi/g, pCi/mL].

Thus, the doses contribution and consequent excess carcinogenic risk from external and internal (inhalation and ingestion) exposures pathways exposure from TENORM waste disposed in an evaporation pond scenario have been calculated based on above fate and transport mathematical model and simulated using RESRAD 6.5 version.

Assessment results

Based on the defined conditions in the simulation, there are only two potential pathways for radiation exposure of radionuclides U-238 and Th-232: external radiation and internal radiation (inhalation and ingestion). Using RESRAD (Version 6.5), these pathways of exposure were simulated for 1000 years for three different levels of TENORM waste activity concentrations ($^{226}Ra/^{228}Ra$ activity, 0.603, 1.12, and 1.63 Bq/g).

Figs. 3.5 and 3.6 show the total doses from external and inhalation exposure pathways over 1000 years for the three activity concentrations. In general, as activity concentration increases, the estimated total doses from external and inhalation pathways also increases. The contribution to total carcinogenic risk from each pathway also increases as activity concentration increases. These are described in more details in Figs. 3.7 and 3.8.

3.4 TENORM risk assessment benchmarking with other literature

3.4.1 Case study #2: Risk assessment of TENORM wastes disposed of in an evaporation pond (Othman and Hassan, 2013)

A similar risk assessment study of TENORM wastes disposed of in an evaporation pond at different oil and gas locations was presented by Othman and Hassan (2013). The analysis was conducted to assess radiation doses and increased carcinogenic risk resulting from radiation exposure caused by TENORM accumulation in an evaporation pond during petroleum production. In this study, radioactive contamination of produced water was modeled using a RESRAD (Version 6.5) to estimate the total effective doses equivalent for external gamma radiation exposure pathway of radionuclides U-238 and Th-232, and excess carcinogenic risk to industrial workers

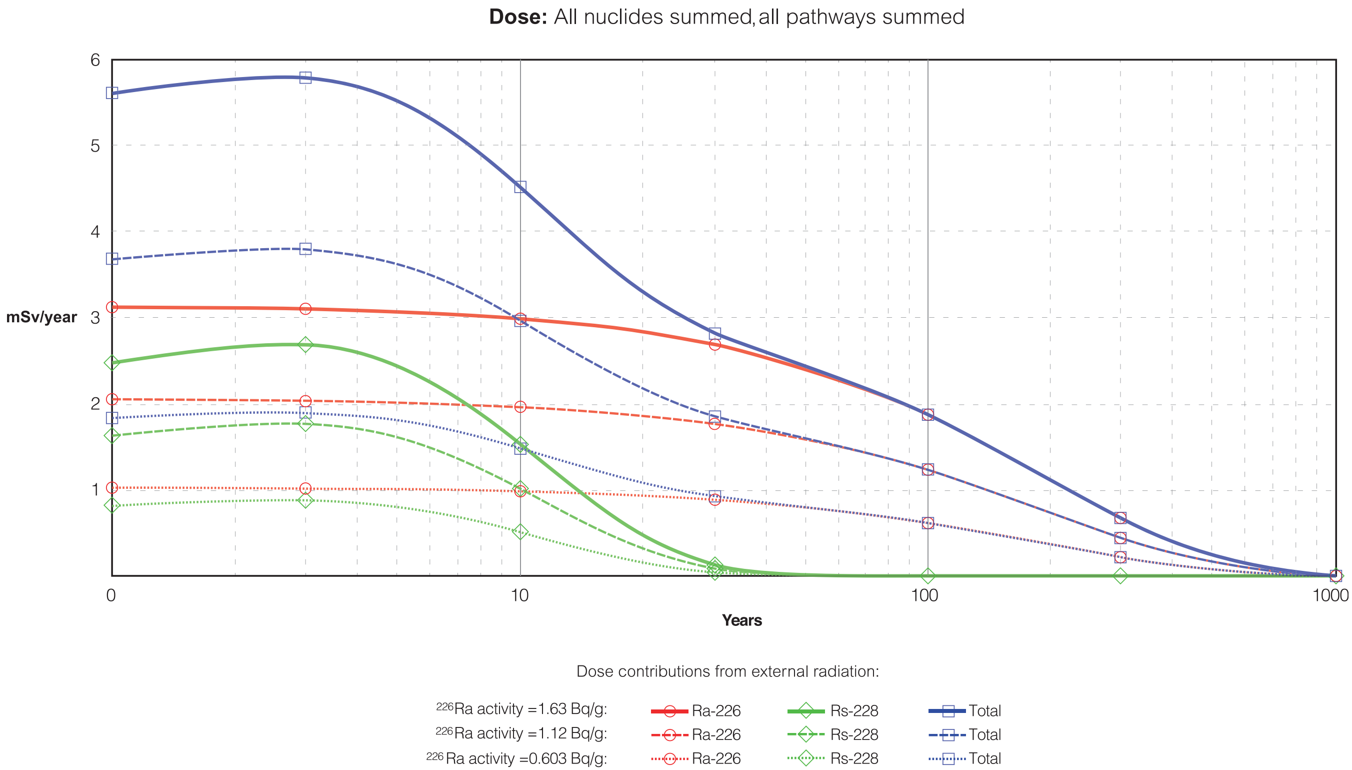


Fig. 3.5 Doses contribution from external radiation exposure pathway ($^{226}Ra/^{228}Ra$ activity concentration 0.603, 1.12, and 1.63 Bq/g).

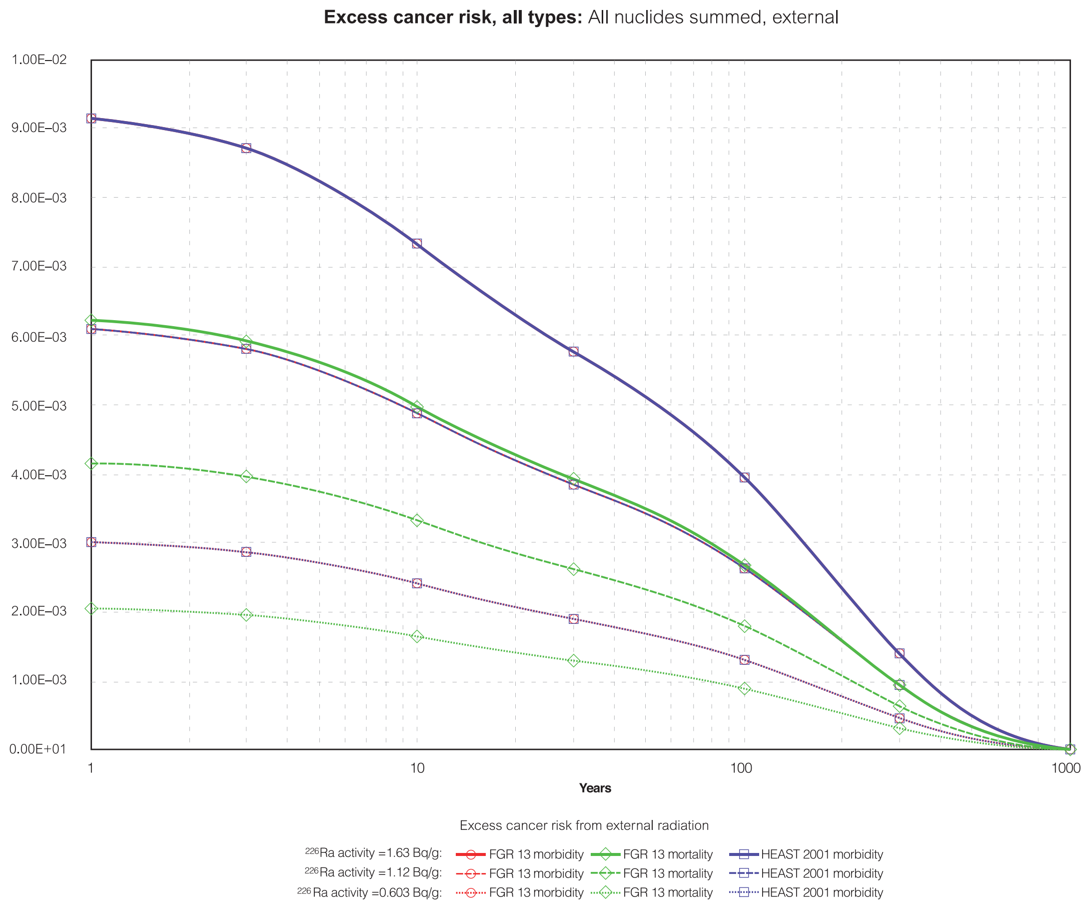


Fig. 3.6 Doses contribution from inhalation exposure pathway (^{226}Ra/^{228}Ra activity concentration 0.603, 1.12, and 1.63 Bq/g).

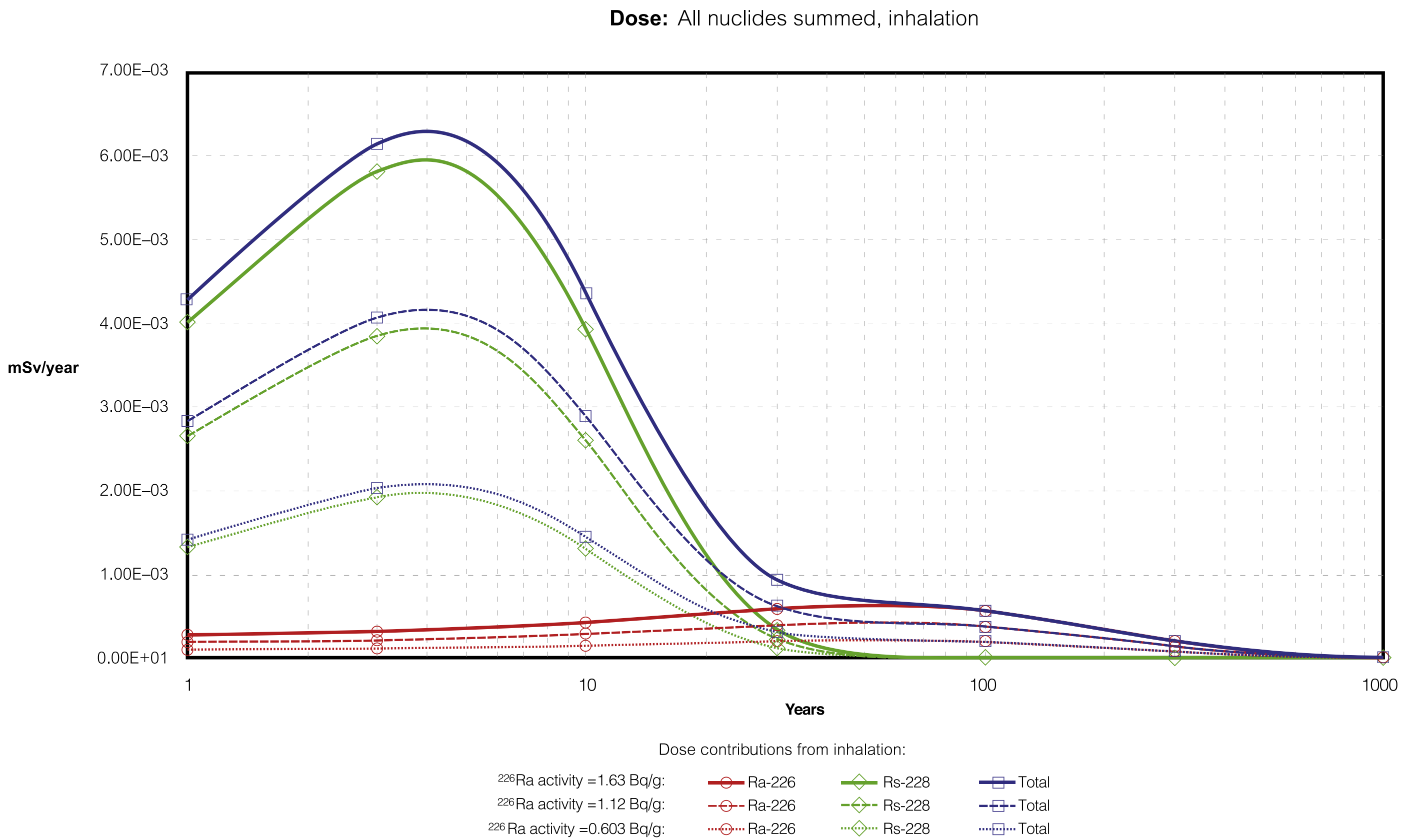


Fig. 3.7 Excess carcinogenic risks from external radiation exposure pathway (^{226}Ra/^{228}Ra activity concentration 0.603, 1.12, and 1.63 Bq/g).

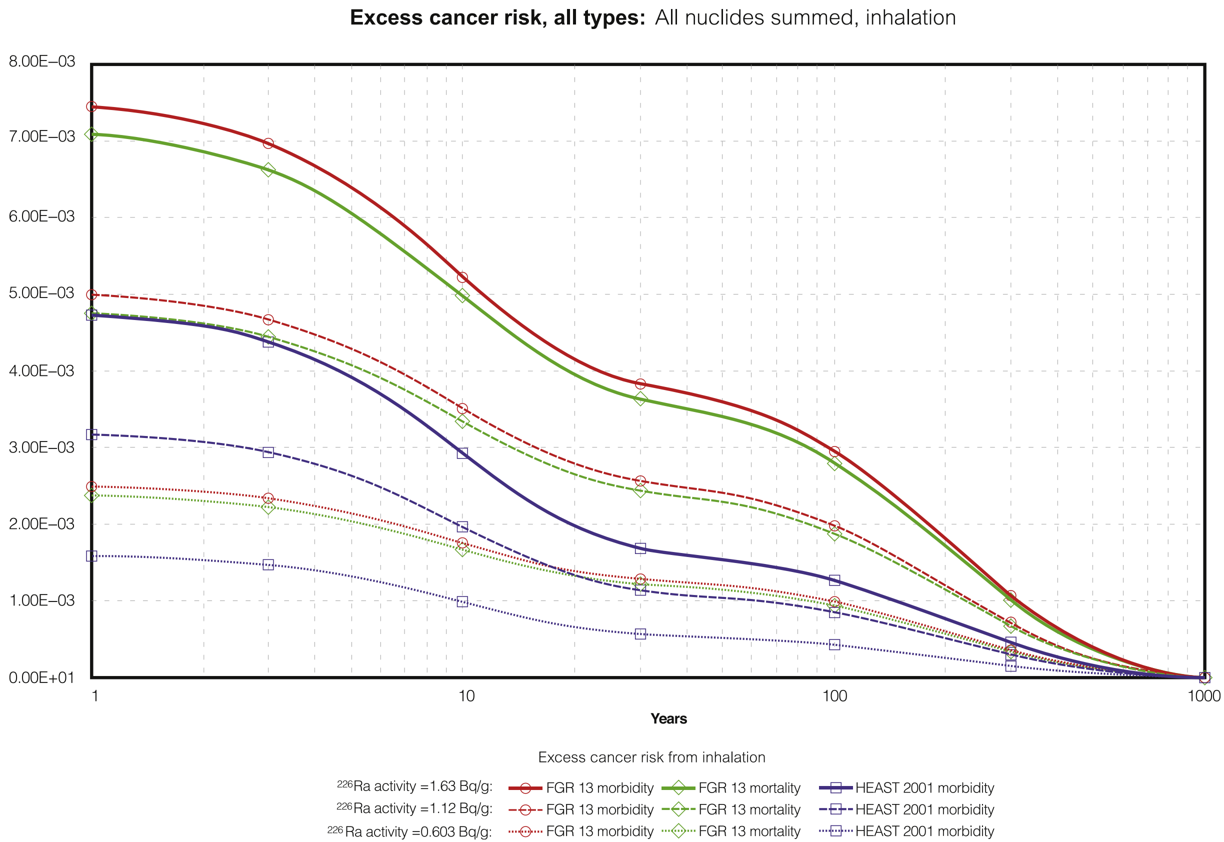


Fig. 3.8 Excess carcinogenic risks from inhalation exposure pathway (^{226}Ra/^{228}Ra activity concentration 0.603, 1.12, and 1.63 Bq/g).

exposed to the evaporation pond. In this assessment, two samples were collected with the average radionuclide concentrations of U-238 and Th-232 series of NORM of produced water being 12 and 8.5 Bq/L respectively. Additional samples of radionuclides U-238 and Th-232 were collected from three different soil categories:

- Category (I) was defined with a radiation level higher than 10 μSv/h.
- Category (II) was defined with a radiation level between 5 and 10 μSv/h.
- Category (III) was defined with a radiation level lower than 5 μSv/h.

The average concentration of radionuclides U-238 of soil categories I, II, and III were 42,323, 13,578, and 9236 Bq/Kg and for Th-232 were 36,100, 12,180, and 8290 Bq/Kg, respectively. The exposure source parameters were adjusted for a period of 1000 years. The area of the evaporation pond was 1300 m^2 and 10 m in depth. The predicted maximum total effective doses equivalent received by workers from produced water contaminated with TENORM in the evaporation pond were 1.5×10^{-5} mSv/year and 0.732, 0.244, and 0.150 mSv/year for soil categories I, II, and III at 0.5 m depth. While the total excess carcinogenic risks received by workers from produced water contaminated with TENORM in the evaporation pond found to be 1.3×10^{-9} and 6.0×10^{-5}, 2.0×10^{-5}, and 1.2×10^{-5} for soil categories I, II, and III, respectively. Results are described in greater detail in subsequent sections of Fig. 3.9.

3.4.2 Case study #3: Risk assessment of TENORM wastes disposed of in land farms (Smith et al., 1996)

Smith et al. (1996) have presented a similar risk assessment study of the radiological dosage found TENORM wastes disposed of in land farm. The authors modeled their scenario conservatively using the RESRAD (Yu et al., 1993) and assigned residential usage of the land on which TENORM had been disposed. Residential land usage is predicated on a number of assumptions: (a) individuals live on the site; (b) they drink the groundwater or surface water; and (c) they produce most of their food on-site, including vegetables, milk, meat, and fish. Multiple pathways were analyzed in this study, including (a) external irradiation; (b) inhalation of resuspended dust and radon; (c) ingestion of crops, milk, and meat grown on the property; (d) ingestion of fish from a nearby pond; (e) ingestion of contaminated soil; and (f) ingestion of surface water or groundwater.

In this study, it was assumed that the total soil contaminated area was 4050 m^2 (1 acre) with a contaminated zone 20 cm thick. Three soil concentrations were measured and modeled. The concentration ratio of

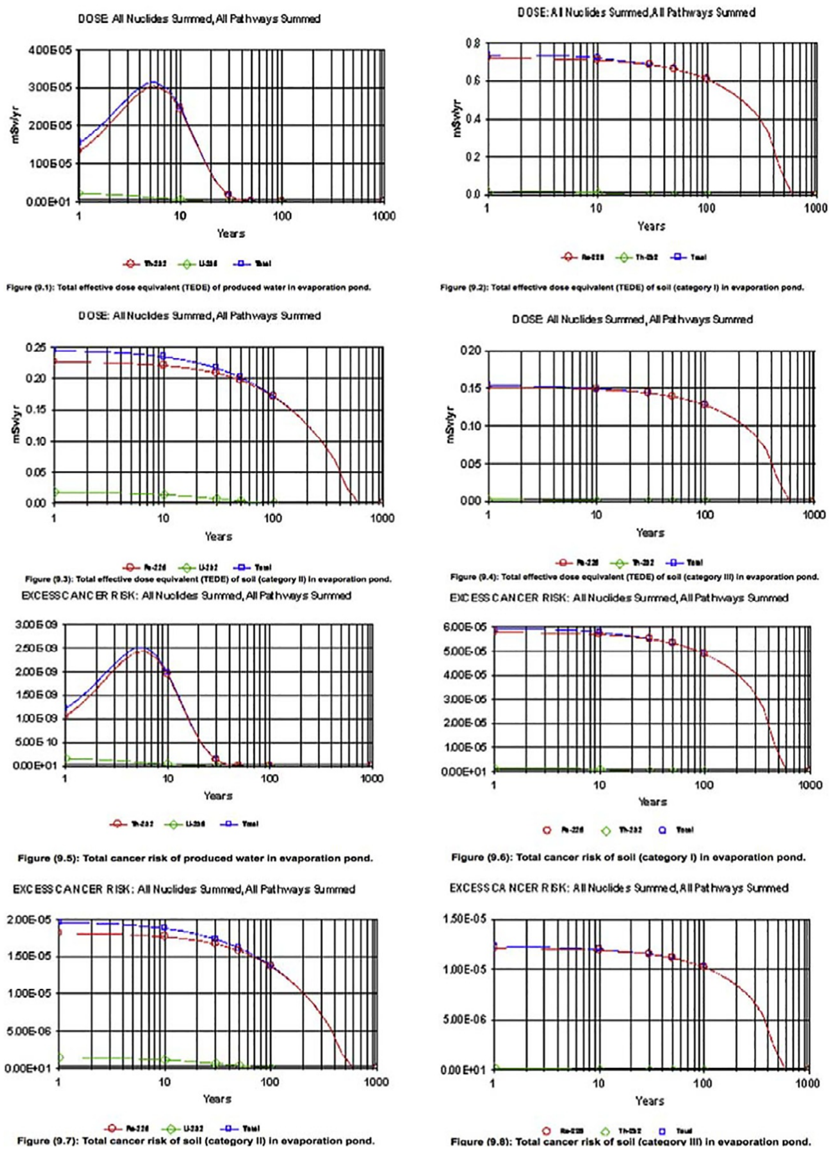


Fig. 3.9 Total effective doses equivalent (TEDE) from U-238 and Th-232 radionuclides and total carcinogenic risk for industrial workers exposed to produced water and contaminated soil in the evaporation pond (Othman and Hassan, 2013).

Ra-226: Ra-228 was assumed to be 3:1. The decay progeny were assumed to be in secular equilibrium. All pathways were considered in the analysis. It was also assumed that a scale-specific, emanation coefficient factor of 0.05 was used for Radon pathway calculation (Baried et al., 1996; US

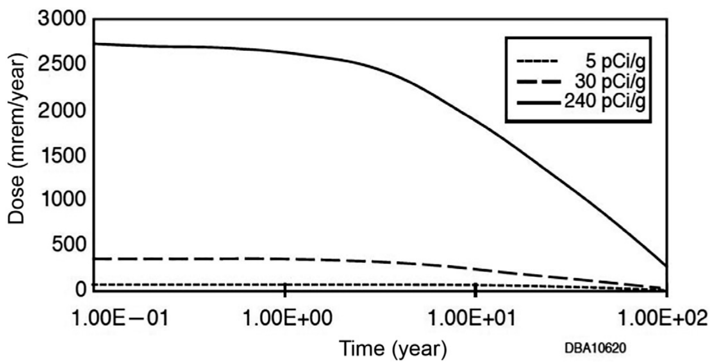


Fig. 3.10 Total doses over time summed over all pathways for land spreading with dilution (Smith et al., 1996).

EPA, 1993a,b). However, a shielding factor of 0.6 was assumed to account for the attenuation of gamma radiation by the walls of the house for the external irradiation pathway. All other input parameters required for doses and excess cancer risk calculation were set as RESRAD default values (RESRAD default values represent a generic scenario with default input parameters that are intended to be conservative).

Fig. 3.10 shows the total doses from all exposure pathways over 10,000 years for the three radium concentrations. For the concentration level of 240 pCi/g—equivalent to 8.88 Bq/g total radium, the estimated total doses for all pathways were 3000 mrem/year at the time the property was released. However, when soil concentration was decreased to 30 pCi/g (equivalent to 1.11 Bq/g) and 5 pCi/g (equivalent to 0.185 Bq/g), the total doses for all pathways decreased also. The contribution to the total dose from each pathway in this scenario risk assessment is described in more details in Fig. 3.10.

3.5 Analysis and discussions

It has been found that current TENORM waste disposal alternatives are not sufficiently based on scientific evaluations or radiological risk assessments from both engineering and medical perspectives. Although some radiological risk assessment studies have been conducted to assess increased carcinogenic risk resulting from exposure to TENORM waste disposal in the oil and gas industry, it still remains unclear whether or not exposure to low-doses radiation will increase carcinogenic risk. Furthermore, the evaluations of the performance of TENORM waste disposal method and assessments of radiological risk to workers, the general public and the environment was based exclusively on the risk value itself. The majority of these studies consider a low-dose exposure to be safe and harmless, and therefore conclude that the TENORM disposal method itself is safe. On the other hand, some of these studies compare the estimated doses with existing or proposed regulatory radiological safety standards where there is no commonly agreed standard about a precise characterization of a safe low radiological dose. For example in 1991, the International Commission on Radiological Protection (ICRP) recognized that workers' exposure to TENORM doses exceeding an average of 1 mSv/year is unsafe and that a full system of radiation protection control over TENORM-sources is needed. By contrast, the Canadian Nuclear Safety Commission (CNSC) recommended a formal safety program including personal dosimetry if occupational workers are exposed to 20 mSv/year. Moreover, it is not necessary that results obtained from radiological risk assessment in the oil and gas industry be 100% accurate because they do not include the medical final conclusion on these small numerical results obtained from radiological risk assessment, particularly with low doses exposure and low risk values. The low numerical values obtained from such risk assessments could be substantially based on uncertainty in each parameter estimation, input assumption, and the final computation of risk factors. Thus, the accuracy of conclusions based on a single deterministic value may be subject to uncertainty. Such uncertainty can arise from the following factors:

- Inaccurate input data or assumptions, or default input made by the simulator, or simulator quality.
- Some parameters may not be considered or may be inaccurately assumed in the model due to its continual change as a function of time and of the inability of the simulation program to dynamically update these variables as a real-time function. For example, continuous feed of TENORM waste causes changes in radionuclide concentrations and source term concentrations, yet the input assumptions are of a conservative nature.
- Doses assessment limitation due to site characterization of progeny radionuclides and the status assumptions of equilibrium/disequilibrium/in-growth for each sample.
- Each sample may contain a series of at least 12 radionuclides some of which emit alpha or beta, and others gamma. This makes it hard to precisely quantify the amount of radionuclides and their progenies in the sample such as radon gas. Consequently, analysis reports of TENORM samples vary from laboratory to laboratory, yielding different figures of

final doses and excess risk. It is highly recommended to first segregate the sample contents, and use as much as possible real-time standard measurement tools that are able to quantify each radionuclide and its progenies amounts in that sample.

- To derive single radionuclide and doses-based acceptance criteria, some of the modeling simulators require a good understanding of the physical, chemical, biological, geological, and geochemical factors/inputs parameters applicable to the selected exposure scenario(s) to be incorporated in a radiological risk assessment simulator. Additional understanding of the status of equilibrium is necessary to accurately perform a doses/risks assessment in support of doses/risks-based acceptance criteria. Historical information about the site processes/ors, selection of appropriate analyses to identify key decay series radionuclide and a comprehensive review of the characterization data are needed to understand the equilibrium status of the decay series present.
- Biological effect should not be generalized or characterized to be similar for all people exposed to different levels of radiation. Indeed not all living cells in the same body are equally sensitive to radiation, therefore different cell systems in different individuals have different sensitivities to radiation (US National Research Council, 2003). Many other factors such as differences in genetic structure, medical history, age, and gender type are factors that have a great impact on the biological effects of radiation exposure.

To eliminate or minimize the above uncertainties, the use of real-time input data is highly recommended, as it has a dramatic impact on results. This is clearly demonstrated by comparing the results of doses and excess carcinogenic risk obtained from the risk assessment of TENORM wastes disposed of in evaporation ponds based on a real scenario (case study 1), with the outcome from similar risk assessments obtained from the literature reviews described in case studies 2 and 3. A simulation risk assessment program need to be developed with the capability of dynamic updating of risk factors and other time function variables. It is also strongly recommended to integrate important medical parameters in the same simulation program that directly affect life risks, such as medical history, age, gender, current, or historical doses effects versus biological response.

Given the above-mentioned limitations, the results of risk radiological assessment still indicate that excess carcinogenic risk is caused by TENORM waste disposal in the oil and gas industry. The comparison of the estimated doses provides a preliminary indication of the relative risks associated with each TENORM waste disposal method. However, the performance of TENORM waste disposal methods and radiological risks to workers, the general public and the environment using radiological risk assessments should not be evaluated exclusively based on the risk value itself, or by comparing the estimated doses with existing or proposed regulatory standards. Furthermore, they should be analyzed based on medical opinion due to the fact that not all types of radiation have the same biological effects on the human body, or even in the same body. Whether the source of radiation is natural or man-made, and whether it is a small or large dose of radiation, there will be some biological effects (US National Research Council, 2003). The effects of other factors such as age, gender, medical history, genetic structure, effective doses, type of radiation, exposure duration, and exposure frequency all play an important role in the body's responses to radiological doses that have not yet been considered in many engineering TENORM risk assessments in oil and gas industries. Moreover, it has been scientifically proven that exposure to high-doses radiation increases the risk of solid cancers and leukemias. Such proof is based on evidence from epidemiological studies in atomic bomb survivors and radiation workers (Preston et al., 2004, 2007; Cardis et al., 2007). These data suggest that the risk of cancer from high-doses radiation is proportional to the doses following the linear non-threshold (LNT) model. This model is accepted by the US National Research Council since it appears to be the most conservative and defines the "NO-THRESHOLD" concept (i.e., any doses, no matter how small, involve some level of risk). The LNT model is being used to extrapolate risk from low-doses radiation, and an approach of this kind is endorsed by the BEIR VII (2006). Based on this model, it has been confirmed that even the very lowest doses of radiation may poses an increased risk that is proportional to the doses. This approach proves that there is no safe radiological exposure level, not even for exposure at low doses.

The above is confirmed by epidemiologic studies of atomic bomb survivors that have shown an increased carcinogenic risk, even in those exposed to low-doses radiation (5–100 mSv) (Preston et al., 2004; Cardis et al., 2007). Further confirmation comes from medical studies conducted on radiation workers. An international study on over 400,000 radiation workers with an average doses of radiation of approximately 20 mSv and cumulative doses of less than 150 mSv showed increased carcinogenic mortality (Cardis et al., 2007). Consistent with these findings, another study found that radiation workers followed by a national registry also had increased carcinogenic mortality associated with low-doses radiation (Muirhead et al., 2009).

Epidemiological studies, experimental data, and radiological risk assessment models suggest that the presently available models may not be able to adequately explain the relationship between doses and carcinogenic risks, but that they do explain the potential risk from exposure to low radiological doses as a result of the response and effect concept.

It follows that there is an urgent need for extensive research toward the development of a new scientific approaches to explain how exposures to low-doses radiation can increase carcinogenic risk. The current safety recommendations are limited only to advising the use of caution and to alert people of potential harm. Although the scientific community has been aware for more than 30 years that some workers in the oil and gas industry are at a great risk of being exposed to technologically enhanced levels of nuclear radioactivity (Gesell, 1975; Steinhäusler, 1980), the industry has been rather reluctant to acknowledge the potential exposure of its employees to radiation. (This could be attributed to economical and political reasons in addition to lack of knowledge, and these issues will be addressed in greater detail in the Chapter 6.) Based on these findings, medical benchmarking has sounded the alarm for workers exposed to radiation in the oil and gas industries as well as for the general public. Steinhäusler (2004) has concluded in his study that workers' exposure to TENORM in the oil and gas industry is truly a global concern, and that the impact of the collective doses is not uniform due to the global distribution of reserves that contains different levels of nuclear radioactive material. Accordingly, it is expected that the number of workers subject to TENORM exposure in the oil and gas industry is significantly higher in the Middle East and Central Asia than in all other regions combined. Therefore, workers and those living near TENORM waste disposal areas or oilfields must be informed of potential accidental radiation exposure and its associated risks. Unfortunately, this precaution action is mostly absent in the oil and gas industry in many countries around the world.

3.6 Conclusions

TENORM wastes in the petroleum industry have become a serious concern as a potential source of radiation that threatens the health and safety of workers, public health, and the environment. The huge amount of daily produced TENORM wastes during oil and gas extraction and production processes and related radiological risks are a major concern addressed in this study. It has been found that current TENORM waste disposal alternatives are not sufficiently based on scientific evaluations or radiological risk assessments from both engineering and medical perspectives. This study demonstrated the potential risk of radiation exposure resulting from the most common TENORM waste disposal methods using a scenario-based approach that was applied to support the proposed risk assessment, considering various fate and transport exposure pathways. A real scenario of TENORM waste disposal in an evaporation pond was used and simulated using the RESRAD 6.5 modeling system. The main purpose of this study was to measure doses and excess carcinogenic risks through different pathways of exposure using real input data. These results were used as the basis of comparison with results obtained from risk assessments of other similar TENORM waste disposal options found in other literature reviews that were based on many conservative assumptions. The comparison helps to better understand how real data and related assumptions affect the results and the degree of confidence we should have in them.

This study concluded that the current understanding of carcinogenic risk from low-doses radiation resulting from engineering radiological occupational exposure risk assessment is still limited and is not in line with medical opinion. Thus it was concluded that it might not be appropriate to evaluate the safety performance of TENORM waste disposal methods based only on the risks obtained from radiological risk assessments, or to draw conclusions based exclusively on the risk value itself without taking the medical perspective into account. This is because of uncertainty associated with those values, and also the fact that crucial factors such as radiation source, types, dose rate, dose effects, dose frequency, tissue type/cell/genes, and many other biological factors that are not being considered in the limited available TENORM radiological occupational risk assessments in the oil and gas industry, making it difficult to estimate with high accuracy the health risk from low-dose radiation. As a result, estimates remain controversial and associated with uncertainty. Therefore, the proposed approach related to TENORM waste disposal management can be used as a guideline or model to evaluate the performance and the effectiveness of current and future disposal methods in the oil and gas industry. Accordingly, the most prudent recommendation is to minimize the absolute exposure to all sources of radiation, as recommended by the regulation (10 CFR Part 20) of US National Research Council. And more researches are urgently required to further investigate safer TENORM waste disposal methods from the perspectives of environmental and human health protection.

References

Abdel-Sabour, M.F., 2014. NORM in waste derived from oil and gas production. Retrieved 02/17, 2015 from. http://www.researchgate.net/profile/Mamdouh_AbdelSabour/publication/264722815_NORM_in_Waste_Derived_From_Oil_and_Gas_Production.pdf.

Al-Farsi, A., 2008. Radiological aspects of petroleum exploration and production in the sultanate of Oman (Doctoral Thesis). Available from QUT database. (Document ID 29817/1). Available from: https://eprints.qut.edu.au/29817/1/Afkar_Al-Farsi_Thesis.pdf (Accessed 18.09.15).

API, 1989. A national survey on naturally occurring radioactive materials (NORM) in petroleum producing and gas processing facilities. API Dallas, Texas.

Baried, R.D., Merrl, G.B., Klein, R.B., Rogers, V.C., Nilson, K.K., 1996. Management and disposal alternatives for norm wastes in oil production and gas plant equipment. American Petroleum Institute, 1-1-5-18.

BEIR VII Phase 2, 2006. Health risks from exposure to low levels of ionizing radiation. National Academy of Science e National Research Council Committee, Washington, DC

Bou-Rabee, F., Al-Zamel, A.Z., Al-Fares, R., Bem, B., 2009. Technologically enhanced naturally occurring radioactive materials in the oil industry (TENORM). A review. Nukleonika 54, 3–9.

Cardis, E., Vrijheid, M., Blettner, M., 2007. The 15-country collaborative study of cancer risk among radiation workers in the nuclear industry: estimates of radiation-related cancer risks. Radiat. Res. 167, 396–416.

Clark, C.E., Veil, J.A., 2009. Produced water volume and management practices in the United States. Report ANL/EVS/R-09-1 US Dept. of Energy, Office of Fossil Energy, National Technology Laboratory, Washington, DC, 1–64.

Efendi, Z., Jennings, P., 1994. An assessment of the environmental radiation dose for residents of the Perth metropolitan area. Radiat. Prot. Aust. 12, 8–12.

EPA.1993a. Draft diffise NORM-waste characterization and preliminary risk assessment. US Environmental Protection Agency, Office of Radiation and Indoor Air, Washington, DC.

EPA, 1993b. A preliminary risk assessment of management and disposal options for oil field wastes and piping contaminated with NORM in the state of Louisiana. Peer Review Draft. Office of Radiation and Indoor Air, Washington, DC.

E&P Forum, 1988. Low specific activity scale: origin, treatment and disposal. The Oil Industry International Exploration & Production Forum Report, London.

Gesell, T.F., 1975. Occupational radiation exposure due to 222Rn in natural gas and natural gas products. Health Phys. 29 (5), 681.

Jonkers, G., Hartog, F.A., Knaepen, W.A.J., Lancee, P.F.J., 1997. Characterization of NORM in the oil and gas production (E&P) industry. In: Proceedings of International Symposium on Radiological Problems With Natural Radioactivity in the Non-nuclear Industry. Amsterdam, September 8–10, 1997, 23–47.

Kolb, W.A., Wajcik, M., 1985. Enhanced radioactivity due to natural oil and gas production and related radiological problems. Sci. Total Environ. 45, 77–84.

Muirhead, C.R., O'Hagan, J.A., Haylock, R.G., 2009. Mortality and cancer incidence following occupational radiation exposure: third analysis of the national registry for radiation workers. Br. J. Cancer 100, 206–212.

O'Brien, R.S., Cooper, M.B., 1998. Technologically enhanced naturally occurring radioactive material (NORM): pathway analysis and radiological impact. Appl. Radiat. Isot. 49, 227–239.

Othman, M.H., Hassan, H.B., 2013. Application of RESRAD model to assess radiation doses due to TENORM accumulation in evaporation pond during petroleum production. Arab. J. Nucl. Sci. Appl. 46, 172–179.

Paranhos Gazineu, M.H., deAraujo, A.A., Brandao, Y.B., Hazin, C.A., de O'Godoy, J.M., 2005. Radioactivity concentration in liquid and solid phases of scale and sludge generated in the petroleum industry. J. Environ. Radioact. 81, 47–54.

Preston, D.L., Pierce, D.A., Shimizu, Y., 2004. Effect of recent changes in atomic bomb survivor dosimetry on cancer mortality risk estimates. Radiat. Res. 2004 (162), 377–389.

Preston, D.L., Ron, E., Tokuoka, S., 2007. Solid cancer incidence in atomic bomb survivors: 1958–1998. Radiat. Res. 168, 1–64.

Reed, A.C., Mathews, J.L., Bruno, M.S., Olmstead, S.E., 2001. Chevron safely disposes one million barrels of NORM in Louisiana through slurry fracture injection SPE 71434, Proceedings of 2001 Annual Tech. Conference, New Orleans, Louisiana, September 30–October 3, 2001.1–13. Available at: http://www.terralog.com/article/spe7134.pdf.

Rood, A.S., White, G.J., Kendrick, D.T., 1998. Measurement of Rn-222 flux, Rn-222 emanation, and Ra-226, Ra-228 concentration from injection well pipe scale. Health Phys. 75, 187–192.

Sharkey, M.A., Burton, J.M., 2008. Remediation of hazardous materials with an emphasis on NORM. SPE 117936. Available at: http://sourceenviro.com/downloads/Remediation_of_Hazardous_Waste_with_an_Emphasis_on_NORM.pdf.

Silverstein, K., 2014. The Secret World of Oil. Verso Books, London, pp. 1–240.

Smith, G.E., Fitzgibbon, T., Karp, S., 1995. Economic impact of potential NORM regulations. In: Proceedings of the SPA/EPA Exploration and Production. Environmental Conference, pp. 181–231. 27–29 March 1995, Houston, TX, USA.

Smith, K.P., Blunt, D.L., Williams, G.P., Tebes, C.L., 1996. Radiological dose assessment related to management of naturally occurring radioactive materials generated by the Petroleum Industry. From. http://www.netl.doe.gov/kmd/cds/disk23/G-Soil%20Projects/NORM%5CANL-EAD-2.pdf (accessed 15.09.15).

Steinhäusler, F., 1980. Assessment of the radiation. TAEC Tech. J. 7 (2), 55–65.

Steinhäusler, F., 2004. Radiological Impact on Man and the Environment From the Oil and Gas Industry: Risk Assessment for the Critical Group. Radiation Safety Problems in the Caspian Region 41, 129–134.

Strand, T., 1999. Handling and disposal of norm in the oil and gas industry. In: WM'99 Conference, February 28–March 4, 1999.

US Environmental Protection Agency (US EPA), 1997. Exposure Factors Handbook. EPA/600/P-95/002F.

USNRC, 2003. Reactor Concepts Manual: Biological Effects of Radiation. USNRC Technical Training Center. from, http://pbadupws.nrc.gov/docs/ML0230/ML023020586.pdf. (Accessed 1 September 2015).

Vandenhove, H., Bousher, A., Jensen, P.H., Jackson, D., Lambers, B., Zeevaert, T., 1999. Investigation of a possible basis for a common approach with regard to the restoration of areas affected by lasting radiation exposure as a result of past or old practice or work activity. European Commission Report 115, September.

Yu, C., Zielen, A.J., Cheng, J.J., LePoire, D.J., Gnanapragasam, E., Kamboj, S., 1993. Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0, ANL/EAD/LD-2. Environmental Assessment Division, Argonne National Laboratory, Argonne, IL.

Further reading

ICRP, 1990. Recommendations of the International commission on radiological protection. ICRP Publication 60 Ann. ICRP 21, 1–3.

Yu, C., Zielen, A.J., Cheng, J.J., LePoire, D.J., Gnanapragasam, E., Kamboj, S., et al., 2001. User's Manual for RESRAD, Version 6. ANL/EAD-4. Argonne National Laboratory, Argonne, IL. Available at: http://web.ead.anl.gov/resrad/documents.

CHAPTER FOUR

Quantitative risk assessment and dynamic accident modeling of TENORM occupational exposure in the oil and gas industry using SMART approach

Chapter Outline

4.1 Introduction

The oil and gas industry are known to be one of the most dangerous and risky operations among many different industries. Fatal accidents, eloquent injuries, loss of assets, and damage to the environment are common examples of consequences from the risks associated with the oil and gas extraction and production operations. Such consequences can seriously harm workers, environment, and influence the reputation of this industry. Despite the efforts made by the stakeholders in the oil and gas industry to prevent the occurrence of accidents, they have managed to reduce the probability of operational or occupational accidents occurrence to certain levels but of course, failed to eliminate them completely.

https://doi.org/10.1016/B978-0-12-816825-7.00004-2

The resulting impacts of these accidents pose a major threat to the future of oil and gas industry due to the potential social, economic, and environmental consequences associated with it. However, there is another serious risk associated with oil and gas extraction and production activities that the oil and gas industry are not fully aware of, which is the nuclear radiological risks, "the silent killer." Nuclear radiological risks pose a serious threat to the health of the workers involved at various stages of oil and gas extraction and production process as well as the public and the environment because of the current unsafe radioactive waste disposal methods that are directly disposed into the environment.

Despite a dearth of available information regarding dynamic modeling and risk assessment of TENORM occupational exposure in the oil and gas industry. Still, 30 years' worth of research have explored and confirmed the fact that technologically enhanced naturally occurring nuclear radioactive materials (TENORM) are coproduced during oil and gas extraction and production and pose significant risks to several people involved in the oil and gas industry (Gesell, 1975; Steinhäusler, 2005). Thus, it is critical to realize that TENORM exposure truly exists and it is a global issue due to the global distribution of reserves and the strong relationship between naturally occurring nuclear radioactive materials and the presence of hydrocarbons. Accordingly, experts fear that some workers in the industry are at risk of being exposed to different levels of radiation doses under adverse conditions, based on the available data on the mass flow and activity concentration of radioactive material involved at various stages of the oil and gas industry.

Unfortunately, it has been found that these doses often exceed the currently acceptable occupational exposure dose limits for occupationally exposed persons where these limits have been found to be inconsistent in many available safety standards from one country to another. Regardless of the exposure level, chronic cancer is the ultimate and eventual consequence of radiation exposure (ALNabhani et al., 2016b). It is worth mentioning that it is possible to mitigate accidents involving radiological exposure at an early stage through preventative methodologies, including effective introduction and maintenance of appropriate safety measures and barriers to reduce risk and life-threatening situations. Radiological poisoning from TENORM is cumulative from chronic exposure and thus difficult to identify, especially in the early stages. Indeed, it can take many years for negative health symptoms to be manifested. The danger of radiation exposure could be combated by periodic medical check-ups for cancer and other negative effects, but this is a generally neglected practice in the oil and gas industry.

This situation could be improved by predicting, controlling, and mitigating exposure at the source, as well as emphasizing incident prevention to achieve an inherently safer process design to enhance safety. To protect the health and foster safety by preventive instances of major exposure, it is imperative to ascertain the presence and adequacy of safety barriers. To bridge current knowledge gap related to the dearth of dynamic accident modeling and quantitative risk assessment studies of TENORM occupational exposure in the oil and gas industry, this chapter presents a new approach on TENORM occupational exposure modeling and quantitative risk assessment in typical oil and gas extraction and production operations using SMART approach, which is a hybrid of SHIPP methodology and rational theory.

The proposed approach has the following unique features: (i) dynamic accident modeling of TENORM occupational exposure considering safety barrier performance, (ii) uncertainty reduction throughout prediction of the failure probabilities of safety barriers, (iii) dynamic updating of any abnormal event probability occurrence as new information or new evidence become available, and (iv) ability to systematically and logically model the accident process and the behavior of all possible root and passive causes in the system and its associated subsystems that usually contribute to an accident occurrence.

The proposed approach provides an integrated framework for dynamic prediction and TENORM occupational exposure risk information update. The outcome of this approach would help to monitor radiation exposure risk dynamically, support the development of effective safety and protective measures, and minimize radiological occupational risks in the oil and gas industry.

4.2 TENORM dynamic accident modeling and quantitative risk assessment using SMART approach

The SMART approach combines the SHIPP methodology and rational theory. The SHIPP methodology is a generic framework used to identify, evaluate, and model accident process (Rathnayakaa et al., 2011, 2013). According to the science of safety engineering and risk assessment management, accident modeling process can be performed using the following models: (1) sequential model where an accident is considered to occur in a sequential order, and usually this process can be represented by a "Swiss Cheese Model." Whereas cheese slices represent the safety barriers for the main system while the random holes in cheese slices represent the latent failures such as human errors and equipment failures that are hard to be quantified; or (2) epidemiological model where an accident is considered to occur because of a combination of physical and latent causes; or (3) systematic model. In this model, an accident is considered to occur because of an interaction between many components of the system and its subsystems. Usually, this model is the most complex model because of the complexities of both the system and its subsystems that make it hard to track or predict the consequences.

While, the rational theory is used to systematically model the behavior of all possible root and passive causes that may contribute to an accident occurrence based on the logical, inductive, and probabilistic analysis. The inductive analysis is a realistic reasoning approach that investigates the true reasons behind accident occurrence to reach a true conclusion (since we are not sure of the accident causes that contributed to its occurrence).

That is why we are investigating the causes or hypothesizes behind accident's occurrence so that we can avoid or prevent accidents from occurring in the future. Such causes or hypothesizes are viewed as supplying strong evidence for the truth of the conclusion; therefore, the truth of the conclusion of an inductive argument is probable, based on the available evidence. For example, if you fall, you might be injured or might not be and this is in line with the probabilistic analysis approach that can be mathematically expressed: if an event A has occurred or is true then its consequence B, or C, or D probably be true to occur.

In the opposite, the deductive approach means that we are sure and confident of the result. Therefore, the conclusion of a deductive argument is certain and can only be applicable to the science of safety engineering and risk assessment management if we are certain about the root cause of that accident. For example, if you fell from the 10th floor, you will die. Mathematically this can be expressed: if the occurrence of an event A is true and certain, then consequences occurrences of B, C, and D are true.

Accordingly, the basic premise of the rational theory is that an accident occurs because of joint conditional behaviors of different parameters in the system and its associated subsystems. Therefore, the rational theory investigates logically all physical and latent causes in the system and its subsystems that have contributed into the accident occurrence with the ability to review, update, and improve any potential errors that may arise from the evaluation of the latent and physical causes.

By integrating the SHIPP methodology and rational theory, the SMART approach is, therefore, able to: (i) identify the interaction between systems and their subsystems, as well as the source of TENORM and their distributions in oil and gas extraction and production processes; (ii) identify and analyze all possible TENORM occupational exposure scenarios; (iii) model all possible different occupational radiation exposure scenarios based on the performance of safety barriers using Monte Carlo simulation; (iv) predict and update the failure probabilities of the identified safety barriers; (v) enable proactive management of TENORM risks using either adaptive risk management techniques or precautionary principle techniques. Fig. 4.1

Fig. 4.1 Flowchart of SMART approach. (TENORM risk estimation in term of the dollar value is not covered by this study.)

illustrates the SMART approach flowchart developed for TENORM occupational exposure accident modeling and quantitative risk assessment in the oil and gas industry that mainly comprises of five major parts, which are:

1. *SHIPP methodology part*: This process includes identifying the components of the system and its subsystems. It helps to give a clear idea of how the system and subsystems are functioning and interacting with each other. Once the system and its subsystems are well identified, hazards identification process can be started in connection to the system and its subsystem. This step will give a better understanding to easily track easily all possible hazards in connection with the components of the system and its subsystems. The final step in this part is to simulate all possible accident process and their behaviors for thousands of times to make sure that all possible causes have been recognized for ease reasoning purpose. Accordingly, if we find out that the hazard is really a major risk, and then we can proceed to the next step of rational reasoning part and if it is not, then it is recommended to use any of classical qualitative risk evaluation for nonmajor hazards.
2. *Rational reasoning part*: Rational reasoning part starts immediately after identifying the main components of the existing system and its subsystems, which will start via identification and evaluation of available safety prevention barriers in term of their efficiency and performance. This can be done by gathering historical data related to their failures, abnormal events occur during the operational process and then calculating the consequences of occurrence probabilities using the event tree model. During this process, keep updating dynamically arrival of any new information, new evidence, or occurrence of abnormal events. The importance of this step is to systematically model the behavior of all possible root and passive causes within the system and its subsystem that usually contributes to the accident occurrence based on the performance of the identified safety prevention barriers using logical, inductive, and probabilistic analysis to improve the risk certainty. Once the cumulative risk evaluation based on the rational reasoning provide sufficient certainty, then move to the third part of the SMART flowchart, which is the prediction part. If the uncertainty level is still high, then use the precaution principles, which will provide high-level safety protections in the absence of any details about the risk level.
3. *Prediction part*: In this part, the quantitative risk assessment is attempting to predict the likelihood of failure probabilities of the identified safety barriers during the next time of interval $(t+1)$ based on the precursor

accumulative knowledge and historically gathered data. This data will then be simulated using Monte Carlo simulation for thousands of times to systematically model the behavior of all possible root and passive causes that usually contribute to the accident occurrence within the system and its subsystem based on the performance of the identified safety prevention barriers. This can be achieved by using logical, inductive, and probabilistic analysis to improve the certainty and have a more accurate understanding of the accident process and its behavior.

4. *Updating part*: Once all likelihood of failure probabilities has been calculated based on all expected scenarios during the next time of interval ($t + 1$), Bayesian inference mechanism is applied in which Bayes' theorem is used to update the probability for all the hypothesis and scenarios created by the simulator as more evidence or new information become available. The Bayesian update is particularly important in dynamic accident modeling and quantitative risk for a better and accurate decision-making. In the philosophy of decision theory, Bayesian inference is closely related to subjective probability, often called "Bayesian probability." Once safety failure probabilities have been updated based on the arrival of any new information or availability of new evidence or occurrence of any abnormal events, then these probabilities are called posterior failure probability that again feed into the event tree model to update the consequences occurrence probabilities, which eventually will provide a holistic idea about the system degradation in the next time of interval ($t + 1$). Accordingly, it helps tremendously with decision makers to make the right decision at an early stage and therefore, prevents accidents from occurring.
5. *Risk management part*: Finally, once the certainty for the identified risk has been improved, then the risk is then must be converted into a dollar value to evaluate if the risk is within the acceptable level or not. Accordingly, the decision is taken depending on which of the risk management techniques described further will be used to bring the risk to an acceptable low level:
   - *Adaptive risk management technique*: This technique utilizes the available knowledge about the level of risk certainty and makes necessary changes in the system to reduce the risk accordingly. It entirely depends on the experience of the managers and decision maker to decide what types of risk reduction to be implemented.
   - ALARB risk management technique: This technique focuses on bringing down the risk to an acceptable level through the adoption of risk reduction measures as a function of the cost. The main premise

of this technique is that the cost should be kept as low as possible compared to the benefit gained otherwise it is useless to implement it. For example, if the benefit gained from the adoption of risk reduction measures is less than the cost paid to introduce new safety barriers, then it is not recommended to implement based on ALARB's premise.

6. Finally, after the adoption of risk reduction measures using any of the above-suggested techniques or through introducing a new improvement or modification to the existing safety prevention barriers, the SMART will automatically and dynamically update and evaluate the performance of the safety barriers and associated risk.

The proposed SMART approach was demonstrated and validated in the following section using a case study of showing all possible TENORM occupational exposure scenarios for a sample of 2271 workers involved at different kinds of typical oil and gas activities including upstream, midstream, and downstream.

4.3 TENORM occupational exposure scenario modeling and prediction

The world has witnessed an increase in the production of oil and gas over the past several years to meet the increase in the demand of energy globally. This makes the oil and gas industry as the main economy source for many countries around the world. Accordingly, the oil and gas industry can be considered the biggest industries in the world that accommodate millions of workers to meet such huge global energy demand. Unfortunately, massive production of oil and gas has led to increased technological risks because of the adoption of new technologies to increase the production, such as enhanced oil recovery technologies (EORTs). Some of the risks include TENORM (technologically enhanced naturally occurring radioactive materials: the silent killer) production where their activity concentrations have been enhanced and therefore pose serious radiological risks to workers, the public, and the environment.

As has been mentioned earlier, many of the available studies have found that level of radioactivity concentrations in the oil and gas industry can range from low to extremely high levels. Despite this, many of the oil and gas industries are reluctant to acknowledge the presence of TENORM in its operation and this could be attributed to many reasons such as a lack of knowledge and understanding, political and economic reason, or a lack of scientific studies related to radiation exposure risk assessment and management in the oil and gas industry.

All these reasons left people working in the oil and gas industry with no clue about the probabilities of being exposed to radiological risks and their long-term consequences. In the oil and gas industry, the exposure of workers to TENORM can occur at various stages during oil and gas extraction and production process starting from the upstream, midstream, and downstream activities as well as at waste disposal facilities as shown in Fig. 4.2. Those who may be affected include workers performing drilling and associated services, including but not limited to crewmembers involved in work over, fluid filtration, coring, hydraulic fracturing, fishing and milling, waste management, perforation, wire line logging, and directional drilling services. As well as those who work in the midstream and downstream such as crew members working in gathering and production station, flow line maintenance, and refineries.

In the present study, scenarios of TENORM occupational exposure were modeled and simulated using the SMART approach. A sample was

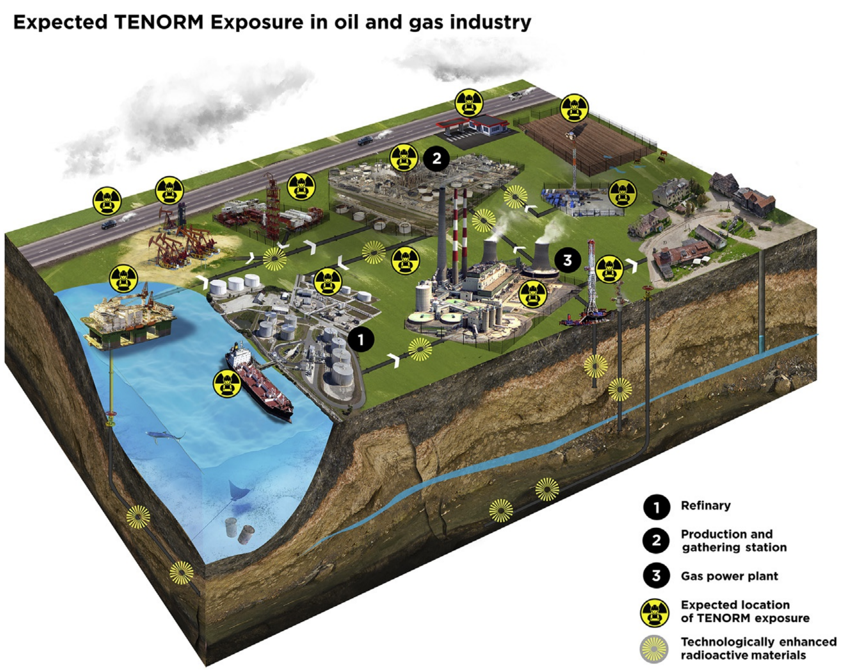


Fig. 4.2 An overview of TENORM presence during oil and gas extraction and production activates.

taken from 2271 workers involved in different oilfield activities where TENORM occupational exposures are expected as shown in Fig. 4.2 to simulate different possible radiological occupational exposures in the oil and gas industry because of the possible failure of identified safety barriers. A period of 10 years was considered for serious carcinogenic risk to be noticed as well as it is a suitable period to monitor the system and provide a reasonable prediction about the degradation of the system and its subsystems as a function of the performance of the safety prevention barriers. The prior estimate of abnormal events was used for preliminary decision-making, and then the Bayesian updating theorem was utilized to calculate the posterior failure probabilities of safety barriers during the ensuing time interval. The probabilities of consequences occurrence were then generated through an event-tree analysis model.

As new evidence or new information or new abnormal events became available at any time during the evaluation process, the safety barrier failure probabilities were dynamically updated. Subsequently, the updated risk for each consequence level was estimated using new posterior failure probabilities. This way time-dependent risk profiles were developed dynamically for each TENORM exposure. The intention of the SMART approach is to bring to the attention of oil and gas industry the importance of TENORM dynamic accident modeling and quantitative risk assessment and management that is currently absent in the oil and gas industry, to give an example of how TENORM dynamic accident modeling and quantitative risk assessment can be performed using the proposed SMART approach, and to develop an effective quantitative risk assessment and management strategies that aid in identifying critical safety barriers and their performance that need to be maintained in the oil and gas industry in order to foster the safety culture and provide enough protection to the workers.

4.3.1 SHIPP methodology

System identification

During oil and gas extraction and production procedures, the oil, gas, formation water, and TENORM mixture ascends to the surface via drilled wells through downhole completion and production equipment. In this mixture, TENORM can be found either soluble or insoluble as suspended particles, or in gaseous form, as the temperature and pressure change as oil and gas are lifted, their chemical and physical properties changes.

Accordingly, they can be found in different forms such as scales or sludge or soluble with hydrocarbon or formation water or can be found in the gaseous form such as radon gas.

This mixture then travels to midstream equipment via a separator, which removes the gas and relays it to a downstream gas purification plant while the degassed oil stream is further pumped to midstream production from the upstream facilities via flow lines. The gathering and production stations then remove the oily sludge, sand, and geological formation water that are contaminated with TENORM. During this process, a portion of the TENORM has a solidified form and deposits on the internal surfaces of the oil field extraction and production equipment (Testa et al., 1994; Kvasnicka, 1996; Al-Masri and Aba, 2005; Othman et al., 2005; ALNabhani et al., 2015).

Eventually, pipelines transport crude oil to the downstream facilities for further refining, where the refined products may still harbor TENORM according to many scholars. Smith (1992), for example, reported that TENORM can be transported in different forms in the produced hydrocarbons, which confirms their existence during this oil and gas extraction and production process and even in the final products that are used in power plants, petrochemicals, and manufacturing industries. In confirmation of this, Al-Masri and Haddad (2012) concluded from their study on TENORM emissions from oil and gas-fired power plants that TENORM was present in fly and bottom ash collected from major Syrian power plants fired by heavy oil and natural gas. On the other hand, many scholars also have reported that benzene used in several industry applications was found to cause carcinogenic diseases associated with leukemia, and more specifically with acute myeloid leukemia cancer (Vigliani and Saita, 1964; Aksoy et al., 1974; Infante et al., 1977; Yin et al., 1978; Jamall and Willhiteb, 2008; World Health Organization (WHO), 2010).

Alongside oil and gas extraction and production, TENORM are found as generated wastes. Yearly, the global petroleum industry generates millions of tons of TENORM wastes in form of produced water, scales, sludge, and contaminated equipment. These wastes are disposed of directly into the environment either above ground or underground. Accordingly, TENORM coexists with oil and gas during extraction and production, which pose serious radiological risks to the workers involved in these processes, the public, and the environment. As a result, there is a serious concern as to how to protect workers, the public, and the environment from the nuclear radiological risks in the oil and gas industry.

4.3.2 Rational methodology

Safety barriers identification and evaluation

During the oil and gas extraction and production processes that combine upstream activities with midstream and downstream operations. Five sequential and interconnected safety barriers for radiation prevention could be identified in this whole process, which remains largely unimplemented in the oil and gas industry. These are as follows:

1. *Early detection safety prevention barrier (EDSPB)*: This is the release prevention barrier (RPB) that is responsible for preventing the initiating event for TENORM release at the upstream source. This includes, but is not limited to the following sub-barriers:
   - Field and well logging data, such as spectral gamma logs that are considered as a good source of information on early TENORM presence associated with hydrocarbon evaluation, and its level of radioactivity prediction.
   - Downhole real-time detectors that can detect the radioactively level from rock formation during drilling activities.
   - Upstream surface sensors should also be fixed at different locations in drilling rigs such as at the cellar, the wellhead, the flowline connected to the bell nipple, the mud system, the waste pits, and the rig floor.
   - Midstream activities sensors that can be placed in flow lines between the wellhead and gathering stations, equipment in the gathering and production stations such as separation tanks and eventually in refinery utilities, particularly in storage tanks.
2. *Isolation integrity safety prevention barrier (IISPB)*: This is a dispersion prevention barrier (DPB) at the midstream phase. It includes, but is not limited to, the following sub-barriers: equipment insulation carrying TENORM coproduced with oil and gas, including flow lines, separation tanks, pumps, and other associated processing equipment in gathering and production stations; emergency shut down mechanisms and work permits.
3. *Personal protection equipment and exposure duration safety prevention barrier (PPE&EDSPB)*: It includes, but is not limited to, the following sub-barriers: leaded shield personal protection equipment—LPPE (protective clothing, face mask, hand gloves, and safety boots) and personal radiation monitors.
4. *Emergency management safety prevention barrier (EMSPB)*: This safety barrier is considered as the mitigation barrier to control hazardous TENORM exposure and its consequences. It includes, but is not limited to, the

following sub-barriers: emergency response plan, emergency preparedness, emergency medical plan, emergency and safety drills, worker awareness.

5. *Management and organization safety prevention barrier (M&OSPB)*: This safety barrier intervenes either positively or negatively with all other barriers based on the management's behavior and responsibility. It includes, but is not limited to, the following sub-barriers: training and competency programs, safety policies, legislation, operating procedures, cancer medical check-ups, effective risk and safety management system, decision-making, management practices and knowledge, leadership, and communication.

Event tree model

An event tree analysis (ETA) is an inductive procedure that is used to calculate the occurrence probabilities of consequences based on the success or the failure probabilities of the identified safety prevention barriers. Raus and Høyland (2004) summarize the main steps that should be used to calculate the probabilities/frequencies for the identified consequences using the ETA model, which are to.

1. Identify a relevant initial accidental event and the positional consequences
2. Identify the safety prevention barriers that are designed to mitigate and prevent from accidents occurrence
3. Construct the event tree
4. Describe the potential resulting accident sequences
5. Calculate the failure probabilities/frequencies of the identified safety prevention barriers
6. Calculate the probabilities/frequencies for the identified consequences
7. Compile and present the results from the analysis

In this study, the associated event tree model was utilized to demonstrate the consequences of TENORM occupational exposure accidents based on the failure of each of the five identified safety barriers. These five safety barriers were assigned six possible states ranging from safe to catastrophe. The occurrence of each state is possible through the failure of different safety barriers, as is shown in Fig. 4.3.

In this risk assessment, the radiation exposure scenario was described in terms of safety barrier performances (failure and success). Due to a dearth of the relevant literature on this subject, the failure probabilities of the identified safety barriers were assigned by professional academic experts from

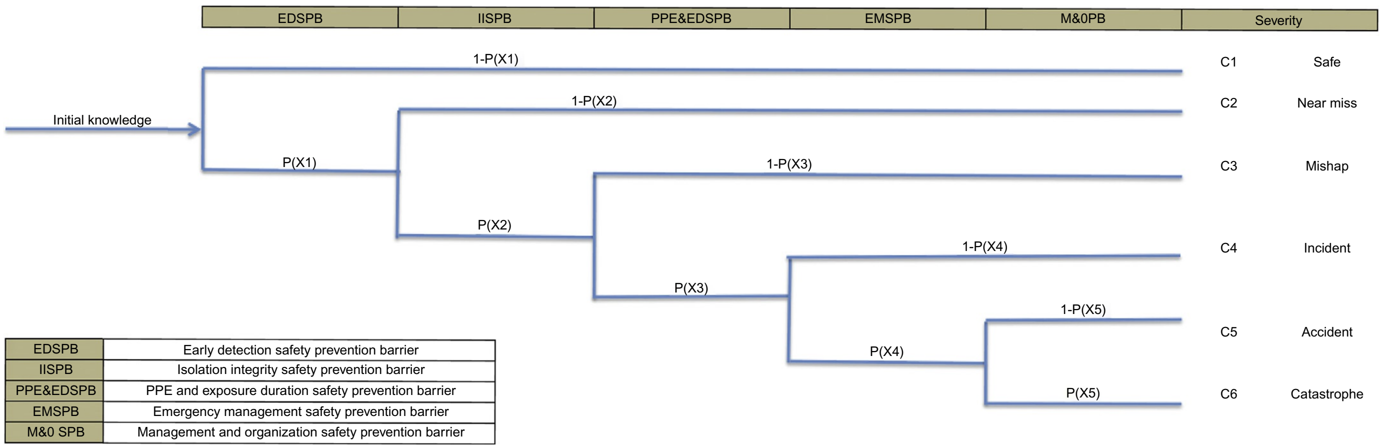


Fig. 4.3 Event tree of TENORM occupational exposure in the oil and gas industry.

Centre for Risk, Integrity, and Safety Engineering (C-RISE-Memorial University) (Table 4.1). These values are utilized here for illustration and validation purposes.

The failure and success of a safety barrier are represented as a node with two outcomes. For example, if the first safety barrier EDSPB is successful, then the desired outcome is "safe." If it is unsuccessful, the penultimate safety barrier, IISPB, is activated. If this node is successful, the outcome is labeled "near miss," which is defined as an undesirable event of a radiological exposure that is about to occur; but luckily did not occur, but with a potential for serious consequences. If unsuccessful, the safety function PPE&EDSPB is activated. The successful outcome of this node is "mishap," which is defined as an undesirable event of a radiological exposure that happened with very minor consequences considered less than the incident. In the case of a failure, the next safety barrier, EMSPB, is activated and this leads to the consequence being labeled "Incident," which is defined as an undesirable event of a radiological exposure that can cause medium radiation injuries or other related damages.

If this barrier fails, the last safety barrier M&OSPB is activated. When M&OSPB is successful, the end state is labeled "accident," which is defined as an undesirable event of a radiological exposure that occurred and resulted in major radiation injuries, environmental or property damages. If M&OSPB is unsuccessful, the end-state consequence is labeled "catastrophe," which is defined as a massive tragedy of an undesirable event of a radiological exposure that can result in multiple fatalities, huge losses, and great damages to the environment, public, and assets.

Table 4.1 The failure probabilities of safety barriers (assigned by professional academic experts from Centre for Risk, Integrity, and Safety Engineering (C-RISE-Memorial University)

Failure probability of safety barriers

Safety barrier (X_i)	Failure probability $P(X_i)$
Early detection safety prevention barrier (EDSPB)	0.20
Isolation integrity safety prevention barrier (IISPB)	0.05
Personal protection equipment and exposure duration safety prevention barrier (PPE&EDSPB)	0.05
Emergency management safety prevention barrier (EMSPB)	0.10
Management and organization safety prevention barrier (M&OSPB)	0.10

The prior probability of each outcome (consequence severity level k ($k = 1$, 2, 3, 4, 5, and 6)), denoted by $P(C_k)$, is given as.

$$P(C_k) = \Pi X_i^{\theta, I, k} (1 - X_i)^{1-\theta}{}_{i,k} \qquad (4.1)$$
$$j \in SB_k.$$

where SB_k denotes the safety barrier associated with the level k and; $\theta_{i,k} = 1$ if the level k failure passes the down-branch (failure) of safety barrier i; $\theta_{i,k} = 0$ if the level k failure passes the up-branch (success) of safety barrier i. Table 4.2 illustrates prior probabilities of consequences of occurrence.

4.3.3 Modeling dynamic prediction and updating

Probabilities have wide applications in risk assessment and management and usually used to represent the chances of occurrence of an event A and its associated consequences. In the classical interpretation, a probability of an event A to occur is measured by the number of times that event A occurs divided by the total number of the frequencies of occurrence for that event. There are three types of probabilities commonly used in risk assessment and management, which are: (1) joint probabilities, (2) marginal probabilities, and (3) conditional probabilities. Conditional or marginal probability approaches are widely utilized in many classical accident modeling and risk assessment. These approaches might be associated with a high level of uncertainty in term of risk prediction especially for a complex system of a wide range of operating conditions and variables (Tesfatsion, 2015).

While, the proposed SMART approach in this study is based on a rational prediction model that attempts to ensure a more accurate predictive model for TENORM occupational exposure and associated risks, which considers events occurrence as a joint event (e.g., safety barriers failures and abnormal events are joint events) rather than a single event (abnormal

Table 4.2 Prior estimates of occurrences of each consequence
Prior estimate of occurrence probability of each consequence

Consequences (C_k)	Occurrence probability $P(C_k)$
C_1 (safe)	0.8
C_2 (near miss)	0.19
C_3 (mishap)	9.5×10^{-3}
C_4 (incident)	4.5×10^{-4}
C_5 (accident)	4.5×10^{-5}
C_6 (aatastrophe)	5.0×10^{-6}

events only) that many classical approaches consider. In the study of probabilistic methods, given at least two random variables A, B, for example, are defined on a probability space. The joint probability distribution for A, B, therefore, is the probability distribution that gives the probability each of A, B will fall in any range set of values specified for that variable in the defined probability space. Thus, the joint probability distribution is more accurate due to its comprehensive in analyzing risk assessment for a complex system in a dynamic interaction with many other subsystems.

Therefore, it can be expressed either in term of a joint cumulative distribution function or in term of a joint probability density function (in the case of continuous variables) or joint probability mass function (in the case of discrete variables). These, in turn, can be used to find two other types of distributions: the marginal distribution giving the probabilities for any one of the variables with no reference to any specific ranges of values for the other variables, and the conditional probability distribution giving the probabilities for any subset of the variables conditional on values of the remaining variables.

Accordingly, the rational theory in the proposed SMART approach considers both the occurrence of the abnormal events because of the failure of any element of the safety barrier as joint events. This can be attributed to the fact that the failure of any element in the identified safety prevention barrier of the main system and its subsystem is enough for an accident to occur. Thus, the SMART approach provides a more accurate predictive model that will enhance the accuracy of the decisions for the improvement of the safety system. Mathematically, the rational prediction model is presented as follows:

$$P(\text{data}) = P(\text{data} \mid X_i).$$
$$P(\text{data}) = P(\text{data} \mid X_i \, \text{true}).$$
$$P(X_i) = |\{x : X_i\,(x)\}| / |x : \text{true}|.$$

Then conditional probability expressed as:

$$P(\text{data} \mid X_i) = |\{x : X_i\,(x) \text{ and data } (X)\}| / |x : X_i\,(x)|$$

Finally, the joint probability of this model expressed as:

$$P(X_i \text{ and data}) = P(\text{Data}/X_i)\, P(X_i).$$
$$P(X_i \text{ and data}) = |\{x : X_i\,(x) \text{ and data } (x)\}| / |x : \text{true}|.$$
$$= (|\{x : Xi\,(x)\ \textit{and data}\,(x)\}|\,|\{x : Xi\,(x)\}|)\,/\,(\,|\{x : Xi\,(x)\}|\,|x : \textit{true}|\,)$$
$$= P(X_i)\, P(\text{data} \mid X_i)$$

Using symmetry, this equation can be written as Bayesian updating theorem as expressed in the following equation (which is the basis of this model) to estimate the likelihood and update failure probability of safety barriers in the next time of interval (t + 1).

$$P(X_i \text{ and data}) = P(\text{data} \mid X_i)^* \, P(X_i) \tag{4.2}$$

where $P(X_i$ and data) is the joint probability of two events (failure of safety barrier will occur first, then the abnormal event will take place and vice versa); $P(\text{data} \mid X_i)$ is the occurrence of abnormal events "data" given that failures of safety barriers "X_i" have occurred (Generally described as likelihood failure probability.); $P(X_i)$ is the prior failure probabilities of safety barriers "X_i."

Failure probability estimation

The first step in the predictive model is to estimate the failure probability of the safety barriers for the next time of interval (t + 1) to prevent any TENORM occupational exposure accidents from occurring in the future or during the identified time of interval. Therefore, cumulative abnormal events data or historical data are a necessity to estimate the failure probability. Because of the dearth of occupational radiological risk assessment and absence of safety prevention barriers, it is therefore difficult to provide enough protection against radiological risk in oil and gas industry.

Accordingly, the cumulative abnormal events data were assumed with the support of technical and academic experts around safety engineering and risk assessment management. Assumed data were then simulated for thousands of times using Monte Carlo Simulation to model all possible accidents process and accidents causation behavior to improve data quality and reduce uncertainty, which is shown in Table 4.3. The probabilities (Table 4.4) of precursors to abnormal events were computed based on the data provided in Table 4.3.

According to rational theory, the SMART approach considers the joint probability of the occurrence of both events $P(X_i$ and data) as a basis for the ensuing prediction of failure probability that is presented in Table 4.5.

Rational cumulative precursor data $P(X_i$ and data) were then simulated using a Monte Carlo simulation, where the objective was to simulate events of an identified period (t = 10 years) in an existing scenario for 1000 cycles to determine how random variation and associated errors affect the uncertainty and performance of the modeled parametric system. The cumulative

Table 4.3 Cumulative precursor data of abnormal events of TENORM exposure in the oil and gas industry over 10 years

Cumulative precursor data of abnormal events *P*(data | X_i)

Years	C_1 (safe)	C_2 (near miss)	C_3 (mishap)	C_4 (incident)	C_5 (accident)	C_6 (catastrophe)
1	28	30	10	6	3	1
2	36	40	15	9	7	2
3	44	48	17	12	9	3
4	47	55	19	13	11	4
5	50	65	25	16	14	6
6	47	82	33	20	15	8
7	55	89	42	30	27	15
8	62	100	53	42	39	25
9	74	109	60	45	43	38
10	80	114	65	60	67	87
Total	523	732	339	253	235	189

Table 4.4 Probabilities of abnormal events precursor data of TENORM exposure in the oil and gas industry over 10 years

Cumulative precursor data of abnormal events *P*(data | X_i)

Years	C_1 (safe)	C_2 (near miss)	C_3 (mishap)	C_4 (incident)	C_5 (accident)	C_6 (catastrophe)
1	0.359	0.385	0.128	0.077	0.038	0.013
2	0.330	0.367	0.138	0.083	0.064	0.018
3	0.331	0.361	0.128	0.090	0.068	0.023
4	0.315	0.369	0.128	0.087	0.074	0.027
5	0.284	0.369	0.142	0.091	0.080	0.034
6	0.229	0.400	0.161	0.098	0.073	0.039
7	0.213	0.345	0.163	0.116	0.105	0.058
8	0.193	0.312	0.165	0.131	0.121	0.078
9	0.201	0.295	0.163	0.122	0.117	0.103
10	0.169	0.241	0.137	0.127	0.142	0.184

precursor data $P(X_i$ and data) is defined as input for the parametric model for simulation and is denoted by $f\{(X_1$ and data), (X_2 and data), …, (X_i and data)}.

The probability distribution of the defined parametric model was utilized to generate another set of random inputs. These newly generated inputs were then evaluated and the same process was repeated for 1000 runs so that this data best matched with the other data, or best represents the current

Table 4.5 Rational probabilities of precursors of abnormal events of TENORM exposure in the oil and gas industry over 10 years

	Cumulative precursor data $P(X_i$ and data)					
Years	C_1 (safe)	C_2 (near miss)	C_3 (mishap)	C_4 (incident)	C_5 (accident)	C_6 (catastrophe)
1	0.187	0.077	0.006	0.004	0.004	0.001
2	0.172	0.073	0.007	0.004	0.006	0.002
3	0.172	0.072	0.006	0.005	0.007	0.002
4	0.164	0.074	0.006	0.004	0.007	0.003
5	0.148	0.074	0.014	0.005	0.008	0.003
6	0.119	0.080	0.008	0.005	0.007	0.004
7	0.111	0.069	0.008	0.006	0.010	0.006
8	0.100	0.062	0.008	0.007	0.012	0.008
9	0.104	0.059	0.008	0.006	0.012	0.010
10	0.088	0.048	0.007	0.006	0.014	0.018

knowledge state, and is denoted by $\{(X_i \text{ and data})_1, (X_i \text{ and data})_2, \ldots, (X_i \text{ and data})_q\}$. Table 4.6 illustrates the improved quality of the cumulative precursor data of abnormal events extracted randomly from the simulated data.

The generated data then were used to calculate the likelihood for failure probability of safety barrier in the next time interval of 10 years using the following equation:

$$P(data|x_i) = [N_{F,i} \,|\, (N_{F,i} + N_{S,i})] \tag{4.3}$$

Table 4.6 Cumulative precursor data of abnormal events simulated over 10 years of TENORM occupational exposure

	Cumulative precursor data of abnormal events $P(X_i$ and data)					
Years	C_1 (safe)	C_2 (near miss)	C_3 (mishap)	C_4 (incident)	C_5 (accident)	C_6 (catastrophe)
1	0.184	0.075	0.006	0.004	0.004	0.001
2	0.169	0.072	0.007	0.004	0.006	0.002
3	0.170	0.070	0.006	0.004	0.007	0.002
4	0.161	0.071	0.006	0.004	0.007	0.003
5	0.144	0.071	0.009	0.004	0.008	0.003
6	0.117	0.078	0.008	0.005	0.007	0.004
7	0.108	0.065	0.008	0.006	0.010	0.006
8	0.100	0.060	0.008	0.006	0.012	0.008
9	0.102	0.057	0.008	0.006	0.011	0.010
10	0.083	0.045	0.007	0.006	0.014	0.018

$$N_{S,i} = N_{C,k}, \text{ for } k = \text{i}.$$
$$N_{F,i} = \sum N_{c,k,} \text{ and } k > i; i = 1,2,3,4 \text{ and } k = 1,2,3,4,5.$$

where $N_{c,k}$ is the number of abnormal events of consequence kth level, $N_{S,i}$, and $N_{F,i}$ are the number of successes and failures for the ith barrier.

The failure probabilities for all safety barriers are listed in Table 4.7.

Safety barriers failure probability update

The Bayesian updating mechanism was then utilized to update the likelihood of failure probability of the safety barriers over the following 10 years when new types of evidence arose, or any changes occurred in oil and gas processing. Bayesian updating mechanism derives the posterior failure probabilities of the safety prevention barriers because of two antecedents: a prior probability and a "likelihood function" derived from a previous statistical model for the observed data. Bayesian updating mechanism computes the posterior probability according to the basics of Bayes' theorem shown in the following:

$$P\,(\text{Hypothesis} \mid \text{Evidence}) = [P\,(\text{Evidence} \mid \text{Hypothesis})\ \text{P}\,(\text{Hypothesis})]/P\,(\text{Evidence}).$$

where P (Hypothesis | Evidence) is the posterior probability, which is a function of the Hypothesis that we are looking for given Evidence is observed; P (Evidence | Hypothesis) is the likelihood of failure probability and it is a function of the Evidence. It shows the compatibility of the evidence with the given hypothesis. P (Hypothesis) is the prior probability,

Table 4.7 Likelihood for failure probabilities for all safety barriers

	Likelihood failure probability for each safety barrier $P(X_i$ and data)				
Years	**EDSPB**	**IISPB**	**PPE&EDSPB**	**EMSPB**	**M&OSPB**
1	0.328	0.164	0.577	0.574	0.259
2	0.349	0.205	0.645	0.667	0.226
3	0.344	0.215	0.681	0.670	0.255
4	0.361	0.219	0.694	0.704	0.272
5	0.398	0.256	0.631	0.720	0.305
6	0.464	0.231	0.666	0.705	0.353
7	0.467	0.312	0.729	0.744	0.362
8	0.485	0.362	0.762	0.757	0.394
9	0.475	0.383	0.780	0.779	0.470
10	0.519	0.497	0.854	0.837	0.569

which is the estimate of the probability of the Hypothesis before the current Evidence, is observed; *P* (Evidence) is the marginal likelihood probability.

Thus, updated failure probabilities uncover the consequence occurrence probabilities, which were updated using ETA. According to rational theory, the likelihood of failure probabilities of a given safety barrier X_i is affected by a combination of latent or physical and dependent or independent random variables in the identified system and its subsystem. These variables are considered as new evidence and therefore are updated into to the SMART model using the Bayesian updating theorem (Bedford and Cooke, 2001) as follows:

$$P(X_i \mid \text{data}) = [P(\text{data} \mid X_i)\, P(X_i)] / \sum [P(\text{data} \mid X_i)\, P(X_i)] \quad (4.4)$$

where $P(X_i \mid \text{data})$ is posterior to failure probability of the safety barrier, $P(\text{data} \mid X_i)$ is the likelihood of failure probability of the safety barrier, $P(X_i)$ is prior to failure probability of the safety barrier, data are the new information or evidence arrived, and $\sum[P(\text{data} \mid X_i)\ P(X_i)]$ is the normalizing factor.

Table 4.8 and Fig. 4.4 illustrate the updated failure probability for each safety barrier over 10 years (incorporated with new evidence arrived of random variables contributed to the failure).

Consequence occurrence probability update

The updated failure probabilities of the safety barriers in this model were utilized to estimate occurrence probabilities for each severity level.

Table 4.8 Posterior to failure probability data for safety barriers failures over 10 years

Posterior failure probability for each safety barrier over 10 years $P(X_i \mid \text{data})$					
Years	**EDSPB**	**IISPB**	**PPE&EDSPB**	**EMSPB**	**M&OSPB**
1	0.109	0.010	0.067	0.130	0.037
2	0.118	0.013	0.087	0.182	0.031
3	0.116	0.014	0.101	0.184	0.037
4	0.124	0.015	0.107	0.209	0.040
5	0.142	0.018	0.083	0.223	0.047
6	0.178	0.016	0.095	0.210	0.057
7	0.179	0.023	0.124	0.244	0.059
8	0.190	0.029	0.144	0.257	0.067
9	0.185	0.032	0.157	0.281	0.090
10	0.212	0.049	0.235	0.363	0.128

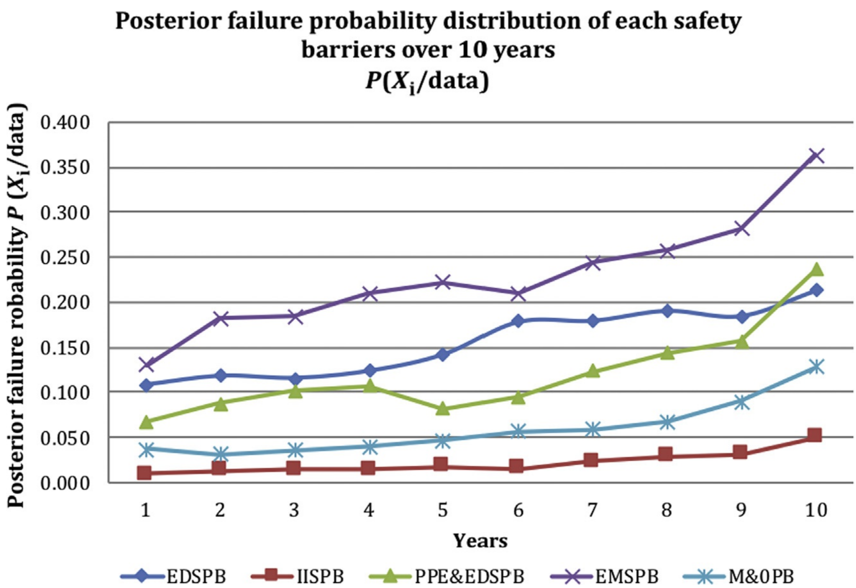


Fig. 4.4 Posterior to failure probability distribution of each safety barriers failure over 10 years.

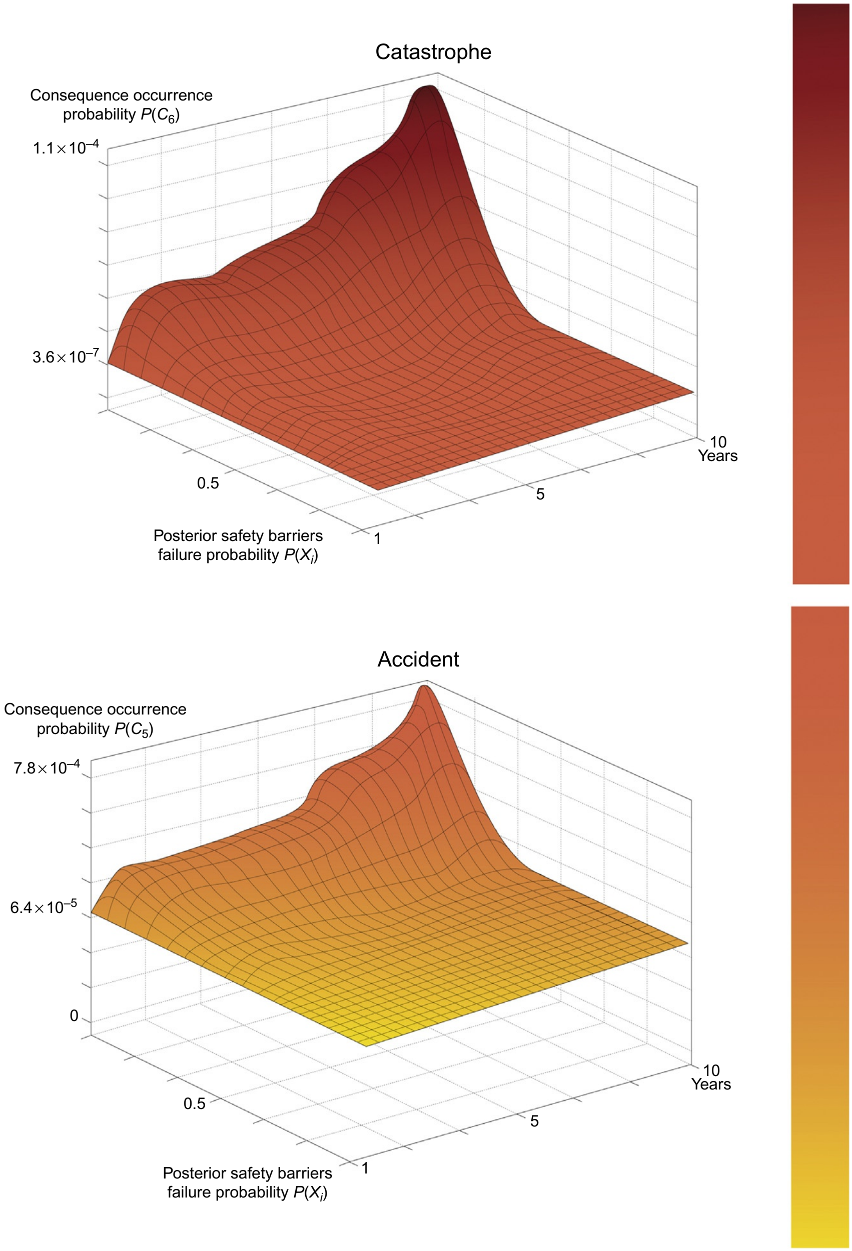
These probabilities were then fed into relevant branches of the event tree shown in Fig. 4.5, and the following equation was utilized to estimate the posterior occurrence probabilities of each severity level over the 10 years as shown in Fig. 4.5.

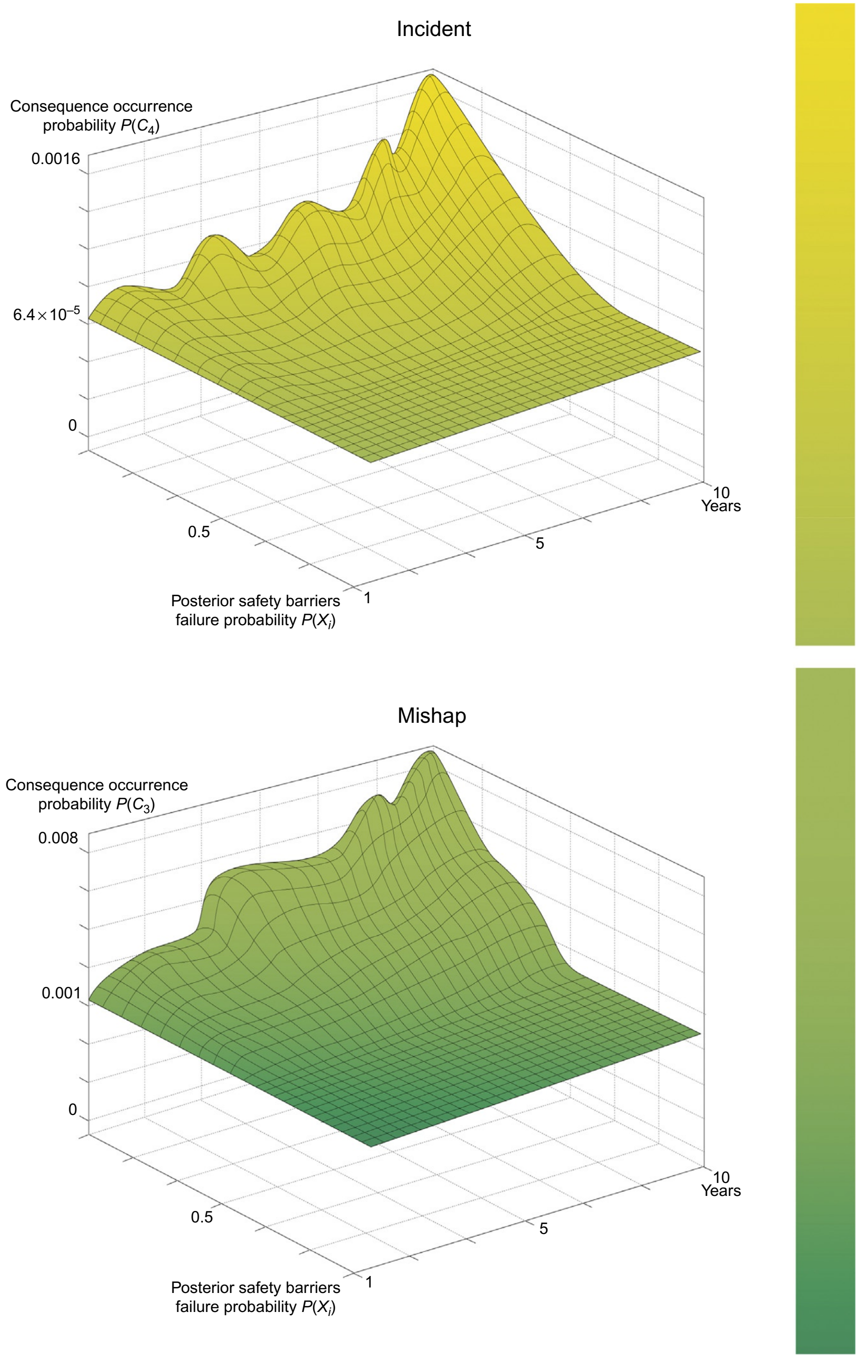
The posterior probabilities of consequences occurrence in year 10 (consequence severity level k ($k=1$, 2, 3, 4, 5, and 6), denoted by $P(C_k)$, are given as.

$$P(C_k) = \Pi X_i^{\theta, I, k}(1 - X_i)^{1-\theta}{}_{i,k} \quad (4.5)$$
$$j \in SB_k.$$

where SB_k denotes the safety barrier associated with the level k and; $\theta_{i,k}=1$ if the level k failure passes the down-branch (failure) of safety barrier i; $\theta_{i,k}=0$ if the level k failure passes the up-branch (success) of safety barrier i.

Table 4.9 illustrates the posterior probabilities of consequences occurrence in year 10.


Catastrophe
Consequence occurrence probability $P(C_6)$
1.1×10^{-4}
3.6×10^{-7}
0.5
Posterior safety barriers failure probability $P(X_i)$
1
5
10
Years
Accident
Consequence occurrence probability $P(C_5)$
7.8×10^{-4}
6.4×10^{-5}
0
0.5
Posterior safety barriers failure probability $P(X_i)$
1
5
10
Years


Incident
Consequence occurrence probability $P(C_4)$
0.0016
6.4×10^{-5}
0
0.5
1
Posterior safety barriers failure probability $P(X_i)$
5
10
Years
Mishap
Consequence occurrence probability $P(C_3)$
0.008
0.001
0
0.5
1
Posterior safety barriers failure probability $P(X_i)$
5
10
Years

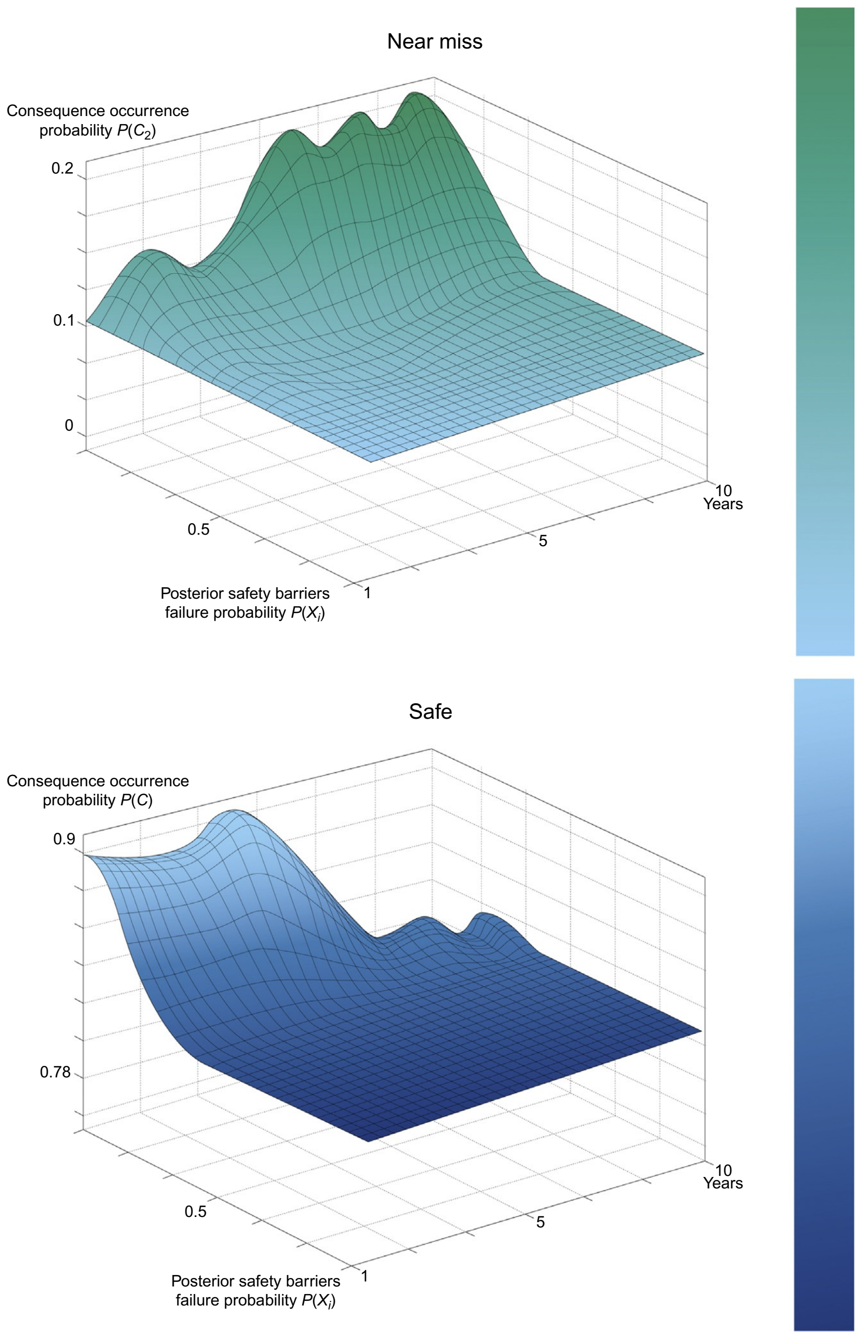


Fig. 4.5 Overall variations of updated consequences occurrence probability distributions over a period of 10 years.

Table 4.9 Posterior estimate of occurrence probability of each consequence in year 10

Consequences (C_k)	Occurrence probability $P(C_k)$
C_1 (safe)	0.788
C_2 (near miss)	0.201
C_3 (mishap)	8×10^{-3}
C_4 (incident)	1.6×10^{-3}
C_5 (accident)	7.8×10^{-4}
C_6 (catastrophe)	1.1×10^{-4}

4.4 Analysis and discussions

In this study, the dynamic TENORM occupational exposure accident modeling and quantitative risk assessment were based on the performance of five identified sequential safety prevention barriers and their sub-elements that were assigned by professional academic experts. The five identified sequential safety prevention barriers are mostly absent in many oilfields due to many reasons that could be attributed to the lack of knowledge and understanding, political and economic reasons (because oil and gas industry is considered as the most important source of economy for many countries), the lack of radiation exposure accident modeling, and risk assessment studies. These safety barriers were found to be sufficient to provide enough protection for workers from being exposed to radiological risks and they are: (1) the EDSPB; (2) the IISPB; (3) the PPE&EDSPB; (4) the Emergency Management Safety in Prevention Barrier (M&OSPB).

To test the validity of the model, a dynamic accident modeling and quantitative risk assessment were performed using the proposed SMART approach coupled with a probabilistic methodology for 2272 workers involved at different oil and gas streams. Model validation was based on three important phases comprised of safety barriers analyses and evaluation, model prediction and updating, and consequences occurrence probability updating.

According to the prior results, the consequences of higher severity have low probabilities of occurrence, which is obvious in events of catastrophe and accident. On the other hand, the consequences of lower severity have higher probabilities, such as safe events. For example, the probability of maintaining a safe system was 0.8, whereas the estimated probability of an accident and catastrophic cancer fatality were very low 4.5×10^{5} and 5×10^{-6}, respectively. Based on the initial knowledge, it has been found that the probabilities of occurrence of other severity levels, such as near misses, mishaps, and incidents gradually decreased from 0.19, 9.5×10^{-3}, and to 4.5×10^{-4}, respectively, as the system had not yet started to degrade, and this is obvious as a result of the assumption that identified five safety prevention barriers are in place and are functioning well.

The results obtained from this model provided both qualitative and quantitative information about TENORM occupational exposure risk in the oil and gas industry. These results indicated that the proposed model is amenable to practical applications with the occurrence of a safe mode higher than fatal cancer-causing events (according to general medical radiological cancer data).

The rational prediction and Bayesian updating theorem were adopted in the second phase of the SMART approach. They were utilized to predict the failure likelihood and update the prior failure probabilities of the identified safety barriers over the 10-year period. The prediction attempted to present a better visualization of the safety performance in a 10-year period so that appropriate decisions can be made to bolster current safety strategies. As shown in Fig. 4.4, Bayesian posterior probability values for the safety barrier failures have drastically increased because of system degradation within the 10-year period. This degradation could be attributed to many factors, the most important being a dearth of dynamic and quantitative radiological risk assessment studies related to TENORM risks in the oil and gas industry.

Other factors include the lack of the dedicated radiation protection legislation for the oil and gas industry, and the fact that TENORM producing industries are reluctant to admit the presence of radiological risks in their operations even as they avoid any association with the word "nuclear," which is in itself a clear admission that the workers are exposed to radiation risks (ALNabhani et al., 2016a) despite that previous studies confirm that TENORM are coproduced with oil and gas production and can range from low to extremely high levels. And while the medical community considers it unsafe according to epidemiological studies, some industries consider that exposure to TENORM at a low dose is safe (ALNabhani et al., 2016b). Moreover, the implementation cost is a potential barrier for acknowledgement and action concerning TENORM risks and inhibits safety barrier improvement. Consequently, no action yet has been taken by the industry to introduce or bolster safety barriers. As a result, the system will continue to degrade.

The posterior failure probabilities of safety barriers were utilized in the third phase and were fed into event tree branches to estimate the updated occurrence probabilities of consequences. The results demonstrated that system degradation causes the end-state probability (consequence occurrences probability) to change dramatically over the 10-year period. Despite the prior probability of occurrence of the safe (C_1) condition being high, its posterior probability was gradually reduced from 0.89 to 0.79 as time increased, as illustrated in Fig. 4.5 (safe). This sharp drop raises the worrisome implication that the industry would have been able to prevent such system degradation at early stages if the identified safety barriers had been well-maintained or in place for early-stage activities. For example, if an early detection prevention barrier was in place, it would allow the industry to predict the presence of TENORM in their oilfields and well holdings at early stages by using well logging data that contains radioactivity data, which is used as an indicator of the presence of oil and gas in targeted pay zone formation (ALNabhani et al., 2015), and therefore appropriate safety precautions could be taken at a very early stage.

Because of the safe mode deficiency, posterior probabilities of occurrence of incidents, accidents and catastrophes continued to drastically increase over time to 1.6×10^{-3}, 7.8×10^{-4}, and 1.1×10^{-4}, respectively, as shown in Fig. 4.5 (catastrophes). The continual drastic increase could be attributed to failure of the subsequent safety barriers. If the first safety barrier failed, TENORM would then be brought up from the rock reservoir that holds oil and gas in their matrix, along with oil and gas extraction and production activities, and continue to flow from the drilled wells to gathering and production stations and finally to the refinery via well completion equipment, flow lines and associated equipment (Holland, 1998; Jonkers et al., 1997; Wilson and Scott, 1992; Hamlat et al., 2001; Abdel-Sabour, 2014).

These pieces of equipment are unfortunately not radiologically insulated or designed to prevent gamma radiation emitted by TENORM passing through or in their scale depositions. Because of the failure of the second safety prevention barrier, many of the workers in the oil and gas extraction and production activities are at risk of being exposed to different radiation levels. In current standard personal protective equipment (third safety prevention barrier) is not designed to protect against accidental exposure to any radiation, let alone with nearly constant daily, weekly and even yearlong exposure times. The risk of exposure to radiation doses at elevated levels may develop into fatal cancer within 10 years of continuous exposure.

According to the model results, the posterior probability of a fatal cancer catastrophe (C_6) improved greatly during the 10 years of continuous exposure; however, it has a sharp increasing tendency in probability from 3.6×10^{-07} to 1.1×10^{-4} as shown in Fig. 4.5 (catastrophes), which is almost a 3000-fold increase, and this raises serious concerns. Most importantly, some safety barriers such as the EMSPB and the M&OSPB can interact and intervene with the whole safety system at any stage during an operation, and their interaction can promote safety strategies or have the opposite effect and weaken the safety system based on the management's behavior and their awareness of safety importance. This can be clearly observed when looking at the posterior occurrence probabilities of near miss (C_2), mishap (C_3), incident (C_4), and accident (C_5) that frequently occur in the industry. Fig. 4.5 (near miss, mishap, incident, and accident) shows a fluctuating trend between steadily rising and sudden sharp increases over time. The reason behind the fluctuation is that only when observing radiation are the preventive measures applied based on its causal factors and occurrence frequency, and therefore prove this phenomenon. However, over extended time periods, the system re-exhibits performance impairment.

4.5 Conclusions

The production of oil and gas has increased greatly in recent years due to the growing global demand for energy. Accordingly, the oil and gas industry are considered as a key component of many countries' economy around the world. This industry can be considered as one of the biggest industries in the world that accommodate millions of workers to meet such huge global energy demand. This industry is also known to be one of the most dangerous and risky industries. Fatal accidents, eloquent injuries, the loss of assets, and damage to the environment are frequent accidents seen during the oil and gas extraction and production operations that negatively harm workers, environment, and influence the reputation of this industry.

In addition to these known risks, there is, unfortunately, a hidden risk yet neither explored nor paid much attention to, which is the radiological risk, the silent killer. Many pieces of the literature have revealed that the huge daily production of oil and gas has resulted in an increase in the production of different levels of nuclear radioactive materials that range from low- to high-level activity concentrations because of the adoption of new technologies to increase oil and gas production, such as EORTs. TENORM is a potentially serious environmental and occupational risk in oil and gas operations. Despite this, most of the oil and gas industries have not been effective in addressing this issue or providing enough protection to their workers, public, and the environment against the effect of radiological risks from the oil and gas industry. This can be attributed to political and economic reasons, the lack of knowledge, and related risk assessment studies.

However, this study attempted to provide a guideline to assess radiation exposure risk to workers, where a new methodology of dynamic accident modeling scenario-based risk assessment was developed. This model was based on the SMART approach that integrates the SHIPP methodology and rational theory. This approach provided a systematic and comprehensive risk assessment framework based on safety barrier performance evaluation and analysis. Five important safety barriers are identified and are considered to provide sufficient protection from radiation exposure during oil and gas extraction and production activities if they are implemented. The SMART approach provides a systematic framework for modeling, predicting, updating, and managing the TENORM exposure risk during oil and gas extraction and production processes. This study represents the first attempt in the radiological occupational exposure risk assessment area of the oil and gas industry to quantify TENORM risks and its consequences and assess it based on safety barrier performance.

Based on the results, it is apparent that there is an urgent need to develop appropriate safety measures for protection against radiation exposure during extraction and production of oil and gas. It is equally important to find an effective scientifically based solution to minimize the large production of the volume of the radiological materials created during production in form of radioactive waste that is usually disposed of directly into the environment, which is not systematically based on scientific evaluations or radiological risk assessments from both engineering and medical perspectives. Also worrisome are the adverse effects of radiological pollution from TENORM waste disposal methods and the potential sources affecting workers, the public, food, water resources, soil, and the environment. Thus, future studies to be done according to the SMART approach process flowchart including the estimation of the TENORM economic risk, and how to establish a successful and thorough TENORM management system.

References

Abdel-Sabour MF (2014) NORM in waste derived From oil and gas production. http://www.researchgate.net/profile/Mamdouh_AbdelSabour/publication/264722815_NORM_in_Waste_Derived_From_Oil_and_Gas_Production.pdf.

Aksoy, M., Erdem, S., Dinçol, G., 1974. Leukemia in shoe-workers exposed chronically to benzene. Blood 44, 837–841.

Al-Masri, M.S., Aba, A., 2005. Distribution of scales containing NORM in different oilfields equipment. Appl. Radiat. Isot. 63, 457–463.

Al-Masri, M.S., Haddad, K.H., 2012. NORM emissions from heavy oil and natural gas fired power plants in Syria. J. Environ. Radioact. 10, 71–74.

ALNabhani, K., Khan, F., Yang, M., 2015. Technologically enhanced naturally occurring radioactive materials in oil and gas production: a silent killer. Process Safety and Environment Protection, PSEP. http://www.psep.ichemejournals.com/article/S0957-5820(15)00177-9/pdf.

ALNabhani, K., Khan, F., Yang, M., 2016a. The Importance of Public Participation in Legislation of TENORM Risks Management in the Oil and Gas Industry. Process Safety and Environmental Protection. https://doi.org/10.1016/j.psep.2016.04.030. http://www.sciencedirect.com/science/article/pii/S0957582016300489.

ALNabhani, K., Khan, F., Yang, M., 2016b. Scenario-based risk assessment of TENORM waste disposal options in oil and gas industry. J. Loss Prev. Process Ind. 40, 55–66.http://www.sciencedirect.com/science/article/pii/S0950423015300838.

Bedford, T., Cooke, R., 2001. Probabilistic Risk Analysis: Fundamentals and Methods. Cambridge University Press, Cambridge.

Gesell, T.F., 1975. Occupational rad. Exposure due to Rn222. Health Phys. 29 (5), 681.

Hamlat, M.S., Djeffal, S., Kadi, H., 2001. Assessment of radiation exposures from naturally occurring radioactive materials in the oil and gas industry. Appl. Radiat. Isot. 55, 141–146.

Holland B (1998) Experience with operations involving NORM in the United Kingdom (UK) and some other regions. Report of the RCA Expert Advisory Group Meeting to Review and Develop Radiation Protection Guidance for Naturally Occurring Radioactive Materials in the Oil and Gas and Other Mineral Extraction and Processing Industries. Australian Nuclear Science and Technology Organisation, Lucas heights, Sydney, 16–20 March. http://www.2412.org/orders/463/10.1016_S0969-8043(01)00042-2-Assessment-of-radiation-exposures-from-naturally-occurringradioactive-materials-in-the-oil-and-gas-industry.pdf.

Infante, P.F., Rinsky, R.A., Wagoner, J.K., Young, R.J., 1977. Leukemia in benzene workers. Lancet 310, 76–78.

Jamall, I.S., Willhiteb, C.C., 2008. Is benzene exposure from gasoline carcinogenic? J. Environ. Monit. 10, 176–187.

Jonkers G, Hartog FA, Knaepen WAJ, Lancee PFJ (1997) Characterization of NORM in the oil and gas production (E&P) industry. In: Proceedings of the International Symposium on Radiological Problems With Natural Radioactivity in the Nonnuclear Industry. Amsterdam, 8–10 Sept. 1997, 23–47.

Kvasnicka J (1996) Radiation protection in the offshore petroleum industry. In: Proceedings of the International Congress on Radiation Protection, IRPA 9.

Othman I, Al-Masri MS, Suman H (2005) Public and regulatory acceptability of NORM contaminated soil disposal: the Syrian experience. E&P NORM Workshop, Sultanate of Oman, Muscat.

Rathnayakaa, S., Khan, F., Amayotte, P., 2013. Accident modelling and risk assessment framework for safety critical decision-making: application to deep-water drilling operation. J. Risk Reliab. 227, 1–20.

Rathnayakaa, S., Khana, F., Amyotte, P., 2011. SHIPP methodology: predictive accident modeling approach. Part I: methodology and model description. Process. Saf. Environ. Prot. 89, 151–164.

Raus, M., Høyland, A., 2004. System Reliability Theory Models, Statistical Methods, and Applications. Wiley Series in Probability and Statistics, Wiley.

Smith KP (1992) An overview of naturally occurring radioactive materials (NORM) in the petroleum industry. Report No. ANL/EAIS-7. Argonne National Laboratory, Argonne, IL.

Steinhäusler, F., 2005. Radiological impact on man and the environment from the oil and gas industry: risk assessment for the critical group. In: Radiation Safety Problems in the Caspian Region. Springer, pp. 129–134.

Tesfatsion L (2015) Introductory notes on rational expectations. http://www2.econ.iastate.edu/tesfatsi/reintro.pdf.

Testa, C., Desideri, D., Meli, M.A., Roselli, C., Bassignani, A., Colombo, G., Fresca Fantoni, R., 1994. Radiation protection and radioactive scales in oil and gas production. Health Phys. 67, 34–38.

Vigliani, E.C., Saita, G., 1964. Benzene and leukemia. N. Engl. J. Med. 271, 872–876.

Wilson, A.J., Scott, L.M., 1992. Characterization of radioactive scale petroleum piping scale with an evaluation of subsequentl and contamination. Health Phys. Soc. 63 (6), 681–685.

World Health Organization (WHO) (2010) Preventing disease through healthy environments exposure to benzene: a major public health concern. http://www.who.int/ipcs/features/benzene.pdf.
Yin, S.N., Li, G.L., Tain, F.D., Fu, Z.I., Jin, C., Chen, Y.J., Luo, S.J., Ye, P.Z., Zhang, J.Z., Wang, G.C., 1978. Leukaemia in benzene workers: a retrospective cohort study. Br. J. Ind. Med. 44 (2), 124–128.

CHAPTER FIVE

Management of nuclear radioactive materials produced with oil and gas extraction and production

Chapter Outline

5.1 Introduction

In all, 30 years' worth of research conducted in thousands of oilfields around the world all proves the presence of nuclear radioactive materials with different levels of radioactivity concentration in the geological formations contains oil and gas that are coproduced with oil and gas extraction and production processes. These nuclear radioactive materials are brought to the surface along with formation water coproduced during oil and gas extraction and production process via drilled wells through downhole completion and production equipment. Despite this fact, however, not all oil, gas,

Nuclear Radioactive Materials in the Oil and Gas Industry
https://doi.org/10.1016/B978-0-12-816825-7.00005-4

and nuclear radioactive materials in sandstone or shale reservoir can be extracted from it. Usually, the sandstone or black shale contains grains in spaces that are filled with water, uranium, thorium, oil, and gas. Oil sticks to these grains that also contain different levels of uranium and thorium nuclear materials. This cohesiveness and porosity limit how much oil, gas, uranium, and thorium can be produced from the reservoir simply by conventional pumping. While uranium and thorium production along with oil and gas extraction also depend on as oxidation–reduction potential (ORP), pH, alkalinity, and the type of complexing agents present, such as carbonates, phosphates, vanadates, fluorides, sulfates, silicates, silicates, and many other factors in the geological formation that contains hydrocarbons (Kumar et al., 2012). This may explain why radiation concentrations vary from well to another or from an oilfield to another. Grains consistency also plays a significant role in the amount of natural gas that will bubble out of the reservoir. Based on the well formation pressure life, the production rate of a well declines with time, resulting in an unrecovered of a significant amount of oil, gas, uranium, and thorium in the reservoir.

The amount that is recovered during the first phase that is known as the primary recovery utilizes natural reservoir pressure where oil, gas, uranium, and thorium production during this phase is generally does not exceed about 5%–15% of the total volume of hydrocarbons and nuclear radioactive materials contained in the reservoir. After a period of time, the well naturally depletes. However, about 20%–45% of the oil, gas, uranium, and thorium can be extracted from the reservoir by applying additional secondary recovery methods. Secondary recovery methods or water flooding involves methods that partially repressurize and temporarily raise declining production rates. This is done by either reinjecting produced formation water into the reservoir or by injecting produced natural gas into the sandstone reservoir. Eventually, the production rate will once again begin to decline, and at this point, the tertiary recovery methods are applied, which is also known as enhanced oil recovery technology. The goal of this stage of production is to scrub the remaining oil, but it also scrubs uranium and thorium off sediment grains and then sweeps the freed oil, uranium, and thorium to a production well where about 10%–40% of freed oil, gas, uranium, and thorium can be extracted during this stage. This scrubbing and sweeping are accomplished by injecting a steam or gas or chemicals or polymers directly into the reservoir. Fig. 5.1 depicts a typical well production rate versus time.

One of the common methods used in the oil and gas industry is CO_2 injection that acts as a soap on the oil, reducing its viscosity and chemically

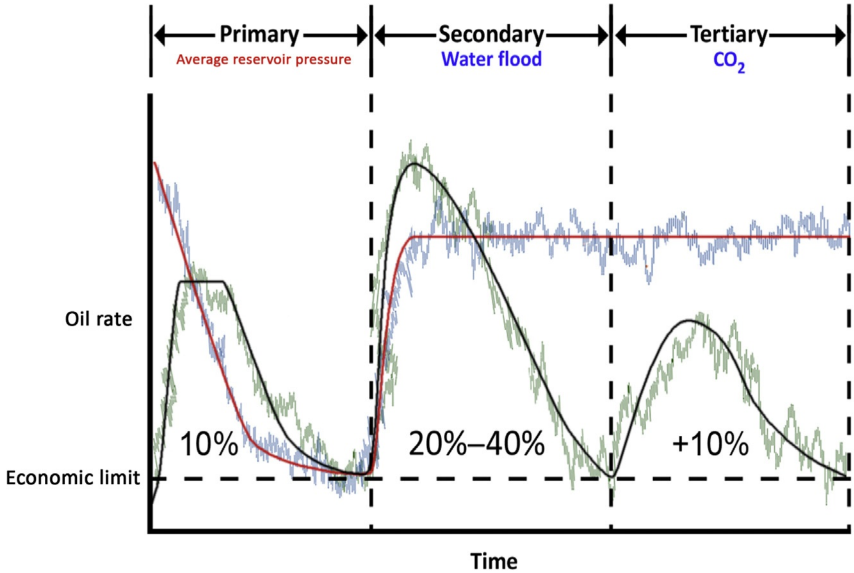


Fig. 5.1 The production rate of a typical oil and gas well versus time.

dislodges it from the sediment grain and flow more easily into the pore water that eventually being pushed to the production well with a subsequent injection of water and subsequently increases oil production by 10%–30%. Furthermore, gas injection into the hydrocarbon reservoir that also contains uranium and thorium in the presence of saline formation water play a significant role in creating ORP status in the reservoir, which contributes in making more uranium particles to dissolve in formation water and hydrocarbons as a result of its known high oxidation status as well as carrying other insoluble thorium particles that are known for their low oxidation status.

It is worth mentioning that, in some cases, the oil may reach a degree of viscosity that ranges from extra heavy oil to light crude oil. In countries like Canada, Russia, and Venezuela are known by their extra-heavy oil production. While many countries in the Middle East are known by their heavy to light oil production. Sultanate of Oman for example, is currently considered as a hot spot for deployment of advance new technologies in a range of enhanced oil recovery techniques to produce different types of heavy oil. Mukhaizna oilfield is a good example of heavy oilfield that is located in the south central of Oman. The sandstone reservoir in Mukhaizna oilfield is known of its high permeability but containing oil of very high viscosity on average of 90 cP crude oil. This makes it difficult to extract this Haigh viscus crude oil using conventional methods such as pumping or water flooding projects or even polymer flood pilot project, which are considered uneconomic, at this stage. The alternative was the use of heat or steam flood approach to soften oil and reduce its viscosity. The basic premise of this technique used to enable the process of drawing, is that the gas extracted from the well in the generation of electricity is exploited in pushing hot steam to the bottom of the well, this steam helps to rise the temperature of oil, and then reduce its viscosity and making it easy to flow. In the case of Mukhaizna field, a steam flood approach with vertical steam injection around horizontal producers was used and at the end of 2009, the total daily production rate had grown to >10 times, which is about 100,000 barrels per day compared to the year 2005 (Schlumberger, 2011).

In addition to the known enhanced oil recovery technologies, there are also many other new techniques such as biotechnologies by which certain bacteria are injected into the well to help analyze hydrocarbon compounds into lighter products, and thus can be withdrawn to the surface.

In current oil and gas extraction and production process, the mixture of oil, gas, formation water, nuclear radioactive materials such as uranium and thorium particles, and possibly other materials of large amounts of sulfur and nitrogen compounds, that are also, might be economically recovered are all lifted to the surface through downhole completion equipment. Fig. 5.2 illustrates a detailed schematic diagram of the typical oil and gas extraction and production process flow.

This mixture is then passing to midstream equipment via a separator, which removes the gas. The gas, after further processing, is relayed to a gas purification plant downstream. Here, various gas fractions are separated and purified. Meanwhile, the oil stream is further pumped to midstream production from upstream facilities via flow lines. Gathering and production stations in the midstream then remove the geological formation water that is extracted with the oil and gas and contain nuclear radioactive materials such as soluble uranium and thorium, and large amounts of sulfur and nitrogen compounds. Produced water with nuclear materials and other minerals materials often are generated during the production of oil and gas from both onshore and offshore wells. Scholars such as Rood et al. (1998) and Gazineu et al. (2005) argued that the amount of nuclear radioactive materials produced and incorporated in oil and gas extraction and production are directly proportional to the volume of produced water generated during the pumping of the oil. According to the American Petroleum Institute (API, 1989), the ratio of produced water to oil is approximately 10:1. However,

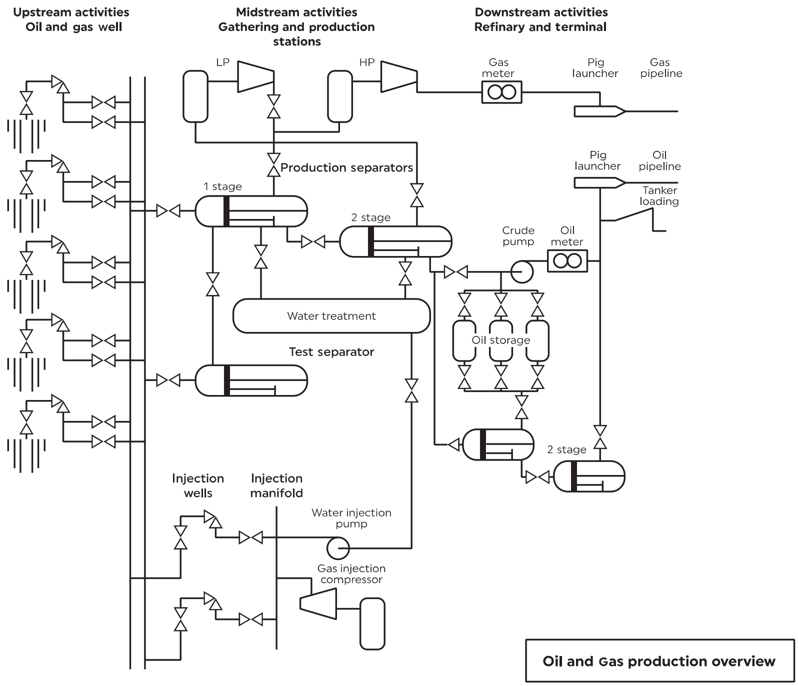


Fig. 5.2 Process flow chart of oil and gas extraction and production.

Neff et al. (2011) reported that the ratio of produced water to oil equivalents or to gas equivalents (WOR, WGR) varies widely from well to another and essentially that can go to >50. Typically, when the field is nearly depleted, it produces about 98% of produced water and only 2% for fossil fuels (Neff et al., 2011). Usually, the water-gas ratio is higher than the water–oil ratio. Moreover, Neff et al. (2011) defined produced water as "a complex mixture of dissolved and particulate organic and inorganic chemicals." Produced water's physical and chemical properties usually vary from oilfield to another depending on many characteristics such as the geologic age, the depth, and geochemistry of the hydrocarbon-bearing formation, and many other chemical compositions in the reservoir. Therefore, no two produced waters are alike.

After the formation water is separated in the gathering and production station, the formation water or some called it produced water is either discharged to the ocean or sea in case of offshore activities and in evaporation ponds in case of onshore activities, which eventually creates a serious environmental risk, or used for reinjection purposes as part of enhanced oil recovery technology, which enhance recovery in the depleted formations. Unfortunately, the oil and gas industry are not aware that disposal of formation water that contains nuclear materials including uranium, thorium, and many other valuable minerals undermines the opportunity to process this valuable source and exploiting them as additional potential energy source. Finally, contaminated oily sludges, scales, and contaminated sand, obtained from the reservoir during oil and gas separation in the gathering and production station are also removed and disposed of on farmlands or sometimes disposed of directly into the sea.

In confirmation to the production of uranium and thorium along with oil and gas extraction and production process, different types of nuclear radioactive materials with different activity concentrations were found in the waste generated from gathering and production stations as well as different measurements that were taken during the flow process of oil and gas from drilled wells, flow lines to the separators in the gathering and production stations all confirm the presence of nuclear radioactive materials along with oil and gas (ALNabhani et al., 2016b,c). In this context, annually, the global petroleum industry generates millions of tons of nuclear radioactive in the form of soluble and suspended particles with produced water, scales, sludge, which are disposed of either above ground or underground (Strand, 1999; ALNabhani et al., 2016c). Based on the current practice in the oil and gas industry, there is a growing concern as to how these massive volumes of daily produced nuclear radioactive materials can be safely managed or converting them from a serious risk to be exploited as a useful alternative source of energy.

5.2 An overview of geochemistry of nuclear materials in the hydrocarbon's geological formations: Evidence #1

According to several geological studies conducted in different parts of the world, all confirm the existence of varying percentages of reserve stocks uranium and thorium in the ground is in different geological layers and are concentrated more in the layers of shale and sandstone. In this context, intensive research and studies were conducted during the 1944–54 period of intensive search for sources of uranium in the United States utilizing new technologies other than conventional mining process. Important geological studies conducted for the Division of Raw Materials by the US Atomic Energy Commission revealed that black shale is a major source of uranium and oil and they may be referred to as uraniferous oil shales. Some black rocks contain up to a hundred times more uranium than other sedimentary rocks, and they also contain organic substances that are responsible for oil and uranium production. Furthermore, Swanson (1960) argues that a sample collected in that study revealed that in central Tennessee, the upper member of the Chattanooga shale, which is about 15 ft thick, contains 0.006% uranium, and will yield about 10 gal of oil per ton of shale. A sample of a layer <1 in. thick from Chattanooga shale that was taken and found, made up largely of compacted opaque coaly attritus, contained 0.7% uranium. Moreover, there are some of the marine black shales in the cyclothems of Pennsylvanian age in Illinois, Kansas, and Oklahoma contains between 0.004% and 0.010% uranium and yield 8–15 gal of oil per ton of shale. In Sweden, it has been reported that both oil and uranium have been recovered in large quantities from the Upper Cambrian black shales, which yield about 14 gal of oil per ton of shale and contains about 0.023% uranium (Swanson, 1960). Likewise, in southern Sweden, the black organic-rich kolm lenses which are sparingly distributed through parts of the Cambrian and Ordovician alum shales contain about 0.4% uranium.

According to the Geological Survey (US) (1960), the shale is considered uraniferous (containing or producing uranium) only if it contains 0.002% or more uranium through most of its vertical and lateral extent. Thus, this could lead us to a significant preliminary conclusion that a fair positive relation between oil yield and uranium content exists in some shales due to the fact of proportional or homogeneous distribution of the presence of sapropelic and humic organic matters that are responsible for oil and uranium, respectively, and therefore, shale can be considered as a good potential source for both oil and uranium.

Exploration by the Polish Geological Institute found uranium mineralization in the Ordovician dictonema shales in the Podlasie depression and the lower and middle Triassic sediments (sandstones) of the Peribaltic Syneclise. These geological materials are categorized as uranium bearing (Bareja, 1984). The uranium content in various samples taken from the same deposit differs from one another, and dictyonema shales contain the highest uranium content compared with other minerals found, whereas the calculated mean value for uranium content is three times higher than that in dictyonema shales. Similarly, Jonkers et al. (1997) reported findings from the Netherlands geology that indicated various concentrations of both uranium and thorium in sedimentary rock and geological formations that contain oil and gas such as sandstone, conglomerate, black shale, limestone, and carbonate.

On the other hand, and according to the uranium mining studies based on in-situ recovery (ISR) approach, uranium produced by ISR accounts for 46% of the uranium produced worldwide (Hore-Lacy, 2016). The in-situ uranium recovery approach is extracting of uranium from geological formations using exactly same process used to extract oil and gas through drilling a producer well to the pay zone and nearby by producer well many injection wells are drilled in order to inject lixiviant solution into to the geological formations that contain uranium and push uranium toward the producing well. Major historic and current uranium production operations using in-situ uranium recovery approach are found in Australia, Asia, Eastern Europe, and the United States. For example, in 1990, 70% of the uranium produced in Bulgaria of ore deposits with very low grades of 0.02%–0.07% of uranium has reached approximately 345 tU/year (Hore-Lacy, 2016).

Swanson (1960) argued in the study made for the Division of Raw Materials of the US Atomic Energy Commission that the amount of uranium in these shales under the study is extremely large, reckoned in billions of tons of metallic uranium. Moreover, Mao et al. (2014) argue that the majority of hydrocarbon source rocks are rich of uranium. Not only that, the United States Geological Survey recommended that the uranium contents are much high in the Standard Devonian oil shale, Mecca shale, and Alum shale and are as high as 48.8, 130, and 206 ppm, respectively (Huyck, 1990; Leventhal, 1993; Mao et al., 2014). While, the uranium content in the Pennsylvanian (Upper Carboniferous) black shale of Oklahoma and Iowa are as high as 101 and 212 ppm, respectively (Anna and Timothy, 2004; Mao et al., 2014). Similarly, it has been found that the uranium content in the Western Canadian Sedimentary Basin of Upper Besa River and Muskwa are as high as 194 and 161 ppm, respectively (Mao et al., 2014). On the other hand, it has been found that the uranium contents in the argillaceous hydrocarbon source rocks ($T_3y^{1,3}$) of the Ordos Basin in China to be very rich and are generally reaching 41.6–83.2 ppm (Zhang et al., 2008; Mao, 2009).

Mao et al. (2014) concluded that organic–inorganic interaction exists universally and is important in the process of mineral resources formation. It is the essential reason why organic oil, gas, coal, and uranium coexist, accumulate, and mineralize in the same sedimentary basins. Hydrocarbon-generating simulation experiments carried out by Mao et al. (2014) provided a vital scientific proof that there is a strong positive relationship between hydrocarbons and uranium present in the same sedimentary basins. It also proved that uranium influences the hydrocarbon generation of hydrocarbon source rocks. Experiment results also show that uranium can enhance the yield of gas and hydrocarbon, promote the total gas output, and increase the total hydrocarbon production (mass or volume).

From the geochemistry science perspective, both uranium and thorium are classified as strongly lithophilic materials, and both occur in the 4^+ oxidation states. However, uranium can also be oxidized to the oxidation state 6^+ as UO_2^{2+}. This is well within the redox potential range in geological environments (Krauskopt, 1969). Uranium enrichment precipitation occurs more in reducing environments, often of an acidic nature and typically in organic-rich sediments like darker marine shale, sandstone, and carbonate that contains more hydrocarbons, where more radioactivity concentration levels were measured and found with a high content of organic matters (Russell, 1945).

This explains the presence of uranium and thorium materials in the formation of rocks that contains hydrocarbons and why uranium/thorium radioactivity ratio is used as an indication of hydrocarbons presence and quantity identification. Some uranium is found in silt and clay-sized minerals. In essentially all geologic environments, oxidation states 4^+ and 6^+ are the most important oxidation states of uranium, whereas U^{6+} ion is even more soluble than the U^{4+} ion, which also explains why nuclear radioactive materials are found more soluble with hydrocarbons and formation water coproduced during hydrocarbons production. At the same time, U^{4+} generally precipitates as stable and very insoluble uranous oxides and hydroxides, in the form of uraninite (UO_2(c)), pitchblende (UO_2(am)), schoepite ($UO_2(OH)_2H_2O_2$-(c)), and coffinite ($USiO_4$(c)) (Langmuir, 1978). By oxidation, U^{4+} passes easily to valence U^{6+} as UO_4^{2-} or $U_2O_7^{2-}$. U^{6+} is typically present as the soluble uranyl ion (UO_2^{2+}), which can also form stable complexes with a variety of anions, such as phosphates, carbonates, and sulfates.

Furthermore, U^{6+} may form complexes with organics. Depending on their stability, these complexes may affect the Eh value required for the precipitation of UO_2 to occur (Lisitsin, 1971). Therefore, the conversion between uranyl and uraneous ions is highly dependent upon Eh and pH conditions (hydrogen ions (pH), and the activity of electrons (Eh)). Therefore, UO_2 (uraninite) and $USiO_4$ (coffinite) forms have been reported in the sandstone and (UO_2) (CO_3) in the limestone (Jonkers et al., 1997).

Owing to its solubility, UO_2^{2+} is chiefly transported in solutions. However, under reducing conditions UO_2^{2+} forms numerous complexes with organic compounds (e.g., humic acids), which facilitates uranium fixation by organic sediments (peat, lignite, and coal) and mineral matter. Localization of uranium in organic shale is another typical example of this fixation. These organic substances are particularly important in the absorption of uranium from water. Thermal diagnosis of organic matter that is responsible to produce hydrocarbons found to contribute in enhancing uranium concentration, as uranium remains with the residual organic matter (Erickson et al., 1954).

On the other hand, thorium can exist only as Th^{4+} in the natural environment owing to its insolubility and is almost wholly transported in suspension. Thus, it concentrates in the silty fraction of shale as thorium minerals or thorium-bearing assessor minerals such as monazite, the major thorium-bearing mineral. Thorium is also found mostly in heavy minerals of silt and clay fraction and in intrusive rocks such as granite, garnierite, and syenite. Jonkers et al. (1997) reported in their study that ThO_2 (thorianite) and $ThSiO_2$ (thorrite) are common thorium forms found in the sandstone.

Generally, the mobilization of uranium, thorium, and the radionuclide isotopes leaching from minerals or rocks is governed by various factors including the physical mineral/rock condition, disequilibrium fractionation, polymerization, chemical reactions, the nature of their occurrence in mineral/rock, and the chemical composition of the leaching water (Zukin et al., 1987).

In conclusion, significant scientific research, laboratory studies, and field studies have concluded that the main sources of uranium or thorium materials are found mainly in sedimentary formations of common shales, black shale, sandstones, orthoquartzites, siltstones, claystone, carbonates, bentonites, carbonate rocks, halite, anhydrite, and phosphate rock. Therefore, the oil extracted from shales, and sandstones having a relatively high uranium content logically is considered as a potential significant byproduct if the uranium is extracted from the extracted oil or from other geological formations covered by drilled wells at various depths.

5.3 Production of nuclear radioactive materials with extraction and production of oil and gas: Evidence #2

From the geochemical point of view, it can be concluded that there is a strong relationship between uranium, thorium, and organic carbons content where hydrocarbon potential can be identified easily, the same conclusion has been reached by many authors, such as Beers and Goodman (1944), Russell (1945), Swanson (1960), Supernaw et al. (1978), Zimmerle (1995), and Mao et al. (2014). It is also concluded that uranium is commonly found in clays of reducing environments, particularly in the presence of carbonaceous material where organic-rich dark shales or sandstone that are highly radioactive and show high gamma-ray log counting rates as well as spectral gamma log responses with high potassium, thorium, and uranium readings as you will see in the following section. Such readings give very accurate confirmation that shales and sandstone are ordinarily radioactive and a good source of both hydrocarbon, uranium, and thorium.

According to many works of literature, oil and gas extraction, and production activities are always associated with the production of nuclear radioactive materials and their progenies. Researchers such as ALFarsi (2008) have reported that the discovery of radioactivity associated with the extraction and production of oil and gas goes back >100 years. The US EPA confirmed also that the geologic formations that contain oil and gas deposits also contain uranium, thorium and their decay products, radium and their decay products, potassium-40, lead-210, and polonium-210. The International Association of Oil and Gas Production (IAOGP, 2008), reported in its guideline for the management for naturally occurring radioactive materials in the oil and gas industry that radioactive materials such as uranium and thorium are incorporated in the Earth's crust and can be found at various concentrations in the rock formations, which are common in sandstone and shale (IAOGP, 2008). These nuclear materials are mobile and can be transported from the reservoir to the surface with the produced oil and gas products being recovered and associated produced water. During oil and gas extraction and production process, these nuclear radioactive materials flow with the oil, gas, and water mixture and sometimes because of the pressure and temperature change as they reach the surface; some of these nuclear materials start to accumulate in the form of scale, sludge, or thin films. The IAOGP depicts in Fig. 5.3 the origins of these radioactive materials and also indicating where they may accumulate during oil and gas recovery process.

According to many field studies, the reported radioactivity concentration of nuclear radioactive materials that are coproduced with oil and gas production may vary from low to extremely high levels. Moreover, the US APE, reported that uranium and thorium and their radioactive decay products have different solubility level with formation water that is usually coproduced with oil and gas, where the dissolved or suspended nuclear radioactive materials may remain in solution or settle out to form sludges or scales or thin films. For example, according to the US EPA (1993) and Smith et al. (1996), it has been estimated that between 25,000 and

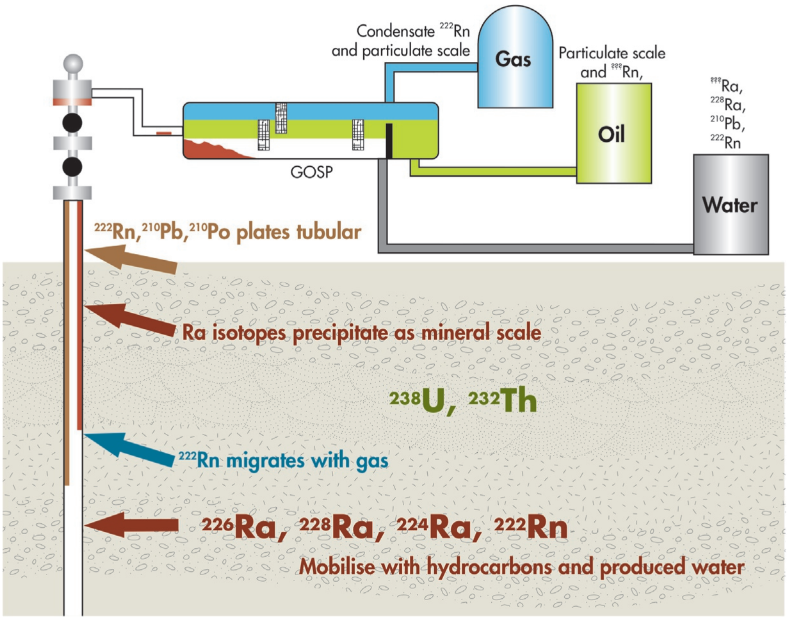


Fig. 5.3 The origins and accumulations of naturally occurring nuclear radioactive materials—NORM in the oil and gas industry. *(Reproduced with permission from International Association of Oil and Gas Producers, 2018. Report 412—guidelines for the management of Naturally Occurring Radioactive Material (NORM) in the oil & gas industry, vol. 1.)*

225,000 tons of nuclear radioactive materials in the form of scale and sludge wastes are generated annually from the US petroleum industry, where their average radioactivity concentration found to reach 15,170 Bq/g in scale and 25,900 Bq/g in sludge or sometimes to higher levels. It has been also estimated that an average of 100 tons of scales are annually generated from the individual well and taking into account that in some cases one oilfield may contain >1000 wells. Therefore, if this has been considered on the global scale, that's mean the oil and gas industry produces annually massive and frightening volumes of nuclear radioactive wastes where their radioactivity concentration are a source of concern and threat to the people and the environment as these wastes are not reused through science-based recycling approaches and instead are disposed of directly into the environment.

On the other hand, in the 1990s, offshore fields in Europe recorded an annual release of some nuclear radioactive materials progenies such as radium-226 and radium-228 with produced water at around 5 TBq (1 TBq = 1012 Bq) per year and 2.5 TBq per year, respectively (Bou-Rabee et al., 2009; ALNabhani et al., 2016a). Water Environment

Federation (2018) and many other studies reported that produced water that comes out of the well with the crude oil during oil and gas extraction and production processes found containing soluble and non-soluble nuclear radioactive materials, organics, suspended solids, dissolved solids, and various minerals and chemicals. In this contexts, El Afifi and Awwad (2005) have concluded also in their study related to nuclear radioactive materials in the oil and gas industry that nuclear radioactive materials waste generated from the oil and gas industry contain mainly uranium-238, uranium-235, and thorium-232 series, their radionuclides, and many other minerals and chemical elements such as Si, Fe, Al, Na, Mg, Ca, Sr, Ba as well as trace amounts of heavy metals Mn, Fe, Zn, Cu, and Pb. The portable amounts of soluble and non-soluble nuclear radioactive materials, organics, suspended solids, dissolved solids, and various other minerals and chemicals in the produced water are directly proportional to the volume of produced water generated during the pumping of the oil (Rood et al., 1998; Gazineu et al., 2005). It is likely that the actual ratio of water to oil can be >10–20:1 (Water Environment Federation, 2018). In this context, API (1989) and ALFarsi (2008) reported that about 18–25 billion barrels of waste fluids were being generated annually from the United States petroleum industry, versus the total crude oil volume of 2.5 billion barrels (400 million m^3). In 2007, about 22,000 m^3/day of this produced water was reinjected for enhanced oil recovery techniques and about 234,000 m^3/day was discharged to the ocean (Clark and Veil, 2009). These figures have increased rapidly as a result of the increase in oil production to meet the growing global demands, thereby increasing the volume of generated nuclear radioactive wastes and subsequently raising the concern of how they are safely managed or disposed of.

Scholars such as Testa et al. (1994), El Afifi and Awwad (2005), Al-Masri and Aba (2005), and Othman et al. (2005) confirmed that nuclear radioactive materials and their progenies were found in different types in many equipment associated with the various stages of oil and gas extraction and production processes including but not limited to downhole equipment and materials such as electrical submersible pumps, drilling bits, drilling tubular and casings, drilling mud systems, waste bits, wellheads, injection station equipment, gathering, and production stations' equipment such as flow lines, separators, pumps, and refining equipment and associated storage tanks. Not only that, nuclear radioactive materials and their progenies have also been found in the final products. In confirmation of this, Al-Masri and Haddad (2012) concluded from their study on TENORM emissions from oil and gas-fired power plants that nuclear radioactive materials were present in fly and bottom ashes collected from major Syrian power plants fired by heavy oil and natural gas.

Based on the available data and aforementioned facts, it can be concluded that nuclear radioactive materials including uranium and thorium are available at various radioactivity concentrations in the geological formations that contain oil and gas and are produced with oil and gas. This conduces us again to a significant conclusion that uranium, thorium, and many other valuable minerals can be extracted and produced along with oil and gas extraction and production process.

5.4 Well-logging data are a good source of information to extrapolating the quantities and depths of nuclear materials and hydrocarbons: Evidence #3

Glover (2000) argues that there is a strong correlation between the presence of uranium and hydrocarbons since organic matter is good at concentrating uranium and in a reducing environment it can be transformed to hydrocarbons. This argument has been scientifically and experimentally proved by Mao et al. (2014) who has conducted hydrocarbon-generating simulation experiment using low-mature hydrocarbon source rock containing kerogen with uranium (UO_2CO_3 solution) and studied the effect of uranium on the hydrocarbon generation of hydrocarbon source rocks. Experiment results show that uranium able to enhance the yield of gas hydrocarbon and increase the total hydrocarbon production (mass or volume). This leads us to the vital question of how to determine the quantities of uranium, thorium, and hydrocarbons to make sure that the issue of extraction economically feasible compared to the availability of quantities percentages of uranium, thorium, and hydrocarbons in the same geological formation containing hydrocarbons, which have already been addressed in Section 5.2.

It has been proved scientifically and practically that it is possible to evaluate the total organic carbon (TOC) content of rocks from the uranium content that can be measured from the spectral gamma ray log. The hydrocarbon potential then is computed by calculating the TOC content from spectral gamma logs, the curve changes between resistivity, porosity logs, and other geochemical logs. Accordingly, uranium and thorium quantity in the reservoir can be easily obtained from spectral gamma-ray logs (SGRL).

In fact, SGRL are one of the important tools used in the oil and gas industry beside other geochemical logs that geologically analyze and determine the content of uranium, thorium, and potassium in the studied deposits, evaluate the types of clay minerals, identify fissure zones, determine the organic matter content, determine the radiogenic heat value secreted during the decay of radioactive elements, and characterize of sedimentary conditions (Glover, 2000). The SGRL measure the natural radioactivity emitted by the natural rocks that contain the commonly known natural isotopes in the geological formations containing hydrocarbons, which are: potassium—^{40}K, uranium—^{238}U, ^{234}U, ^{235}U, and thorium—^{232}Th and their progenies. These isotopes initially are contained mainly in acidic igneous rocks that are then are transported due to volcanic actions and geological processes to sandstone or shale sediments where oil and gas formed. Natural radioactivity is an important lithological indicator easily obtained by geophysical measurements. The main feature of the SGRL is the ability to distinguish gamma emissions from potassium, uranium, and thorium that can be taken at different geological formations intervals. Typically, with the increase of the TOC content of the sediment, that means the concentrations and quantities of uranium and thorium are high. Thus, SGRL can easily measure the concentration and quantities of thorium, uranium, potassium, hydrocarbons, as well as many other important minerals in the rock formations.

Based on the long experience in the adoption in the spectral gamma logs in the oil and gas industry, it has been concluded that high thorium readings usually indicate the presence of heavy minerals in channel deposits. While the increases in uranium readings indicate the presence of organic matter. For example, according to the Ocean Drilling Program's Guide to Logging, particularly high U concentrations (>5 ppm) and low Th/U ratios (<2) often occur in black shale deposits that contain more hydrocarbons and more uranium.

SGRL for borehole Ż-8 are a good example to bring the attention to the possibility of uranium extraction along with oil and gas production. In this context, Klaja and Dudek (2016) have extrapolated from SGRL that was used to evaluate the organic matter content in borehole Ż-8 and argued that the organic matter content was determined quantitatively and qualitatively using gamma spectral log by measuring the thorium/uranium as shown in Fig. 5.4 and CARBOLOG method, respectively. The interpretation of the gamma spectral log for well Ż-8 displayed in Fig. 5.4 shows a decrease in the Th/U ratio values that are caused by an increase of the uranium content combined with organic matter (hydrocarbons).

From the foregoing, it can be inferred that it is possible scientifically and economically feasible the extraction and production of uranium, thorium,

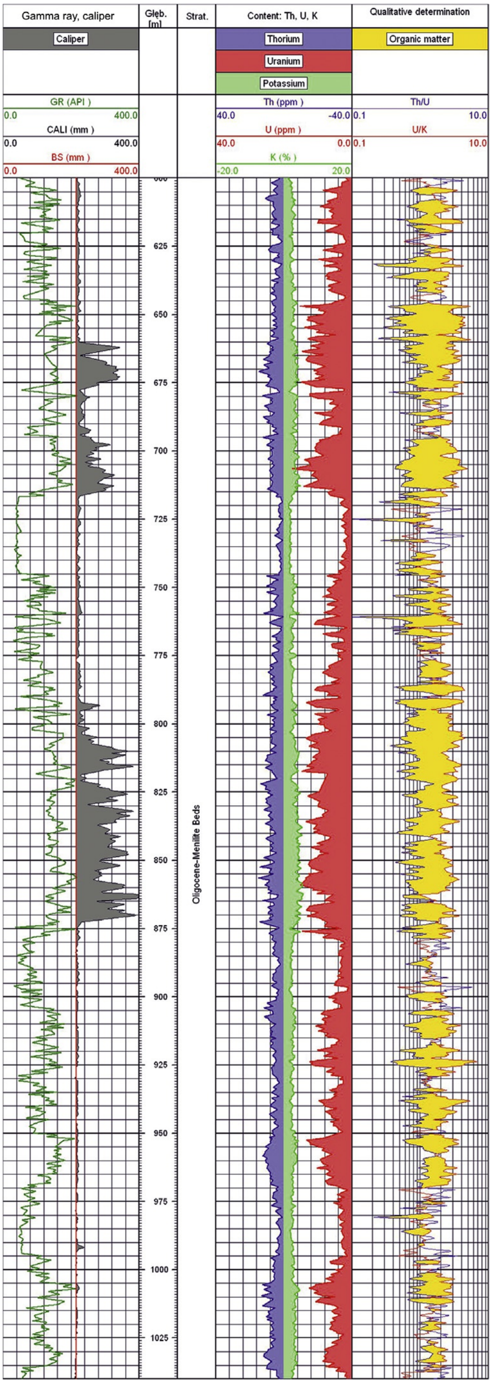


Fig. 5.4 Spectral gamma log for borehole Ż-8. *(Reproduced with permission from Klaja, J., Dudek, L., 2016. Geological interpretation of spectral gamma ray (SGR) logging in selected boreholes. Oil and Gas Institute–National Research Institute. NAFTA-GAZ, ROK LXXII, Nr 1, 3–14.)*

and many other precious metals during oil and gas extraction and production processes. The extraction and production of uranium, thorium, and many other precious metals during oil and gas extraction and production processes using "The integrated in-situ oil and uranium recovery technology" has the following advantages:

1. Besides oil and gas production from the oilfields, a new source of nuclear energy raw materials including uranium and thorium can be produced to be a vital tributary that can be used on the peaceful applications of the atomic energy.
2. Huge cost saving since exploration, extraction, and production process and other ancillary enhanced oil recovery technique are already exist and same will be used for extracting uranium, thorium, oil and gas, and other valuable minerals. The only thing is required to be added in the existing facilities is uranium separation facility to be attached to the existing oil and gas gathering and production stations in the oilfield.
3. Less environmental footprints and pollutions.
4. Processing and converting of huge volumes of radioactive waste that are daily generated from oil and gas industry into energy will permanently help to get rid of current nuclear radioactive waste disposal methods used by the oil and gas industry that pose a serious threat to the public health, environment, and future generations.
5. Minimize radiological risk.

Nuclear materials such as uranium, thorium, and many other valuable minerals can be extracted during oil and gas extraction, and production processes using a new approach called the integrated in-situ oil and uranium recovery. This approach is explained in more details in the subsequent section.

5.5 The integrated in-situ oil and uranium recovery technology

Based on the available geological and geochemical studies, collected seismic data, oilfield well-logging correlation data, and collected coring and cutting samples from the different oilfields, all give us an excellent indication about the possible quantities of uranium and thorium in the reservoir that can be extracted as well they help in identifying exactly at what depths these formations are located in the drilled well and what are their intervals lengths.

During the drilling activity, the drilling cuttings are collected at the surface by the geologist for further geological analysis. The results obtained from the geological analysis help to further identify with some certainty the geological formation where the uranium, thorium, and many other nuclear fission materials were deposited or located. However, these results cannot tell us the exact depth, the quantities, and other important geological parameters related to targeted uranium, thorium, and many other nuclear fission materials. Thus, to confirm the depth and to quantify the quantity, a measurement while drilling techniques can be used as well as a direct uranium logging technique called prompt fission neutrons (PFN) (Givens and Stromswold, 1989). The PFN logging technique comprises of a pulsed source of neutrons flux. In the pulsed source of neutrons flux, a high–voltage 14 MeV pulses at 1000 cycles per second and emits about 108 neutrons per second that accelerate deuterium ions into a tritium as expressed by Eq. (5.1):

$$H_2 + H_3 \rightarrow n + 4He \tag{5.1}$$

PFN logging tool emits neutrons flux to the targeted geological formations, which collide with U-235 and lead to slow-neutron-induced fission of U-235 in the formation. Epithermal neutrons and thermal neutrons returning from the formation after the collision following fission of natural U-235 in the rock formations are counted separately in detectors in the logging tool called thermal/epithermal neutron detector. The thermal/ epithermal neutron detector gives the percentage ratio of U-235 where the ratio of epithermal to thermal neutrons is directly proportional to U-235.

According to Givens and Stromswold (1989), the time-gated ratio of epithermal to thermal neutron counts provides a measure of uranium content. Uranium content measurements obtained from PFN logs have shown good agreement with core measurements, thus this technique provides a major data source for delineation and exploitation of uranium mineralization. The PFN technique provides a precise direct measurement of in-situ uranium over even very narrow intervals The PFN technique is also useful and able to identify other fissionable material such as plutonium by detecting their thermal neutrons.

Once uranium, thorium, and other fissionable material zones in addition to the hydrocarbon pay zones are identified then cased hole section must be perforated and subsequently a multiple zone completion equipment to be installed as shown in Fig. 5.5 to extract both nuclear materials and hydrocarbons from more than one geological pay zone.

Once the drilled well is classified economically feasible and ready for the production. A recovery project starts, which includes drilling several

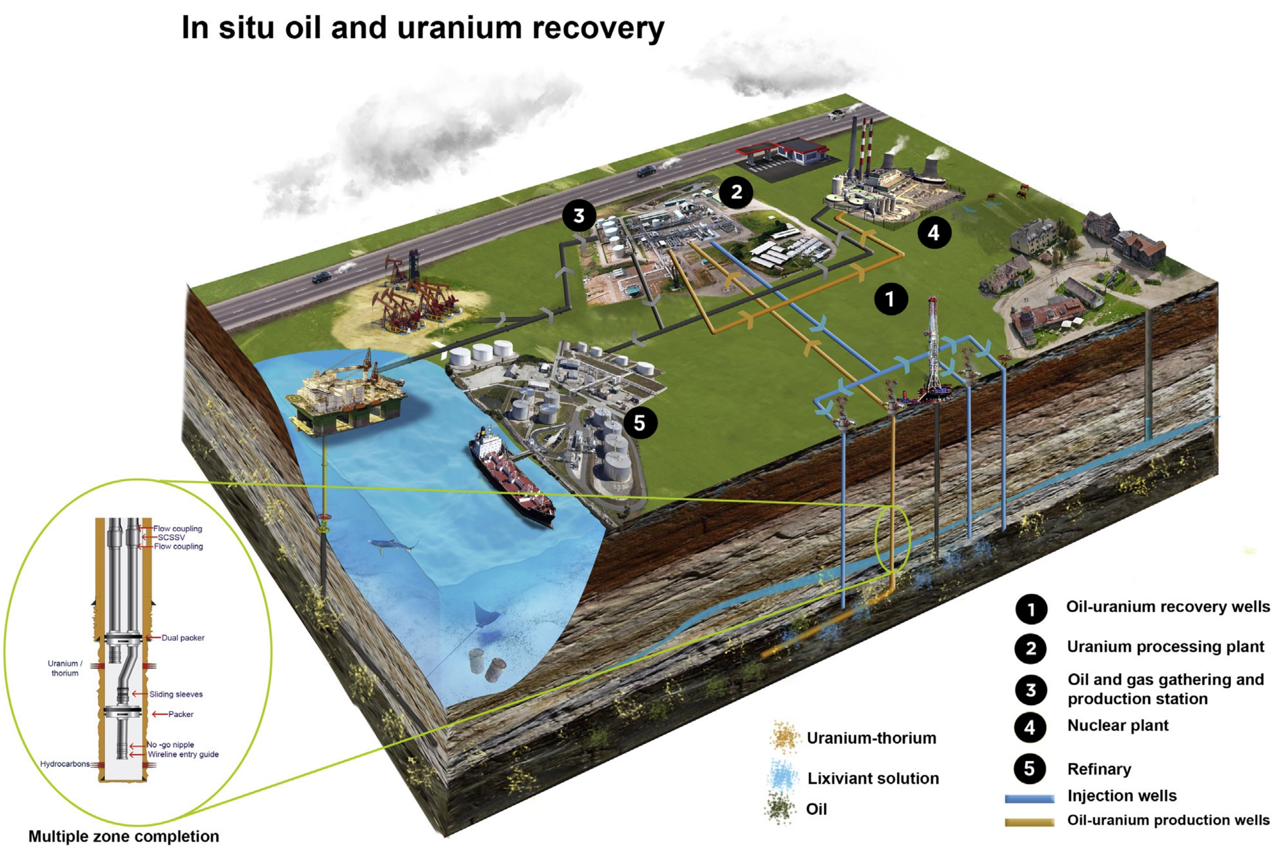


Fig. 5.5 An overview of the integrated in-situ oil and uranium recovery process.

injection wells that pump a lixiviant solution, which is exactly like the solution used for enhanced oil recovery process. The lixiviant solution is a groundwater solution mixed with oxygen or sodium bicarbonate (leachate) or CO_2, or sulfuric acid leach and possibly other chemical additives if needed that is pumped into sandstone or shale containing uranium, thorium, other nuclear radioactive materials, and hydrocarbons. The dissolved oxygen in the lixiviant solution oxidizes and dissolves uranium, and hydrocarbons, which are then lifted to the surface through the recovery drilled well. Since thorium is less soluble then its particles are lifted to the surface in the form of suspended particles in the produced formation water (lixiviant) or hydrocarbons. The solution that contains uranium, thorium, and other nuclear radioactive materials are collected through a specially designed multiple zone completion well equipment that is then pumped from the wellhead directly to the integrated in-situ oil and uranium recovery processing plant inside the oil and gas gathering station in the midstream. Fig. 5.5 demonstrates a diagram of the proposed oil and uranium recovery process flow.

The integrated in situ oil and uranium recovery plant comprises of four stages, which are the ion exchange unit, elution unit, precipitation unit, and filtering and drying unit. The ionic exchange unit contains millions of positive ion resins, which attract and bind the uranium negatively charges particles. These resins then will be transferred to the washing unit (elution unit). Where these resins will be washed by the brine solution that creates a reduced environment and therefore, increases the concentration of the uranium solution. Uranium solution will then enter the precipitation unit where an acid such as the hydrochloric acid is injected to the solution modify the PH. Hydrogen peroxide will be added at this stage to stimulate uranium to precipitate more and fall. The heavy uranium solution is then dewatered and dried. Finally, the uranium is collected in the form of powder. Collected powder is then packed in drums and transported to the nuclear facilities where it will be subjected to further refining and enrichment process to the required level so that it can be used as nuclear fuel for nuclear energy industry or any other industrial applications. On the other hand, thorium separation is much easier compared to uranium as it is mostly found suspended particle with the solution. Finally, once uranium, thorium, and other nuclear materials are separated, the remaining leachate from dewatering process is then passed into a chemically designed circuit to release the solid particles, chemically reconditioned, and subsequently, prepare it to be reinjected back into the in-situ oil and uranium recovery field. Fig. 5.6 depicts a diagram of the proposed oil and uranium recovery process flow.

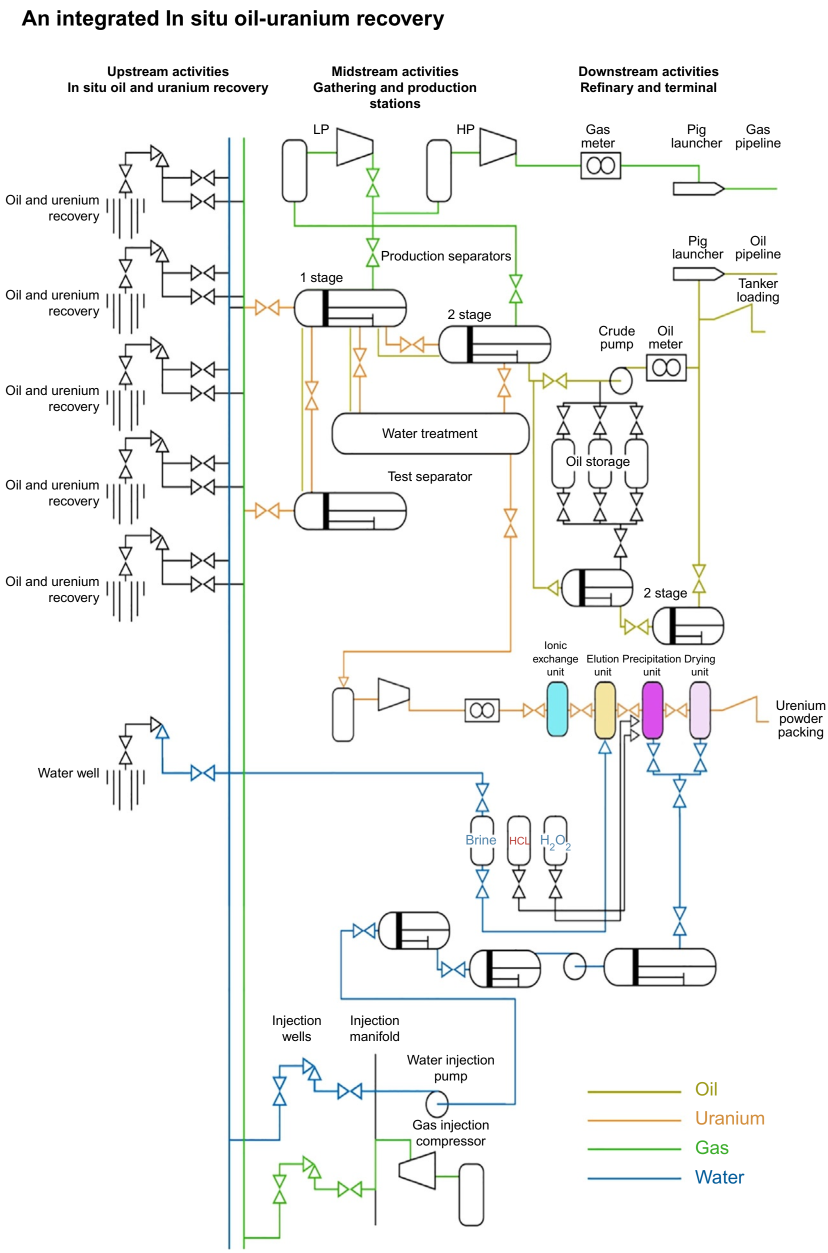


Fig. 5.6 The integrated in-situ oil-uranium recovery process flow chart.

On the other hand, a mixture of oil, gas, formation water, and other soluble and insoluble nuclear materials including uranium, thorium, and possibly other materials of large amounts of sulfur and nitrogen compounds, that are economically recovered from the geological formations that are containing hydrocarbons. This mixture is then pumped to the surface through the second part of the downhole multi-completion equipment. This mixture is then pumped to gathering and production station through the flow line. In the gathering and production station, oil and gas are separated and are sent severally to the downstream refinery for further purification or for exportation purposes. While, the separated formation water and lixiviant solution that is produced with produced crude that contains uranium, thorium is then pumped to uranium ISR processing plant built in the oil and gas gathering station to be processed as described above to recover uranium and thorium. The remaining leachate from the dewatering process is then passed into a chemically designed circuit to release the impurities and plankton that will be chemically reconditioned and, subsequently reinjected back into the in-situ oil-uranium recovery field as shown in Fig. 5.6.

The integrated in-situ nuclear and hydrocarbons recovery process provides an excellent solution for nuclear radioactive waste that is currently generated from the oil and gas industry and instead converts this wasted energy into a useful energy. The integrated in-situ nuclear and hydrocarbons recovery process eliminates the huge volume of daily produced nuclear radioactive waste that is currently disposed of directly into the environment and poses a serious threat to people, environment, water, and soil. However, and in case there is still a small amount of nuclear radioactive waste is generated from the oil and gas industry or until the integrated in-situ nuclear and hydrocarbons recovery approach started to be adopted, this chapter still provides another alternative where such radioactive waste can be safely managed through thermo-chemi-nuclear conversion technology (TCT) that will be discussed in more details in the following section.

5.6 Nuclear radioactive waste management based on TCT

On the other side, the adoption of in-situ oil-uranium recovery technology in the petroleum industry may take some time since more studies and researches are required. Since then it is crucial to have a scientific-based solution able to treat the huge amounts of daily produced nuclear radioactive wastes during oil and gas production processes. These wastes actually pose a looming threat to the environment, lives of the people, our grandchildren, and their descendants who will have to live with these nuclear radioactive wastes for centuries in the area where they are currently being disposed. It has been found that current disposal alternatives of nuclear radioactive wastes generated from the oil and gas industry are not necessarily based on the scientific evaluations or radiological risk assessments from engineering, biological perspectives, or even considering various fate and transport exposure pathways. Therefore, the handling of nuclear radioactive waste currently being produced from the oil and gas industry with newer technologies of disposal methods is slowly becoming more efficient. Oxidation–reduction reaction chemicals, solids/fluids separation, and gasification, for example, are good examples of such new technologies in standard waste treatment that have proven their efficiency to handle and treat standard types of waste (Sharkey and Burton, 2008), which at the same time, can generate energy and other synthesis fuels. Low to intermediate radioactive waste can be handled via gasification but can only minimize its volumetric size and cannot provide a complete treatment of radiation risk.

Accordingly, this study proposed a new technology as an extension of the working principle of gasification that will enable the safe management of nuclear radioactive waste, as well as other different types of solid, liquid, and gases, waste being produced from the oil and gas industry. This technology is called TCT. The TCT provides an excellent option for recycling different types of waste simultaneously. In contrast, the current practices used in the oil and gas industries, for example, injection methods into a geological formation, only decrease large transportation costs and temporary out-of-sight storage. These methods pretend to solve problems; however, they enhance the activity concentration of naturally occurring nuclear radioactive materials (NORM) that already exists in the underground formation and possibly contaminate soils and aquifers as a result of channeling, faults, formations' communication, and many other natural and tectonic factors or changes that occur in the geological formation with time. While surface storage, evaporation ponds, and landfarming disposal methods may be the cheapest options available, it is important to remember the long-term ramifications associated with this method.

We need to consider that our grandchildren and their descendants will have to live with nuclear radioactive waste for thousands of years in the area where nuclear radioactive waste are currently disposed because many of these radioactive materials can remain active for thousands of years, food and water resources will be contaminated as well. On the other hand, the proposed TCT allows for the prevention of environmental pollution resulting from current nuclear radioactive waste disposal methods. Additionally, TCT will help to enhance protection for workers, the public, and safely manage and recycle nuclear radioactive waste alongside many other types of waste with no impact on the environment. It does so by converting these wastes into renewable energy and fuel, as described in greater detail in the following section.

5.6.1 The working principle of TCT

The process of TCT consists basically of four major steps, which are: (1) waste feed and handling; (2) Thermo-chemi-nuclear treatment; (3) cooling and condensation; and (4) energy generation. Fig. 5.7 depicts the main components and sequence of operations of TCT, which integrates two processes together, the first process is gasification process inspired from the available studies of the US energy department, and the second process is the nuclear treatment of nuclear radioactive waste, which is considered the most important part of this process.

The proposed Thermo-chemi-nuclear conversion plant is designed to be interconnected with the oil and gas gathering and production station in the oilfield as shown in Fig. 5.8. Furthermore, TCT can be even utilized with gathering stations that contain the integrated in-situ oil and uranium recovery plant as shown in Fig. 5.9. This is because it can provide the optimal utilization of a tremendous volume of produced nuclear radioactive waste from gathering and production stations, such as surplus separated contaminated formation water from the production stations, contaminated soil, sludge, scales, and other collected waste from oilfields and nearby villages that are normally dumped in dumping yards close to the gathering and production areas. The same design can be also tailored in mobile units that can be mobilized to drilling rig sites or other locations.

Nuclear radioactive waste, contaminated formation water, scale, and sludge will feed directly from gathering production stations. Other types of waste such as contaminated scraps, contaminated soils, garbage, household waste, construction waste, and sewage waste can also be transported from other locations to the Thermo-chemi-nuclear conversion facility and conveyed into a shredder. Here, all the waste will be broken down into

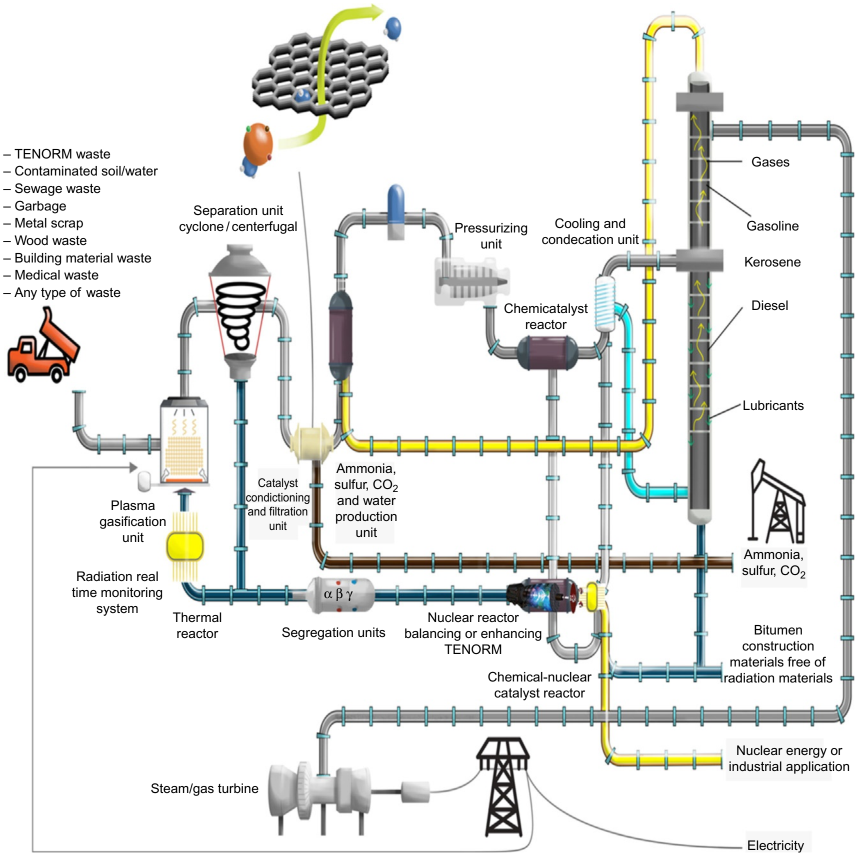


Fig. 5.7 Process flow chart of thermo-chemi-nuclear conversion technology (TCT).

very small fragments; this is done to increase the surface area, thus making the heat transfer more effective as it is moved to the thermal plasma reactor, where it will be gasified by means of thermal plasma torches at extremely high temperatures. The plasma torches thus ensure a homogenous treatment of waste, as temperatures can reach as high as 800°C or more cause materials to disintegrate into their elemental and organic components. Depending on the operation application, the power required could vary between 5 and 2500 kW (WPS, 2012). Organic matters will be decomposed into individual chemical components such as carbon, hydrogen, oxygen, sulfur, ammonia, and many other basic molecules and atoms that can be further used for different industrial applications.

Produced carbon, for example, forms many compounds due to its willingness to bond with other materials; carbon dioxide accordingly plays a

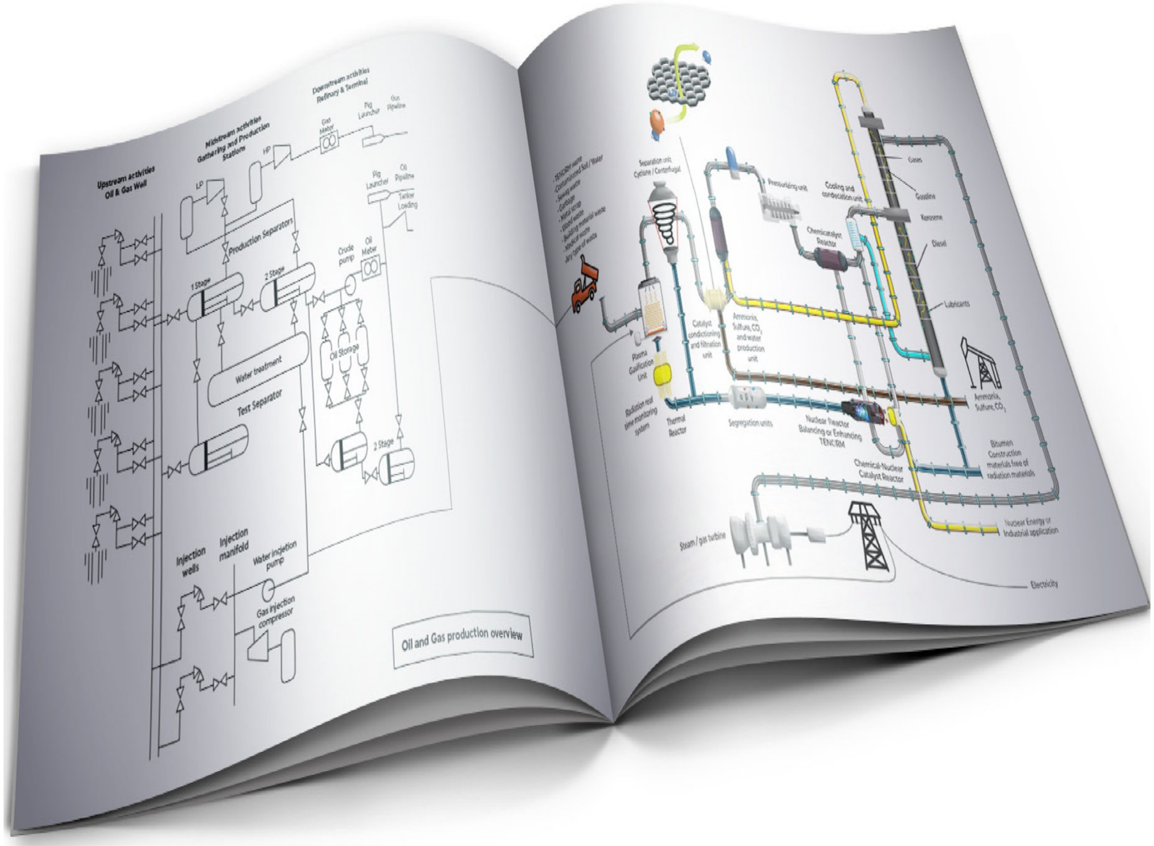


Fig. 5.8 Combined process flow chart of production station and thermo-chemi-nuclear conversion plant (without in-situ oil and uranium recovery plant).

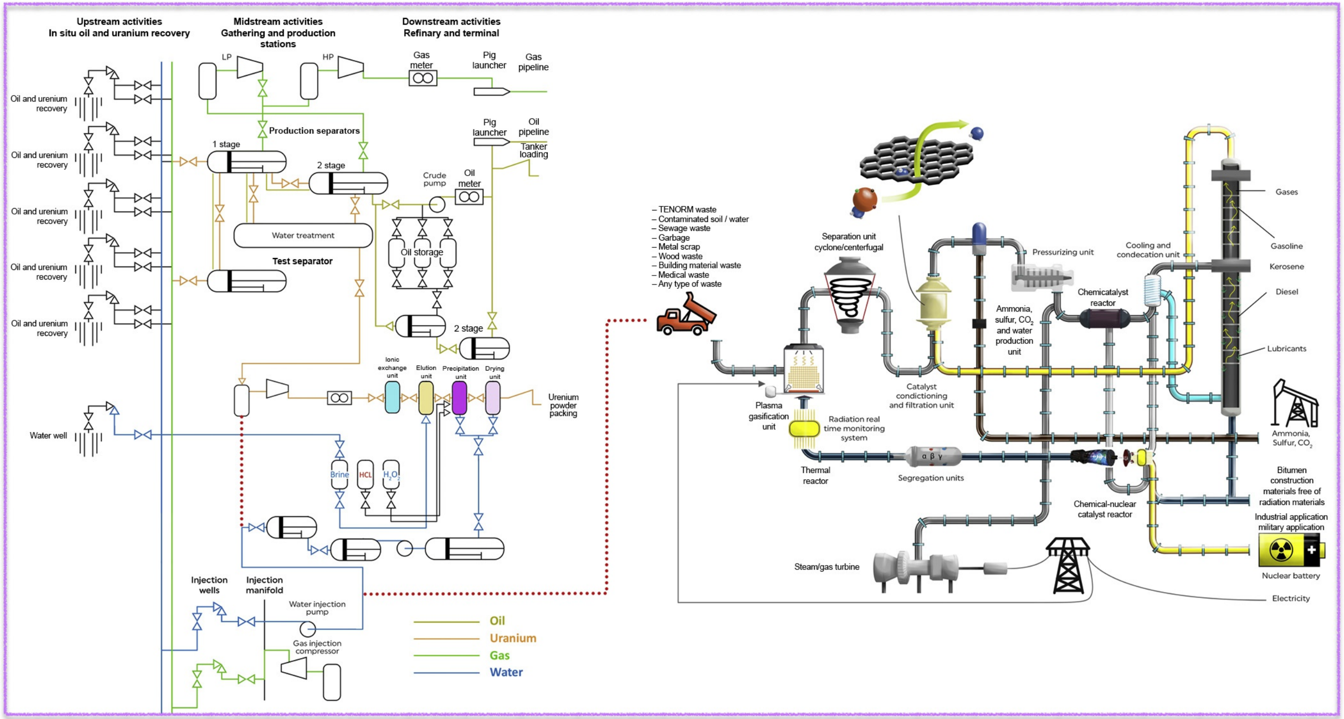


Fig. 5.9 Combined process flow chart of production station and thermo-chemi-nuclear conversion plant (with in-situ oil and uranium recovery plant).

significant role in enhanced oil recovery technologies as well as many other industrial applications (Verma, 2015; Naqvi, 2012). Hydrogen also has extensive applications in petrochemical processing (Schreiner, 2008).

During this process and according to the available studies related to gasification working principle, the gases from gasification reactors will favor the formation of primarily carbon monoxide, diatomic hydrogen molecules, and very often some carbon dioxide; this mixture is known as syngas (Dodge, 2008; Schreiner, 2008). The syngas process takes place between approximately 800°C and 1000°C. Hence, the gas is cooled down further to a temperature of approximately 600°C–400°C just to recover lost heat from gas cooling through a heat exchanger (Zhu, 2015). Gas leaving the gasification unit usually contains suspended particles, which will be removed using different means of separation and cleaning. Syngas then will undergo through additional cleaning and conditioning steps using a series of very small micron filters to further remove finer particles (Held, 2012). When the gas is free of particles, it must afterward undergo a chemical treatment to remove any remaining toxic substances by passing through a series of catalytic converters. This step is followed by a series of chemical scrubbing and stripping processes to remove residual debris, toxic gases, and acids. Syngas is then compressed to increase its pressure before it is passing over the catalysts to form a liquid. The catalysts are contained in a reactor, and the syngas is passed through the reactor where carbon monoxide and hydrogen molecules combine to form larger molecules. These molecules are subsequently cooled and refined in a distillation unit into a clean renewable fuel. The clean and treated syngas produced can also be fed into gas turbines to generate electricity.

On the other hand, the solid wastes such as metals, contaminated scraps, soil, and sand will meltdown and will be collected at the bottom of the thermal gasification reactor unit as slag. This slag containing any nuclear radioactive material will be cooled down, crushed, and converted into powder for further segregation process according to their type, their types of radiation emissions, and other related components. The segregated nuclear materials can be either packed into barrels according to their types and sent to nuclear facilities for further treatment or can be sent through series of nuclear transmutation reactions in a nuclear reactor for further treatment. The reactor contains particle accelerators in which energetic subatomic particles are bombarded toward a target nucleus, based on the common modes of nuclear decay reactions described in below equations (Averill and Eldredge, 2011). Resulting product nucleus can be either converted into a stabilized atom so that these powders can be used safely later for any industrial application as road construction materials for example, or it can be further enhanced to generate more energy according to the principle of energy production from the radioactivity (Kumar, 2015) that can be used for electricity generation.

- Alpha decay

$$ {}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}X' + {}_{2}^{4}\alpha \xleftrightarrow{\text{(Nuclear transmutation reactions)}} (X'' : \text{satable/enhanced}) \quad (5.2) $$

- Beta decay

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}X' + {}_{-1}^{0}\beta \xleftrightarrow{\text{(Nuclear transmutation reactions)}} (X'' : \text{satable/enhanced}) \quad (5.3) $$

- Gamma emission

$$ {}_{Z}^{A}X \rightarrow {}_{Z}^{A}X' + {}_{0}^{0}\gamma \xleftrightarrow{\text{(Nuclear transmutation reactions)}} (X'' : \text{energy enhancement}) \quad (5.4) $$

- Spontaneous fission

$$ {}_{Z+Y}^{A+B+C}X \rightarrow {}_{Z}^{A}X' + {}_{Y}^{B}X + C_{0}^{1}n \xleftrightarrow{\text{(Nuclear transmutation reactions)}} (X'' : \text{satable/energy enhancement}) \quad (5.5) $$

5.7 Nuclear radiological occupational exposure prevention in the oil and gas industry

The world has witnessed an increase in the production of oil and gas over the past several years to meet the increase in the global demand for energy. This makes the oil and gas industry as the main energy and economy source for many countries around the world (ALNabhani et al., 2016b). Researches involving the last three decades of oil and gas production history have confirmed the fact that nuclear radioactive materials are coproduced with oil and gas production. Therefore, produced nuclear radioactive materials pose significant risks to countless people involved in the oil and gas industry during the extraction and production process as well as public and the environment (Gesell, 1975; Steinhäusler, 2005; ALNabhani et al., 2016a,b,c). Accordingly, it is critical to realize that nuclear radiological exposure truly exists, and it is a global issue due to the global distribution of reserves and the strong relationship between nuclear radioactive materials and hydrocarbons presence as explained earlier. Therefore, experts fear that some workers in the industry are at risk of being exposed to different levels of radiation doses under adverse conditions, based on the available data on the mass flow and activity concentration of radioactive material involved at various stages of the oil and gas industry. Despite this, for economic and political reasons, some industries have been reluctant to admit the presence of nuclear radioactive materials in their operation (ALNabhani et al., 2016b).

In the oil and gas industry, the exposure of workers to nuclear radiological risks can occur at various stages during oil and gas extraction and production process as well as at waste disposal facilities, as shown in Fig. 5.10 (ALNabhani et al., 2016a,b,c). Those who may be affected include workers performing drilling and associated services, including but not limited to crew members involved in work over, fluid filtration, coring, hydraulic fracturing, fishing and milling, waste management, perforation, wireline logging, and directional drilling services. As well as those who work in the midstream and downstream activities such as crew members working in gathering and production station, flow line maintenance, workshops, and refineries.

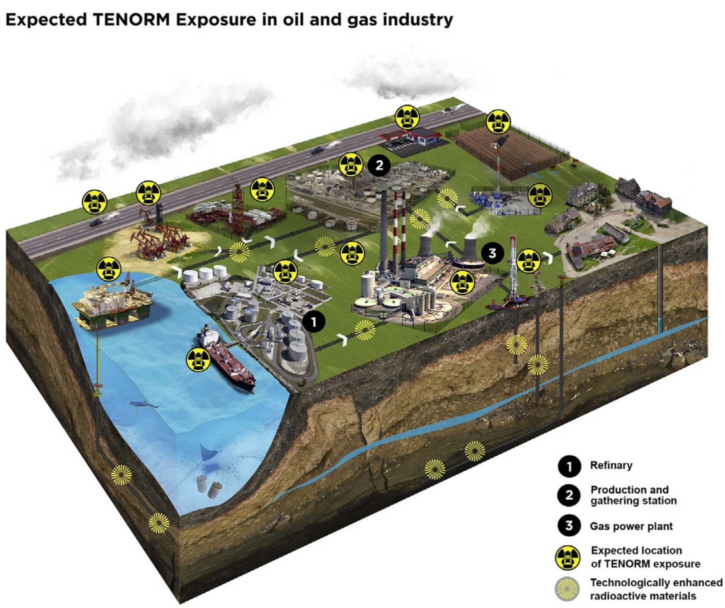


Fig. 5.10 Expected nuclear radiological exposure during oil and gas extraction and production activities.

Nuclear radiological exposure risks can be prevented and mitigated at a very early stage through predicting and controlling the exposure at the source, as well as emphasizing exposure incident prevention to achieve an inherently safer process design to enhance safety. To protect the health and foster safety by preventive instances of major exposure, it is imperative to ascertain the presence and adequacy of safety barriers. They do this by gathering information via radioactivity measurements collected from well-logged databases such as spectral gamma logs, geochemical logs, resistivity logs, and oilfield correlation logs of oil and gas wells in different oilfields where radioactivity measurements are used as a basis to identify the presence of hydrocarbons (ALNabhani et al., 2016a). The correlation of well-logged data makes it possible to calculate expected radioactivity levels in the planned well, and therefore, to get a good indication of the level of the expected radiation level in that particular well or oilfield (ALNabhani et al., 2016a). However, there could be some uncertainty associated with such predictions, so risk reduction and precautionary measures should be adopted to ascertain the presence and adequacy of safety barriers.

Five sequential and interconnected safety barriers for radiological exposure risk prevention could be identified as crucial to provide enough protection against occupational nuclear radiological exposure risks during the oil and gas extraction and production processes that combine upstream activities with midstream and downstream operations, which remains largely unimplemented in the oil and gas industry. These are as follows:

1. Early detection safety prevention barrier (EDSPB): This is the release prevention barrier (RPB) that is responsible for preventing the initiating event for nuclear radioactive materials release at the upstream source. This includes, but is not limited to the following sub-barriers:
   - Field and well-logging data, such as spectral gamma logs that are considered as a good source of information on early nuclear radioactive materials release presence associated with hydrocarbon evaluation, and its level of radioactivity prediction.
   - Downhole real-time detectors that can detect the radioactively level from rock formation during drilling activities.
   - Upstream surface sensors should also be fixed at different locations in drilling rigs such as at the cellar, the wellhead, the flow line connected to the bell nipple, the mud system, the waste pits, and the rig floor.
   - Midstream activities sensors that can be placed in flow lines between the wellhead and gathering stations, equipment in the gathering and production stations such as separation tanks and eventually in refinery utilities, particularly in storage tanks.

2. Isolation integrity safety prevention barrier (IISPB): This is a dispersion prevention barrier (DPB) at the midstream phase. It includes, but is not limited to, the following sub-barriers: equipment insulation carrying nuclear radioactive materials coproduced with oil and gas production, including flow lines, separation tanks, pumps, and other associated processing equipment in gathering and production stations; emergency shutdown mechanisms; and work permits.
3. Personal protection equipment and exposure duration safety prevention barrier (PPE&EDSPB): It includes, but is not limited to, the following sub-barriers: personal radiation monitors, and leaded shield personal protection equipment—LPPE.

LPPE is a special personal protective equipment shielded with an effective, and lightweight layer of leaded material. LPPE combines the high quality of personal protective equipment (protective clothing, helmets, goggles, hand gloves, safety boots, and face mask). It is a composition of various of a strong, lightweight, leaded layer, or any other similar materials, which is known to be the best shielding material against gamma radiation because of its a high electron density blended with other safe and lightweight material that has high electron density to increase the overall number of electron clouds, as well as this composition, can be also mixed with polyethylene C_2H_4 polymers that contains more hydrogen atoms. Fast emitted particles or energies will be slowed by collision with hydrogen atoms, which will be able to absorb high emitted energy such as gamma radiation, fast neutrons. These polymers are known for having high-linear energy transfer and therefore, can absorb and scatter the emitted radiation or energy. When this composition is used as a shield, then gamma electromagnetic wave other emitted particles that are trying to penetrate this fabric will first collide with the high density of electron clouds, and then their energy will be absorbed and scattered by the hydrogen atoms of the polyethylene C_2H_4. LPPE must be used by all workers involved at different aspects of oil and gas extraction and production activities, including drilling crew members, work over crew members, well services and intervention crew members, workshop technicians, flow line crew members, workers in production, gathering stations, and refineries or petrochemical or other related industries relying on hydrocarbon products that contains nuclear radioactive materials.

4. Emergency management safety prevention barrier (EMSPB): This safety barrier is considered as the mitigation barrier to control hazardous nuclear radiological exposure and its consequences. It includes, but is not limited to, the following sub-barriers: emergency response plan,

emergency preparedness, emergency medical plan, emergency and safety drills, and worker awareness.

5. Management and organization safety prevention barrier (M&OSPB): This safety barrier intervenes either positively or negatively with all other barriers based on the management's behavior, unretarding of safety importance, and responsibility. It includes, but is not limited to, the following sub-barriers: training and competency programs, safety policies, legislation, operating procedures, cancer medical checkups, effective risk and safety management system, decision making, management practices and knowledge, leadership, and communication.

5.8 Conclusions

Results from different worldwide field surveys, well-logging data, coring, drilling cuttings samples confirm the presence of enhanced nuclear radioactive materials that belong to uranium and thorium series in the oil and gas production where different levels of radioactivity concentration were recorded that vary in range from low to extremely high levels. It has been also reported that a huge volume of nuclear radioactive waste is annually produced by the oil and gas industry along with oil and gas production. Moreover, many other studies took different measurements of nuclear radioactivity at various stages of oil and gas extraction and production processes. All these studies have confirmed the existence of uranium, thorium, and number of important minerals in the geological formation that contain hydrocarbons, however, these natural sources of energy are not utilized so far and instead, unfortunately, are currently being disposed of as waste directly into the environment causing serious threats to the environment, the public, and future generations. Thus, this chapter has shed a light on this issue and presented some important scientific recommendations that emphasized on the importance of how to recover the abundant deposits of natural uranium, thorium, and many other elements that are available in geological formation hosting hydrocarbons. And how to get the benefit of producing them with oil and gas production and exploiting them as another source of energy. Scientific and practical proofs have been presented to explain how uranium, thorium, and many other valuable minerals are economically feasible to be extracted and produced along with the oil and gas extraction and production processes rather than dumping them as a wasted energy directly into the environment.

Economically, this can be achieved through exploiting the same process currently used for oil and gas extraction and production processes, which are identical same to the process used for in-situ uranium recovery in the modern mining industry in terms of exploration survey, drilling procedures, gathering and separation processes, and enhancement recovery technology including lixiviant, injection, and production wells. This new integrated technology to recover both oil and uranium called In-Situ Oil and Uranium Recovery Technology. This new technology will play a significant role in numerous peaceful applications of atomic energy by providing the raw nuclear materials that can be used for nuclear power generation, or as radiotracers, or many other safe applications.

The adoption of In-Situ Oil and Uranium Recovery Technology in the oil and gas industry will have the following advantages: (1) besides oil and gas production from the oilfields, a new source of nuclear energy raw materials including uranium and thorium can be produced to be a vital tributary that can be used on the peaceful applications of the atomic energy; (2) huge cost saving since exploration, extraction, and production process and other ancillary enhanced oil recovery technique are already exist and same will be used for extracting uranium, thorium, oil and gas, and other valuable minerals. The only thing is required to be added in the existing facilities is uranium separation facility to be attached to the existing oil and gas gathering and production stations in the oilfield; (3) less environmental footprints and pollutions; (4) processing and converting of huge volumes of radioactive waste that are daily generated from oil and gas industry into energy will permanently help to get rid of current nuclear radioactive waste disposal methods used by the oil and gas industry that pose a serious threat to the public health, environment, and future generations; and (5) minimize radiological risk.

The adoption of the In-Situ Oil and Uranium Recovery Technology in the oil and gas industry may take some time as it will be subject to more studies and researches. Therefore, an urgent solution is required to provide scientific solutions to protect people working in the oil and gas industry from being exposed to radiological risk. Thus, five sequential and interconnected safety barriers for radiation prevention have been introduced as crucial in providing enough protection against occupational nuclear radiological exposure risks during the oil and gas extraction and production processes, which are: (1) EDSPB; (2) IISPB; (3) PPE&EDSPB; (4) EMSPB; and (5) M&OSPB.

On the other hand, the adoption of the In-Situ Oil and Uranium Recovery Technology in the petroleum industry may take some time since more studies and researches are required. Since then it is crucial to have a scientifically based solution able to treat the huge amount of daily produced nuclear radioactive wastes during oil and gas production processes, which is really a major concern that poses serious risks to the environment, the lives of the people, and future generations. Therefore, a novel of TCT has been introduced to treat different forms of nuclear radiological waste produced from the oil and gas industry. Not only that, this technology is designed to manage nuclear wastes along with household, sewage, industrial effluent, and hazardous wastes, and eventually convert them into fuel and renewable energy.

References

ALFarsi, A. 2008. Radiological aspects of petroleum exploration and production in the sultanate of Oman Doctoral thesis. Available from QUT Database. Document ID 29817/1. Retrieved 02/11, 2016 from: http://eprints.qut.edu.au/29817/1/Afkar_Al-Farsi_Thesis.pdf.

Al-Masri, M.S., Aba, A., 2005. Distribution of scale containing NORM in different oilfields equipment. Appl. Radiat. Isot. 63, 457–463.

Al-Masri, M.S., Haddad, K.H., 2012. NORM emissions from heavy oil and natural gas fired power plants in Syria. J. Environ. Radioact. 10, 71–74.

ALNabhani, K., Faisal, K., Ming, Y., 2016a. Technologically enhanced naturally occurring radioactive materials in oil and gas production: a silent killer. Process Saf. Environ. Prot. 99, 237–247. Available from: http://www.psep.ichemejournals.com/article/S0957-5820(15)00177-9/abstract.

ALNabhani, K., Khan, F., Yang, M., 2016b. The importance of public participation in legislation of TENORMs risks management in the oil and gas industry. Process Saf. Environ. Prot. 102, 606–614. Available from: http://www.sciencedirect.com/science/article/pii/S0957582016300489.

ALNabhani, K., Khan, F., Yang, M., 2016c. Scenario-based risk assessment of TENORMs waste disposal options in oil and gas industry. J. Loss Prev. Process Ind. 40, 55–66. Available form: http://www.sciencedirect.com/science/article/pii/S0950423015300838.

Anna, M.C., Timothy, W.L., 2004. Trace metal records of regional pale environmental variability in Pennsylvanian (upper carboniferous) black shales. Chem. Geol. 206, 319–345.

API, 1989. A National Survey on Naturally Occurring Radioactive Materials (NORM) in Petroleum Producing and Gas Processing Facilities. API, Dallas, Texas.

Averill, B., Eldredge, P., 2011. General Chemistry: Principles, Patterns, and Applications. Version 1.0, Saylor Foundation.

Bareja, E., 1984. Minerals of uranium in the triassic deposits of the Baltic Sea. Geology. Quart. 28, 353–366.

Beers, R.F., Goodman, C., 1944. Distribution of radioactivity in ancient sediments. Bull. Geol. Soc. Am. (55), 110–118.

Bou-Rabee, F., Al-Zamel, A., Al-Fares, R., 2009. Technologically enhanced naturally occurring radioactive materials in the oil industry (TENORMs): a review. Nukleonika 54 (1), 3–9.

Clark, C. E., and Veil, J. A. 2009. Produced water volume and management practices in the United States. Report ANL/EVS/R-09-1, US Department of Energy's Office of Fossil Energy National Technology Laboratory, Washington, DC. 64.

Dodge, E., 2008. Plasma-gasification of waste clean production of renewable fuels through the vaporization of garbage. Cornell University, Ithaca, NY.

El Afifi, E.M., Awwad, N.S., 2005. Characterization of the TE-NORM waste associated with oil and natural gas production in Abu Rudeis, Egypt. J. Environ. Radioact. 82, 7–19.

Erickson, R.L., Myers, A.T., Horr, C.A., 1954. Association of uranium and other metals with crude oil, asphalt, and petroliferous rock. Am. Assoc. Pet. Geol. Bull. 38, 2200–2218.

Gazineu, M.H.P., Araujo, A.A., Brandao, Y.B., Hazin, C.A., Godoy, J.M.D.O., 2005. Radioactivity concentration in liquid and solid phases of scale and sludge generated in the petroleum industry. J. Environ. Radioact. 81, 47–54.

Geological Survey (US), 1960. Geological survey professional paper. Vol. 355–357. US Government Printing Office, The Ohio State University. Geological Survey Professional Paper, Geological Survey (US).

Gesell, T., 1975. Occupational radiation exposure due to ^{222}Rn in natural gas and natural gas products. Health Phys. 29 (5), 681.

Givens, W.W., Stromswold, D.C., 1989. Prompt fission neutron logging for uranium. Nucl. Geophys. 3 (4), 299–307.

Glover, P., 2000. Petrophysics. Department of Geology and Petroleum Geology. University of Aberdeen, UK, pp. 1–270.

Held, J. 2012. Gasification—status and technology. Rapport SGC 240•1102–7371•ISRN SGC -R-240-SE. Swedish Gas Centre.

Hore-Lacy, I., 2016. Uranium for Nuclear Power: Resources, Mining and Transformation to Fuel. Woodhead Publishing, pp. 1–453.

Huyck, H., 1990. When is a metalliferous black shale not a black shale? In: Grauch, R.I., Huyck, H.L.O. (Eds.), Metalliferous Black Shales, Related Ore, Deposits, Proceedings, 1989 U.S. Working Group Meeting, International Geological Correlation Program, Project 254, US GS Circular, 1058, pp. 42–56.

IAOGP (International Association of Oil and Gas Producers). 2008. Guidelines for the management of naturally occurring radioactive material (NORM) in the oil & gas industry. Report No. 412.

Jonkers, G., Hartog, F.A., Knaepen, W.A.I., 1997. Characterization of NORM in the oil and gas production (E&P) industry. In: Proceedings of Internatonal Symposium On Radiological Problems with Natural Radioactivity in the Non-Nuclear Industry. Shell Research & Technology, Netherlands, Amsterdam, pp. 23–47. September 8–10, 1997. Retrieved 03/09, 2015 from: http://i.iv.7.eu-norm.org/index.pdf.

Klaja, J., and Dudek, L. 2016. Geological interpretation of spectral gamma ray (SGR) logging in selected boreholes. Oil and Gas Institute–National Research Institute. NAFTA-GAZ, ROK LXXII, Nr 1, 3–14.

Krauskopt, 1969. Introduction to geochemistry. McGraw-Hill, New York.

Kumar, A., Karpe, R., Rout, S., Narayanan, U., Ravi, P.M., 2012. A comparative study of distribution coefficients (Kd) for naturally occurring uranium (U) and thorium (Th) in two different aquatic environments, INIS.

Kumar, S. 2015. Atomic batteries: energy from radioactivity, Department of Electrical Engineering, Stanford University, Stanford, CA.

Langmuir, D., 1978. Uranium solution mineral equilibria at low temperatures with applications to sedimentary ore deposits. Geochim. Cosmochim. Acta 42, 547–568.

Leventhal, J.S., 1993. Metals in black shales. In: Engel, M.H., Macko, S.A. (Eds.), Organic Geochemistry, Principles and Applications. Plenum Press, New York, pp. 581–592.

Lisitsin, A.K., 1971. Ratio of the redox equilibria of uranium andiron in stratiform aquifers. Geol. Rev. 13 (5), 744–751.

Mao, G.Z., 2009. Effects of uranium on the hydrocarbon generation of hydrocarbon source rocks (in Chinese). Doctoral dissertation, Northwest University, Xi'an.

Mao, G.Z., Liu, C.Y., Zhang, D.D., et al., 2014. Effects of uranium on hydrocarbon generation of hydrocarbon source rocks with type-III kerogen. Sci. China Earth Sci. 57, 1168–1179.

Naqvi, S., 2012. Enhanced oil recovery of heavy oil by using thermal and non-thermal methods. Master thesis, Dalhousie University, Halifax, NS.

Neff, J., Lee, K., Deblois, E., 2011. Produced water: overview of composition, fates, and effects. In: Produced Water. Springer, New York, pp. 1–52.

Othman, I., Al-Masri, M., S., Suman, H. 2005. Public and regulatory acceptability of NORM contaminated soil disposal: the syrian experience. In: E&P NORM Workshop. Sultanate of Oman, Muscat.

Rood, A.D., White, G.J., Kendrick, D.T., 1998. Measurement of Rn-222 flux, Rn-222 emanation and R-226 Ra-228 concentration from injection well pipe scale. Health Phys. 75, 187–192.

Russell, W.L., 1945. Relation of radioactivity organic content and sedimentation. Bull. Am. Assoc. Pet. Geol. 29 (10), 1470–1493.

Schlumberger, 2011. Heavy oil development in the middle east. 1–3. Retrieved on 15/10/2018 and available from: https://www.slb.com/~/media/Files/industry_challenges/heavy_oil/other/feature_articles/ho_middle_east_development.pdf.

Schreiner, B., 2008. Use of industrial gases in petrochemistry. Hydrocarb. Process. 87 (12). Germany.

Sharkey, M. A., Burton, J. M. 2008. Remediation of hazardous materials with an emphasis on NORM. SPE 117936 Available from: http://sourceenviro.com/downloads/Remediation_of_Hazardous_Waste_with_an_Emphasis_on_NORM.pdf.

Smith, K.P., Blunt, D.L., Williams, G.P., Tebes, C.L., 1996. Radiological dose assessment related to management of naturally occurring radioactive materials generated by the petroleum industry. ANL/EAD-2, Argonne National Laboratory. Retrieved 13/03/2015 from: http://www.netl.doe.gov/kmd/cds/disk23/G-Soil%20Projects/NORM%5CANL-EAD-2.pdf.

Steinhäusler, F., 2005. Radiological impact on man and the environment from the oil and gas industry: risk assessment for the critical group. In: Radiation Safety Problems in the Caspian Region: Proceedings of the NATO, 41, pp. 129–134.

Strand, T., 1999. Handling and disposal of norm in the oil and gas industry. In: WM'99 Conference. Feb. 28–Mar. 4.

Supernaw, I.R., McCoy, A. D., Link, A. J. 1978. Method for in-situ evaluation of the source rock potential of each formation. US Patent 4,071,744.

Swanson, V., 1960. Oil yield and uranium content of black shales: uranium in carbonaceous rocks. Geological Survey Professional Paper 356-A. The US Atomic Energy Commission.

Testa, C., Desideri, D., Meli, M.A., Roselli, C., Bassignani, A., Colombo, G., Fresca Fantoni, R., 1994. Radiation protection and radioactive scales in oil and gas production. Health Phys. 67, 34–38.

US EPA (Environmental Protection Agency). 1993. Produced water radioactivity study. Office of Water and Office of Science and Technology. Washington, DC.

Verma, M. K., 2015. Fundamentals of carbon dioxide-enhanced oil recovery (CO_2-EOR)—A supporting document of the assessment methodology for hydrocarbon recovery using CO_2-EOR associated with carbon sequestration: US Geological Survey Open-File Report 2015–1071, 19.

Water Environment Federation, 2018. IWWC produced water: oil and gas terminology glossary. pp. 1–5. Retrieved on 10/11/2018 form, https://www.wef.org/globalassets/assets-wef/direct-download-library/public/03—resources/wsec-2017-fs-013-iwwc-og-glossary—final—5.21.18.pdf.

WPS. 2012. Plasma torches manual. Westinghous Plasma Corporation, USA.

Zhang, W.Z., Yang, H., Yang, Y.H., et al., 2008. Petrology and element geochemistry and development environment of Yanchang formation Chang-7 high quality source rocks in Ordos Basin (in Chinese). Geochimica 37, 59–64.
Zhu, Q. 2015. High temperature syngas coolers. IEA Clean Coal Centre, UK.
Zimmerle, W., 1995. Petroleum Sedimentology. Kluwer, Dordrecht, p. 413.
Zukin, J.G., Hammond, D.E., Teh-Lung, K., Elders, W.A., 1987. Uranium–thorium series radionuclides in brines and reservoir rocks from two deep geothermal boreholes in the Salton Sea geothermal field, southeastern California. Geochim. Cosmochim. Acta 51, 2719–2731.

Further reading

Neff, J., Lee, K., 2011. Produced Water. Environmental Risks and Advances in Mitigation Technologies. Springer, New York, Dordrecht, Heidelberg, London.
US Energy Information Administration (EIA). 2017. Short-term energy outlook Available from: https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf.

CHAPTER SIX

The role of international atomic agencies in regulating and legislation of radiation protection and the management of radioactive waste in the oil and gas industry

Chapter Outline

6.1 Introduction

Numerous studies, both scientific and technical, indicate that the extraction of oil and gas is accompanied by the production of large volumes of geological formations of water. This water may carry dissolved and suspended nuclear radioactive materials, such as uranium and thorium

Nuclear Radioactive Materials in the Oil and Gas Industry
https://doi.org/10.1016/B978-0-12-816825-7.00006-6

and their decay products down its flow path, depending on their oxidation status. Scholars such as Rood et al. (1998) and Gazineu et al. (2005) argue that the amount of nuclear radioactive material produced by the oil and gas industry is directly proportional to the volume of water produced. The American Petroleum Institute—API (1989) indicates that the ratio of produced water to oil is approximately 10:1 bbl. However, Neff et al. (2011) have since reported that the ratio of produced water varies broadly from well to well. In some instances, they indicate that this ratio can increase to more than 50:1. They cite depletion as a factor in ratio changes. When a field is nearly depleted, they indicate that it produces nearly 98% formation water and 2% oil. As a result of a change in temperature and pressure between the downhole and the surface, natural radioactive materials, as well as technologically enhanced nuclear radioactive materials, precipitate along with carbonate scales and sulfate during the oil and gas extraction process. These materials may be found in the form of scales, sludges, and thin films on the inner walls of pumps, production tubular, separators, valves, and other related equipment. This is one of the main reasons that radioactivity measurements are reported in upstream, midstream, and downstream equipment. These radioactive materials, besides radiation generators and radioactive tracers that are used extensively for different applications such as well logging, gauging, and production optimization, all pose a significant threat to workers involved in the production and maintenance stages of the oil and gas industry, as well as the general public and the environment.

Overall, the oil and gas industry operates in the most hazardous of situations and conditions, but it is nonetheless necessary to maintain controlled working conditions. Precautionary measures must extend to worker safety, as well as the safety of the public and the environment particularly in relation to radiation protection and radioactive waste management in areas where adequate regulations have been lacking. A scientific investigation must be undertaken to address the hazards posed by the immense amount of nuclear radioactive waste that is produced daily by industries, as well as to posit protocols to control the chemical and radiological hazards that are engendered. These safety standards must be specialized for and specific to the oil and gas industry, due to its unique technical and organizational complexities. Legislative regulations must also be distinct to the industry.

According to the International Energy Agency (2019), more than 70% of the global energy demands are currently met through oil and gas, and most of the major oil producing countries are members of the IAEA. These countries contribute to significant quantities of enhanced nuclear radioactive wastes that are directly disposed of into the environment and the effects of which may be felt nearly two millennia into the future. These wastes are comprised of more than 80% radium with a half-life of 1600 years, and may subsequently contaminate both food and water sources, meaning that they pose a threat not only to our future grandchildren but also to a long line of their descendants. It is thus necessary that both international regulatory bodies such as the IAEA, IOGP, and the ICRP, as well as member states, exert occupational control to contain this threat. Currently, the industry has not progressed to the point of developing such controls. This is the next major historical hurdle for oil and gas.

Currently, the oil and gas industry adopted the recommendations offered by exclusive organizations that are based on the best industry practices. However, such practices are not necessarily based on the scientific evaluation, medical research, or epidemiological studies, nor are they necessarily in line with international safety standards. It is, nonetheless, in the best interest of the industry to implement more reliable safety standards, as it is a vital global enterprise with significant impacts on the communities in which it operates. However, the oil and gas industry cannot undertake this process alone. Radiation protection bodies must have steps to work with and assist the oil and gas in promoting health and safety in relation to protection and waste management. Thus, regulatory bodies must also commit themselves to help the industry develop adequate protection.

The IAEA, the IOGP, and the ICRP are three key agencies expected to be concerned with the regulation legislation in relation to the radiation protection and waste management for the industries involving radioactive materials production. The IAEA, which is a pillar of the nuclear industry, as well as other industries involving nuclear waste, has recently extended its attention to naturally occurring radioactive materials (NORM) and their safe management in the oil and gas industry in its Safety Series, no. 34, which is discussed in detail in Section 6.2 of this chapter. The IOGP is a leading forum specific to the oil and gas industry. It plays a prominent role in creating guidelines that assist the industry in implementing best-known practices for the health, safety, and environmental stewardship. Its Safety Report no. 412 posits guidelines for the management of NORM and is discussed in Section 6.3 of this chapter. Finally, the ICRP is an independent, international, nongovernmental organization whose main mission is to provide guidance of radiation protection. Many industries follow their recommendations and guidelines on dose limits. Their recently drafted report is detailed in Section 6.4 of this chapter.

Major weaknesses and gaps that have been noticed in the current guidelines are that they are not designed for specific industries and, therefore, offer only generic guidance. This may introduce elements of uncertainty regarding how to make recommendations applicable to a specific industry process or circumstance. Such uncertainties are not adequate to ensure sufficient and reliable protection against radiological risks. Furthermore, from an epidemiological perspective, many of the available guidelines and regulations do not address the risks associated with technologically enhanced nuclear radioactive materials which have previously been ignored due to the incorrect presumption that its low level of radioactivity poses no serious risk. Thus, such guidelines have focused primarily on protecting against the elevated radiological concentrations which have historically been associated with health risks in medical literature. However, as recent medical studies suggest that low-dose radiation exposure may pose health risks that are as serious as those of high-dose radiation exposure, safety guidelines must be reformed to accommodate these new findings.

In addition to available international regulations and guidelines on radiological protection, regulations and guidelines have also been established on the national level. These national controls not only affect the oil and gas industry, they offer generic direction that may not be explicitly designed for or targeted to oil and gas or able to differentiate between NORM and technologically enhanced naturally occurring radioactive materials (TENORM) which becomes more confusing for the industries and leaving the decision to the industries themselves to choose which policies and guidelines they wish to implement. For example, the United States Environment Protection Agency (EPA) has developed regulations for radiation protection for TENORM (EPA, 2019), while other national bodies have developed regulations for protections against NORM, such as the Canadian Guidelines for the management of NORM (Health Canada, 2013). Likewise, the UK government (2016) has developed a UK-wide strategy for the management of solid low-level radioactive wastes arising from the nuclear industry.

Unfortunately, the available guidelines and regulations often act as a guiding source for managing similar approaches in relation to the management of NORM from different industries and trying to standardize the same procedures to make it implemented in all industries producing radioactive materials in a convenient manner and not mandatory. Available guidelines and regulations are also unable to differentiate scientifically between NORM and TENORM, which makes a major scientific difference and a major risk in the process of drafting guidelines and regulations according to the associated risk level and characteristics of each. Furthermore, the currently used guidelines and regulations do not form any mandatory management principles. It only recommends and explains the controls that are regulated according to various working practices. They lack scientific justifications, compulsory, and detailed instructions for industry-specific practices, as well as quantitative information on risk assessment. Furthermore, they consider the radiation levels associated with the oil, and gas industry to be low, and not in excess of background radiation, therefore, they pose no risk. Despite that, numerous scientific studies indicate elevated levels of radioactivity concentrations, and extremely high levels of radiation, in many oil and gas industries around the world. Accordingly, these guidelines offer incomplete information and exist only as a starting point that needs further development to become reliable and more effective in providing the required protection for workers, the public and the environment. It is important that the public and the industry be engaged with different stakeholders and authorities to create feasible and reliable regulations that can provide the required level of protection and management as well as fostering general awareness. Such regulation must be mandatory and controlled by nuclear commissions authorities otherwise this makes industries act as self-regulators in controlling and managing exposed radiation and radioactive waste the way that meets their capabilities and limited awareness.

Meantime and in the absence of firm regulations, the oil and gas industry must take an active and leading role in protocol development. Such a role requires the industry to further investigate the utility of the proposed guidelines and their scientific efficacy. An examination of the efficacy of these guidelines is urgent and must consider the immediate and long-term risks for the general health of the workers, the public, and the environment. Guidelines must exist that address the exigencies of individual industries and their unique processes.

6.2 IAEA-Safety report series #34: Radiation protection and management of radiation waste in the oil and gas industry

The International Atomic Energy Agency (IAEA) fosters safe and secure applications of nuclear technology, promoting international security, peace, and sustainable development. Established in 1957, it is the leading intergovernmental agency concerned with scientific and technical collaboration in this area, acting as a hub for nuclear research. An autonomous organization, the IAEA nonetheless reports to both the UN's General Assembly and Security Council to establish principles for the nuclear development of member states, as well as working in partnership with research and civil organizations.

The IAEA's position as a body that vanguards individuals, communities, and the environment against the potential threats presented by nuclear energy and its radiations is elaborated in the introductory section of this guideline, in which the IAEA has played a significant role in publishing and formulation of many guidelines and regulation in relation to radiation protection and radioactive waste management. Particularly, the International Basic Safety Standards (BSS) for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Safety Series no. 115) and the Safety Fundamentals on Radiation Protection and the Safety of Radiation Sources (Safety Series no. 120) are, together, cardinal documents for the fundamentals of radiation safety and principles for safe exposure. Likewise, the Safety Guide on Occupational Radiation Protection (Safety Standards Series no. RS-G-1.1) stipulates how to uphold the prerequisites established by the International BSS in occupational work, while the 'Principles of Radioactive Waste Management' (Safety Series no. 111-F) encompasses waste management standards and criteria for the development of waste management programs of member states. Moreover, the "Safety Requirements on Predisposal Management of Radioactive Waste, Including Decommissioning" (Safety Standards Series no. WS-R-2) establishes principles related to predisposal management of radioactive waste from decommissioning of nuclear facilities through cleanup of contaminated sites and industry applications of radionuclides. "The Safety Guide on Management of Radioactive Waste from the Mining and Milling of Ores" (Safety Standards Series no. WS-G-1.2) has provided guidance for NORM waste management, a necessary consideration of the oil and gas industry. Other notable safety guides are the "Decommissioning of Medical, Industrial, and Research Facilities" (Safety Standards Series no. WS-G-2.2) and the Regulatory Control of Radioactive Discharges to the Environment (Safety Standards Series no. WS-G-2.3).

This work details the IAEA's report on radiation protection and the management of radioactive waste in the oil and gas industry. The report looks to deliver information on the practical management of waste and safety measures, as outlined in the reports to fulfill International BSS for the oil and gas industry. It also outlines the structure of the oil and gas industry, its methods, processes, and equipment. The report is aimed at a diverse array of audiences ranging from regulatory bodies, through the oil and gas workers, as well as the professionals concerned with environmental safety, and safety training officers. It establishes guidelines on:

(i) the safe management of radioactive waste,

(ii) the health, as well as the safety of the workforce, public, and the environment, and

(iii) the promotion of radiation safety.

This report was drafted in six meetings held between the years of 1997 and 2002, and one technical committee meeting came to fruition over the course of 5 years. Over these 5 years, it was noted that the industry in question, the oil and gas industry, makes considerable use of radioactive materials, radiation generators, sealed and unsealed sources, and also produces massive radioactive wastes in the form of NORM. These findings suggest a need to control both occupational and public exposure to ionizing radiation. The IAEA thus produced this report. The report addresses the requirements of the International BSS for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS). It integrates, as well, the concepts, principles, and objectives outlined in the Safety Fundamentals on the Principles of Radioactive Waste Management.

6.2.1 An overview

The report consists of seven sections alongside four appendices. Following the report's introduction (Section 1), which outlines its objectives, namely, to provide practical guidance on industry practices for the application of BSS, as well as scope—to provide a framework for its member states to develop a common understanding with service companies and field operators. Section 2 outlines the structure of the oil and gas industry, components of the upstream, midstream, and downstream industries, and drilling methods. Section 3 details the application of sealed sources and radiation generators in well logging, alongside the use of gauging equipment, and aspects of radioactive waste safety and radiation protection. Section 4 further details safety concerns as they relate to unsealed radioactive substances, such as radiotracers and markers, and elements of radioactive waste management that arise from regular use as well as from radiological accidents. The 5th section discusses the transport and treatment of NORM, as well as their deposition forms within gas and oil production. It discusses measures of protection in overseeing NORM, as well as the management and disposal of waste associated with it at oil and gas facilities and decontamination plants. Issues and strategies associated with decommissioning, decommissioning planning, and attendant management issues are illustrated in Section 6. This section includes information on licensee responsibilities.

Section 7 emphasizes and establishes responsibilities and duties toward environmental stewardship and health protection from involved parties. It highlights the critical nature of proper training and supervision for those responsible for waste management. Consequently, detailed instructions on monitoring radiation, characterizing radioactive waste, training, as well as methods for decontamination are offered in the appendices.

Section 5 of this report addresses and details NORM in the oil and gas industry. It outlines the discovery of NORM, as well as its radiological characteristics and emergence. The IAEA has acknowledged that the radionuclides discovered in oil and gas production arise from the decay chains of ^{238}U and ^{232}Th. This leads to the production of daughter radioisotopes of different characteristics and of different physical features regarding their decay modes, half-lives, energies, and types of released radiation.

Section 5.5 deals with aspects of radiation protection as it relates to NORM. According to the IAEA, the oil and gas industry is without suitable measures for radiation protection; consequently, NORM was recognized as a source of external exposure during production as a result of accumulations of gamma-emitting radionuclides in those industries. NORM is also implicated in the internal radiological exposure of members of the industry's workforce, as well as other workers responsible for maintenance, waste transportation, transportation of contaminated machinery, and disposal. These exposures also occurred during decommissioning of production facilities and waste management facilities.

In Section 5.5.4, "Practical radiation protection measures" the requirements mentioned in the BSS for safety and radiation protection are described and made applicable to installations in the oil and gas industry and the NORM associated with it.

The IAEA supports the International Commission of Radiological Protection's (ICRP) principles to keep radiation doses as low as reasonably achievable (ALARA). Implementing this philosophy is, however, challenging, due to economic and social factors, as well as the fact that the exposure that occurs due to external and internal contamination require different practical measures and solutions.

In this vein, Section 5.5.4.1 offers a set measure to limit external radiation exposure, which are:

(i) reduce the duration of any mandatory external exposure,
(ii) ensure the distance between accumulated NORM and possibly exposed people, and
(iii) maintain shielding material between NORM and possibly exposed people.

It is important to recognize that these measures are only possible in those areas that have known radiation variables and characteristics. That is, they are only applicable in controlled environments. These measures are not viable in cases of random radiological variables and exposure such as the case of different activities in the oil and gas industry.

Accordingly, these measures are not of a preventative nature, but offer advisory options for controlling radiological risks in the oil and gas industry.

Section 5.5.4.2 details a set of measures that can be implemented to respond to internal exposure. The chance of inhalation and or ingestion of radioactive contamination can be managed by implementing the following basic rules. These rules require workers to:

- use protective clothing to reduce the chances of contamination transfer,
- avoid eating, drinking, smoking, or applying materials that may introduce radioactive material into the body,
- use proper protective respiratory equipment to prevent inhalation of radioactive containment,
- restrict airborne contamination and keep NORM wet, and
- use industrial hygiene rules such as hand washing and washing contaminated garments.

Section 5.6, "Waste management considerations with respect to NORM," deals with liquid and solid wastes and their responsible management. According to the report, large quantities of radioactive waste in liquid and solid forms are produced during the extraction and production of oil and gas. It has been found that during the process of decommissioning, decontamination, and rehabilitation of production facilities, the radioactivity concentrations of naturally occurring radionuclides range variously from low to high and have different types of radionuclides. This means that extra caution must be taken by handling the radioactive materials and disposal, and the disposal options may be restricted. Section 5.6.5 briefly sheds light on common disposal methods used in the oil and gas industry when describing disposal procedures for solid and liquid NORM within the industry. Described disposal procedures and disposal methods are not necessarily in line with the best international practices and sometimes based on the sound scientific evaluation. The IAEA stated that previously regulatory safety reviews, as well as oversight and protection, were not thoroughly considered and enforced. Today, the management of waste related to NORM has been distinguished as an area of radiation safety and attendant protection programs, one that requires formal regulations by national bodies responsible for the oil and gas industry. Procedures and methods for disposing of NORM need to be formally addressed as a significant aspect of management programs for radioactive waste. Unfortunately, as it stands, many regulatory bodies cede this consideration to the industry, giving it the right to determine its own methods for disposal. This forces the oil and gas industry to run as its own regulatory body. The industry may determine which disposal methods they view as convenient and economical, as well as safe, rather than adhere to scientifically based solutions. In ideal situations, this report requests the industry that they should try to meet the following standards:

- to reduce the radiological risk for humans and the environment associated with a given disposal manner in an economically efficient manner,
- to adhere to occupational and public dose limits according to the ALARA principle, and
- to follow and adhere to all the related regulations and guidelines formed on the national as well as the international level.

IAEA Safety Report 34 outlined four methods for NORM waste disposal:

1. Dispersal and dilution of the gaseous or liquid radioactive wastes in the environment.
2. Containment of the radioactive wastes at the authorized waste disposal area.
3. Processing of wastes with other chemical wastes via incineration or other methods.
4. Disposing of waste by sending it back to its primary source, for example, reinjection into the reservoir.

Lamentably, this report indicates that NORM waste may be disposed of as nonradioactive (normal) waste in consonance with the criteria for the clearance of NORM waste, which can be found in Clearance Levels for Radionuclides in Solid Materials: Application of Exemption Principles (IAEATECDOC-855, Vienna—1996). Many scholarly studies have revealed that nuclear radioactive wastes produced by many oil and gas industries were exceeding the exemption limits set by the IAEA and are often disposed of as nonradioactive wastes. This arises due to both limited knowledge on the part of the industry, regulatory bodies and authorities, as well as due to the lack of auditing.

Furthermore, in Section 5.6.5.2, the IAEA states that risk assessment is a key component in selecting NORM waste disposal methods. While this assessment can be qualitative or quantitative, many industries, such as in the United Kingdom, focus on qualitative risk in selecting a disposal method. This type of qualitative risk assessment often relies on historical data and assumptions that may not be appropriate in the presence of a scientific revolution. It introduces, therefore, a significant element of inaccuracy and unreliability. Indeed, risk assessment alone is not a substantial basis for the selection of an appropriate disposal method as many other factors require consideration. These factors include efficiency, as well as mathematical fate and transport model, exposure pathway modeling, radioactive waste characteristics such as the radionuclides types, radioactivity concentrations, the physical and chemical forms, and half-life of the dominant radionuclide. There are also significant site-specific factors which include climate, geology, and groundwater and surface water characteristics. These have a notable effect on the feasibility of any NORM waste disposal method and procedures that must be included in the decision-making process.

The IAEA in Section 5.6.5.5 offers some examples of disposal methods for formation water that contains radioactive materials, as well as associated risks. These include:

- reinjection into the reservoir,
- discharge into the seabed, and
- discharge into seepage ponds.

Section 5.6.5.6 conversely exemplifies disposal methods used by the industry for sludges and scales:

(i) direct disposal into seawater,
(ii) hydraulic fracturing injection,
(iii) surface disposal,
(iv) incineration, and
(v) deep underground disposal.

According to the IAEA Safety Report no. 34, because of radioactive contaminants and attendant remediation problems caused by disposal methods, some disposal methods may not be suitable.

In Section 7, "Organizational responsibilities and training in the oil and gas industry" the agency underscores the fact that the safety culture of regulatory bodies, oil, and gas operating companies, and service companies are paramount to proper waste management and radiation protection. These service companies include those companies that engage in radiology or affected by radiation, offer work involving gauges, well logging, fishing and milling, hydraulic fracturing, and NORM decontamination. The agency furthermore recommends that even those workers who do not work directly with ionizing radiation, but who may be indirectly affected by it, be trained and educated—this includes, for example, maintenance workers. Appendix III outlines the training courses they advocate for those persons who work with and around ionizing radiation in the industry.

Finally, Appendix I of Safety Report 34 discusses monitoring radiation in the workplace, including general principles for monitoring radiation and different types of instruments for the job. Typically, these instruments are designed to monitor either internal or external exposure from sources such as radiation machines and generators, NORM, and radiotracers. However, these recommendations leave the door open for the industry to interpret for itself which instruments are most applicable to radiation protection. Furthermore, the choice of the proper instrument or the reference level depends on many factors such as exposure conditions, dose rates, and biological effects that are also associated with uncertainty.

6.2.2 Conclusion

The IAEA is dedicated to generating sound standards and guidelines that protect communities and the environment from the radiological issues arising from nuclear energy. It not only regulates the nuclear industry but all those attendant industries that are involved with or affected by radiation risk. One such industry is the oil and gas industry, which is the subject of its 34th report series and described above. The report seeks to foster a mutual understanding between regulatory bodies and the oil and gas industry, as well as within that industry itself to promote radiation protection and responsible management of radioactive waste. The report outlines the best practices of the industry and provides practical guidance for radiation projection. Overall this guideline is very general and based on the best industrial practices. Accordingly, there is an urgent need for systematic and thorough investigations that should be drawn from scientific, quantitative methods. These investigations must address both radiation protections for workers during the extraction and production of oil and gas, as well as appropriate and effectual radioactive waste management processes based on the scientific evaluation rather than best practice. Investigations must, particularly, address the fact that often the wastes generated by the oil and gas industry exceed the exemption levels set by the IAEA. Furthermore, that present methods of radioactive waste disposal in the oil and gas industry lack oversight from a dedicated regulatory body for the industry and, therefore, do not provide adequate protection for workers, the environment, and communities.

6.3 IOGP—Report no. 412: Guidelines for the management of naturally occurring radioactive material (NORM) in the oil and gas industry

The International Association of Oil and Gas Producers (IOGP) constitute the leading forum for the identification and implementation of best practices within the global upstream industry. It is an arena for members to respond to concerns regarding topics ranging from social responsibility, health and safety, security, and aspects of engineering and operations.

IOGP was formed in London in 1974 as the Forum for Oil and Gas Exploration and Production, the organization's goal was to facilitate communications between international regulators and the upstream industry. In 1999, the association adopted its current name (IOGP). Today, its members produce 40% of the world's oil and gas, and it boasts memberships from the majority of the world's publicly traded, as well as state-owned and private, oil and gas companies. Major oil and gas associations and upstream services companies are also members.

As the oil and gas industry is a vital sector that currently supports more than 75% of global energy demands, the IOGP is tasked with developing guidelines to assist the industry in the continued improvement of safety, health, and environmental standards. In 2008, the IOGP's Report no. 412, "Guidelines for the Management of Naturally Occurring Radioactive Material (NORM) in the Oil and Gas Industry" was published and is one example of their attempts to promote knowledge and endorse best industry practices. The report deals with radiation protection in the industry and is offered as supplement guidance to local legislation in dealing with the management of NORM.

6.3.1 An overview

The IOGP Report no. 412, "Guidelines for the Management of Naturally Occurring Radioactive Material (NORM) in the oil & gas industry" comprised of 13 sections, begins with an introduction, Section 1, that first explicates the purpose of the report: to create a road map for the management of NORM and to facilitate uniform implementation of safety practices. To this end, it explains the origins of NORM, provides technical terminology, and expounds the forms of NORM that typically occur in the oil and gas industry, namely sludges, scales, and soluble or suspended particles in the formation water or thin gas films. It also reports on the measured NORM activity concentrations that are ranging from low to high levels. Section 1.6 further outlines the health hazards related to NORM, and details two ways in which industrial workers can be exposed to NORM:

1. Irradiation: external exposure, wherein the radioactive material remains outside of the body.
2. Contamination: internal exposure, wherein the radioactive materials to the body through either inhalation, absorption, or ingestion.

This section goes on to detail the difficulty of obtaining cohesive conclusions on the health effects of exposure to NORM. For example, it notes that "the health effects associated with exposure to ionizing irradiation vary depending on the total amount of energy absorbed, the time period, the dose rate and the particular organ exposed." And, moreover, "chronic exposure to NORM above exposure limits for the general public or following inadequate safety precautions are typically delayed effects such as the development of certain forms of cancer." To a large extent, this is true, but there are many other important factors that play an important role and need to be carefully considered. It is, therefore, important to further study medically the biological effects of NORM exposure. However, the IOGP presents some scientifically controversial conclusions within the section, suggesting that medical surveillance runs as a nonspecific and imperfect tool and that exposure to low doses may be considered safe. The IOGP, therefore, places emphasis on source control and dose monitoring, and undervalues the place of medical surveillance in understanding and controlling the effects of radiation exposure—a place that has been established through decades of scientific research that has likewise proven that even exposure to low dose of radiation can cause damage to DNA and, therefore, poses a serious health risk.

Section 1.7 turns to the environment and examines "Environmental Problems Associated with NORM." However, these problems are reduced to a mere three lines: "Handling, storage, transportation and the use of NORM-contaminated equipment or waste media without controls can lead to the spread of NORM contamination, and result in contamination of areas of land, resulting in potential exposure of the public." This brief summary lacks appropriately detailed or scientific discussion of disposal methods for radioactive waste and the making of associated risk assessments and further ignores safe handling methods, storage, and discussion of transportation, which are all paramount environmental concerns. It also fails to produce scientifically based solutions for minimizing environmental impacts in any transparent or practicable way.

A "Management Process Cycle for NORM" is developed and presented in Section 2. The process cycle focuses on practical and cost-efficient methods for ensuring protection from NORM for industry workers, as well as the public and the environment, and is detailed in Fig. 2. The primary areas for consideration are as follows:

- NORM monitoring and compliance,
- control of NORM-contaminated equipment and waste,

- worker protection and training, and
- development of NORM management guidelines.

Here again, the IOGP's management process cycle seems to be more generic and nonspecific, inviting industry to employ its own radiation protection measures and risk assessments which may not be on par with scientifically developed best practices, nor ensure sufficient protection from radiation. That said, the IOGP does indicate that "NORM management is not an activity that companies can undertake independently, given the contentious nature of radioactivity and radioactive material."

The 3rd section describes components of a NORM monitoring program, which may include: baseline, pre-shutdown, and legacy surveys and operational assessments.

This section has presented important work in clarifying elements of NORM monitoring and surveying that may be overlooked, or otherwise negatively affect the reliability of measurement and associated risk assessments. For example, Section 3.4 deals with "Legacy Contamination Survey" and shows that:

> *Personnel who are required to monitor levels of radiation and contamination associated with NORM should be trained in the use of the instrumentation and the interpretation of the readings/measurements (see Training and Awareness). In this context, there are many important factors which affect the efficiency of radiation detection, as well as personnel who must monitor NORM levels, should be aware of these. For instance, surface coatings of water or oil/grease would attenuate any NORM contamination present on the surface and give a lower than anticipated indication on the detector. Many surfaces may be difficult to directly monitor due to their surface condition or geometry.*

The section also provides a recommendation for appropriate types of radiation detectors for alpha, beta, and gamma emissions. These recommendations, however, should be taken as guidelines rather than an industry standard, as detectors are routinely updated and recalibrated because of the scientific and technology development.

The 4th section offers a useful discussion of "NORM Action Limits." It describes materials that may be exempted from this procedure, such as waste that contains NORM at levels below those listed in Table 4.1 in the IOGP Report no. 412. This exemption level (Bq/g) ranges from 1.1 Bq/g for Ra to 5.5 Bq/g for ^{238}U.

However, numerous field studies have demonstrated that the activity concentration of radioactive waste from the oil and gas industry exceeds exemption levels set by the IAEA and the IOGP. And though the IOGP has set an exemption level for NORM waste, it fails to elaborate or set an industry protocol for what is being done in the case the radioactive waste exceeds such an exemption level. It also fails to direct the industry on regulations that should follow in such a case.

The 5th section details requirements for training and awareness as it relates to NORM. It shows three categories of workers within the oil and gas industry for whom training pertains:

- workers,
- surveyors, and
- supervisors/radiation safety officers.

Figure 5.1 under Section 5 of IOGP Report no. 412 provides a chart indicating the core knowledge topics that are essential for each of these three types of workers, with each training module building on the one above it.

Section 6 goes on to describe 13 steps for NORM decontamination and control procedures, a topic that is further elaborated in Section 9, which sets out the decontamination processes that are most commonly used in the oil and gas industry, due to being cost effective and reliable: simple mechanical/abrasive high-pressure water jetting (HPWJ).

The 7th section categorizes the common industry options for the disposal of NORM waste, which are as follows:

1. land-based management,
2. salt dome disposal,
3. seabed discharge,
4. landfill, and
5. underground injection.

To determine which of these disposal methods is most appropriate, they should consider the following criteria:

- risk,
- technical feasibility,
- cost, and
- general acceptance (regulatory and public).

Although the IOGP outlines these criteria, it does not explain how to evaluate such criteria from a scientific perspective. For example, it does not describe the importance of quantitative dynamic risk assessment, nor does it mention fate and transport models that would allow for an evaluation of the movement and chemical alteration of radiological contaminants to discern the safety of a disposal method.

Section 8 provides a brief discussion of how to control equipment that has been contaminated by NORM and provides a checklist of the minimum requirements for its control. Section 10 moves to a discussion of the

"Worker Protection Requirement." It offers guidelines on safety requirements for workers who are entering NORM-contaminated confined spaces, or who must undertake maintenance works on NORM-contaminated equipment. These recommended requirements are, however, only basic and do not provide sufficient protections for those workers who are exposed to random levels of radiation, as they mostly instruct workers to adhere to the use of Personal Protective Equipment (PPE).

Section 12 focuses on protocols for the transport of NORM-contaminated equipment. Again, the described procedures are general and primarily focus on recommending that NORM materials and contaminated components be moved using "exclusive transport means such as vehicles or boats." It suggests further that organizations keep records of transportation, which indicate:

- description of NORM forms such as sludge, or scale,
- volume/quantity of NORM transported,
- method of transportation,
- destination,
- organization/facility where the NORM waste was generated, and
- any other relevant information.

Lastly, the 13th section recommends that, at a minimum, the oil and gas industry should have support documentation that addresses and clarifies:

- organizational responsibilities,
- NORM monitoring requirements,
- workers' protection and training requirements,
- requirements to control NORM-contaminated equipment, and
- requirements to prevent or minimize workplace contamination.

6.3.2 Conclusion

The IOGP is a leading facet of the petroleum industry's global forum and seeks to achieve the best practices in the service of health, safety, environmental stewardship, social responsibility, and engineering and operations among the oil and gas industry. It has played an essential role in the development of guidelines that facilitate these practices according to the best-known practices. One such report that develops these guidelines is Report no. 412 "Guidelines for the Management of Naturally Occurring Radioactive Material (NORM) in the Oil and Gas Industry."

At only 42 pages, however, the IOGP's Report no. 412 constitutes a basic and brief guideline that operates as a road map for the industry, rather than as an extensive guide to radiological waste management and radiation safety. Furthermore, it focuses on best-known practices, rather than on scientifically based solutions. Accordingly, it may not be sufficient to fully address and develop radiation protection practices and those radiological concerns associated with waste management in the oil and gas industry. Instead, it provides a functional framework for action that requires integration with other sources and further research.

6.4 ICRP: Radiological protection from naturally occurring radioactive material (NORM) in industrial processes

The ICRP is an influential, nongovernmental, nonprofit organization that boasts over 200 volunteer members. Many of the members are leading policy makers working in the field of radiological protection. The Commission's purpose is to offer guidelines and recommendations that mitigate the harmful effects of ionizing radiation, and, furthermore, to offer recommendations and guidance on dose limits. This report summarizes a newly drafted report of the ICRP on "Radiological Protection from Naturally Occurring Radioactive Material (NORM) in Industrial Processes." The report aims to offer a general guideline for all industries that involve NORM, as NORM generates radiological hazards for both workers and the environment that requires protective action. The oil and gas is one such industry that included the report's targeted audience. The ICRP has recently released this newly drafted report to the public for feedback and consultation.

6.4.1 An overview

The report states that managing NORM requires a comprehensive approach, one that both characterizes the hazard and assesses protection strategies already in place to manage it before appraising the need for additional action. A key recommendation of the report is that protection strategies need grading according to the magnitude of the radiological hazard. In this vein, they should select an appropriate reference level for dosage for public exposure, either above or below a few mSv per year, but rarely exceeding 10 mSv. We should select this reference level according to the characteristics of the exposure situation, and specifically the actual and potential exposure pathways, the individual dose distribution, and potential for optimization. Simultaneously, control must be taken of both the workplace and the conditions of work to minimize risk, while further controlling of the workers must be taken when these controls are not sufficient for protection. The report is notable for being the first to address the protection of nonhuman species as part of the environmental assessment and to offer guidelines on this aspect of environmental hazard and impact. It suggests that hazard management should incorporate the identification of exposed organisms using relevant derived consideration reference levels (DCRL) and should determine options for exposure control and by appraising the magnitude of the hazard and its potential impact.

The newly proposed guidance on industry assessments of radiological hazard and attendant protections comprises five chapters. Following the introduction, which talks about other relevant publications from the ICRP, Chapter 2 offers a synopsis of the characteristics of NORM exposure, surveys those industries and practices that engender NORM and potentiate NORM exposure, and describes elements of the NORM cycle. Chapter 3 applies the Commission's system for radiological exposure to situations involving NORM and clarifies types of exposure situations, categories of exposure, and basic principles to be applied for exposure management. Chapter 4 provides guidance on implementing radiological protection for industry workers, the public, and the environment, with specific attention to taking a graded approach. The final Chapter 5 iterates the Commissions' conclusions. An appendix, which elaborates activities that may involve NORM exposure, is offered as an addendum to Chapter 2.

The report's introduction highlights prior developments in, and ICRP publications related to, radiological protection. Item (4) describes Marie Curie's identification of radium and polonium in 1898 but suggests that it was not until nearly a decade later, in the 1980s, that the health, safety, and environmental risks posed by radiation exposure to NORM were widely realized. An important moment in generating this realization was the ICRP's Publication 26 (1977), which stated that certain practices may "increase the level of exposure from the natural background of radiation and that there may be levels of natural radiation that might have to be controlled in much the same way as for artificial sources." The Commission did not at that point, however, offer practical guidance on how to accomplish such control. This guidance did not come until Publication 39 (1984) and the subsequent Publication 60 (1991) of the ICRP, which defined principles for limiting working exposure to natural sources of radiation and, specifically, primordial radionuclides and progeny. Consideration of the prolonged exposure of the public to natural radiological sources followed in 1999, with Publication 82. This publication was the first to use the term "NORM," and noted that "industrial development has further increased the 'natural' exposure of people by technologically enhancing the concentrations of radionuclides in naturally occurring radioactive materials (NORMs)."

It integrated the principles of Publication 60 with a prolonged exposure model and the principle of optimization, which expounded in a 2006 publication entitled "The Optimization of Radiological Protection: Broadening the Process." This paper proposed that dose limits and constraints were applied to NORM exposure though it maintains that they can be applied with "care and flexibility."

The system of radiological protection advanced in Publication 60 has, however, since been revised. A 2007 paper, Publication 103, proposed a new approach wherein an assessment of the characteristics of the radiation exposure situation is to be undertaken, rather than simply implementing the previous process-based model. Such a system is to be applied in its entirety to situations in which the source of exposure or dosage pathway may be controlled but is also applicable to any exposure situation. This shift is significant because it places all exposures, including those that arise from naturally occurring sources, within the scope of a management system wherein justification and optimization need be considered.

In that same year, 2007, Publication 104 addressed another problem of exposure management: the need for international consensus. It acknowledged that industries have variably regulated radiological protection, because such protections have only been understood recently and, furthermore, because the potential for radiation exposure has already been limited by other hygiene procedures such as the control of airborne dust. The publication, therefore, advanced a graded approach to NORM exposure management that considered risk alongside prevailing circumstances.

The ICRP's recently drafted report continues its long history of awareness building and offering management guidance by turning its attention to appropriate reference levels on the dosage for workers and exposure control for nonhuman species too.

Chapter 2 describes how both human intervention and new technologies adopted in the processes in industry potentiate and enhance radiation exposures because of NORM enhancement. Comprehensive reviews of industry-related radiation exposure and its effects on workers, the public, and the environment have undertaken the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 1982 and 2008, the European Commission (EC) in 1999, the International Atomic Energy Agency (IAEA) in 2006, and the European Atomic Energy Community

(EURATOM) in 2013. The ICRP defines industries that may or may not be of radiological concern depending through evaluating activity concentrations in raw materials, adopted processes, final product usage, and recycling and disposal methods. An assessment of these criteria aligns with the corresponding studies' shows it exposes the workers involved in an array of activities and are exposed to radiological risks. This report is very generic because it is designed for all industries working with NORM.

The ICRP's recently drafted report continues its long history of awareness building and offering management guidance but this time by turning its attention to appropriate reference levels for dosages for workers and exposure control for nonhuman species too.

Those working with NORM in the oil and gas industry are at risk for both external and internal radiation exposure. Exposure is of particular concern for those who are dealing with equipment internals, slags, scales, and sludges, as this work may involve external or internal exposure at a low to a high radiation dose rate. Despite this and other avenues for exposure that have created a long-existing potential for risk, it was, however, not until 1996 that the international community fully assessed that occupational exposure. This assessment occurred due to the implementation of the International BSS. Tables 2.1 and 2.2 used by the ICRP in this report grew out of the historical development made by such a standard. They indicate exposure ranges for workers in a range of industries, and they have extracted dose assessments for members of the public from IAEA reports from 2006 and 2010. Although useful, these numbers are, however, not in line with recent studies specific to the oil and gas industry, due potentially to data quality, and offer a conservative picture of exposure.

Conservative data aside, the ICRP has continued to promote radiation protection and to develop frameworks for environmental protection as well. Unfortunately, outside of uranium mining activities, there have been few assessments of the impacts of NORM. These potential impacts require further investigation, as do exposure ranges.

It describes the NORM cycle in Section 2.2, alongside relevant information for industry workers. Some key issues for awareness and further study include:

1. That if not properly managed, significant radiological exposure of workers, the public, and the environment may occur due to the presence of NORM with elevated radionuclide concentrations.
2. That in some situations, the by-products and residues from one industry may be used as feedstock for another. Materials are also reused as a matter

of common practice. As NORM can, therefore, be moved and reprocessed from industry to industry and location to location, exposure can be enhanced.

Chapter 3 "Application of the Commission's System of NORM Protection" describes the three types of radiological exposure situations, alongside a set of attendant recommendations for their management. The three types of exposure situations are as follows:

1. existing exposure situations,
2. planned exposure situations, and
3. emergency exposure situations.

The ICRP advocates they manage the exposure situations through the principle of optimization via congruous dose criteria. In instances of the first exposure situation, however, the principle of optimization for dose limits is not relevant, as the source of radiation establishes before deciding the control. The dose is, therefore, the reference level. The implementation of a protection strategy will also, in this instance, require time.

In situations of environmental protection that implicate the nonhuman species, the ICRP recommends that they should base reference levels on DCRL.

In all types of exposure situations, however, the objective is to design and implement a standard of protection that is commensurate with the level of risk. Accordingly, this guideline advocates for a graded approach in undertaking risk management. This approach places considerations of risk alongside practical concerns such as economics and social responsibility. As these industries often play a significant role in their local economies, the ICRP acknowledges that it must place economic considerations alongside other concerns for responsible management. Furthermore, as these industries often generate a significant amount of waste with limited options for management and disposal, the costs for regulations that ensure reduction of exposure and moderate dose levels must also be given due consideration. However, an economically based approach must be in parity with science, lest the goal of promoting radiation protection be undermined by fiscal considerations. A purely economically based approach would leave industries open to capricious standards for management.

In this vein, however, the ICRP offered some controversial conclusions within this chapter. It states that "doses resulting from the process in which NORM is concentrated are expected to remain relatively low whatever the circumstances," which is somewhat at odds with their model of exposure situations and their prior conclusions. Furthermore, the ICRP concludes that:

The imaginable scenarios of loss of control of the radioactive material in industries involving NORM resulted in a limited impact in terms of doses and subsequent sanitary effects such as tissue reaction or immediate danger to life. Consequently, industries involving NORM present no real prospect of a radiological emergency, and thus are not likely to give rise to an emergency exposure situation, but releases and discharges may cause in environmental damage.

This is a generalized and preemptive conclusion that has not been substantiated by biological, epidemiological, or laboratory studies. Such studies have demonstrated that even low doses of radiation can damage DNA and, thus, have a biological effect. Accordingly, the issue of low-dose exposure requires further scientific investigation, as do various factors related to its proper management, before they can make this conclusion.

This is not the only controversial claim presented in Chapter 3. Elsewhere, the ICRP suggests that occupational dose limits need not apply to workers who are not considered occupationally exposed. That is, that dose limits do not apply in situations where NORM is present without intentional purpose and exists as a natural fact. However, NORM may have health and safety effects whether exposure is extrinsic or adventitious. In Publication 126, which draws from Publication 65 (2014), it indicated workers would not be considered occupationally exposed, and they should treat the members as part of the public. However, elsewhere in that same guideline, it indicated that the exposure should consider the workers.

Within the oil and gas industry, many scholarly studies have demonstrated that exposure of workers ranges from low to high-dosage levels arising from different types of radiation. Therefore, the question of received dosage cannot be generalized across the industry, nor can a single standard for occupational exposure be implemented. Furthermore, the ICRP suggests that the purview of industry management to consolidate radiation risk management with appropriate safety procedures for radiological hazard management. In this way, it suggests that all hazards should address industry standards for workplace health and safety. This strategy, however, has the potential to create conflict with international safety standards, regulations for the worker and public exposure, and the application of appropriate dose limits for the oil and gas industry specifically. We need to place greater emphasis on cooperation with the scientific and international community.

Another area where the report generates potential contention is in its principles for decision-making. We should base the principles for decision-making procedures for radiation protection on justification, optimization, and limitation. These principles state that we shall introduce no practices unless they yield a positive net benefit. They also demand that exposures maintain at levels that are ALARA, that individual doses not exceed the limits recommended for the circumstances by the Commission, and that consideration is given to economics and social responsibility. Despite being well intentioned, however, these three principles remain controversial within the scientific communities due to their necessary and attendant elements of uncertainty. A special concern is the scientific, quantitative analysis of what constitutes low, achievable, and safe.

Recent studies argue that the question of dose limit is, in itself, contentious. These studies posit that the dose limit is not adequate to ensure protection against radiation since the biological effects of radiation are stochastic. They vary from person to person, and even from cell to cell within a single body, as well as from one type of radiation to another. This variation in type further compounds the differences in concentration, energy emitted, the occupancy factor, tissue sensitivity, and so forth. For example, in an equivalent dose of radiation, alpha particles and X-rays would cause biological damage 20 times greater than damage caused by X-radiation, because the weighing factor for alpha particles is 20 times greater than that of X-radiation (Sperelakis, 2001). There are numerous other chemicals, biological, and physical factors that confound dose limits. Even the ICRP itself, which has developed these dose limits, has admitted on a correspondent webpage that "Dose limits alone are not enough to ensure adequate protection. They function in combination with the fundamental principles of justification and optimization."

Chapter 3 closes with the insistence we decide the processes for industries that involve NORM for improved transparency and clarity. This shift would allow for controversial concerns to resolve. The road to resolutions must also populate itself with the opinions of stakeholders, including industry workers and the community. Although it is unlikely that all parties will achieve full agreement, their inclusion is essential to creating informed and equitable policies and practices.

Chapter 4 is about "Implementation of the System of Radiological Protection to Industrial Processes Involving NORM." This chapter identifies three primary exposure scenarios for industries that involve NORM processes. They comprise exposure to large amounts of stockpiled material, such as ore; exposure to small, but concentrated radionuclides, such as scales, sludges, or mineral concentrates; and exposure to material that has undergone high-temperature processes and has been volatilized, such as slag, precipitator dust, or furnace fumes.

It likewise identifies two primary exposure pathways. They comprise external exposure, which generally occurs due to gamma radiation, though may also occur due to beta radiation; and internal exposure, which generally occurs due to inhalation of dust, though maybe also occur less frequently due to ingestion of radioactive dust. Internal exposure may also result from exposure to radon gas and its progeny.

In response to this, the ICRP advocates that a graded approach is necessary for the control of radiation exposures and the protection of workers. Such an approach should consider the annual effective dose of radiation received from activities involving NORM and the necessary scope for dose reduction if the reduction is necessary. Implementation of this approach, is, however, challenging. The ICRP notes that the diversity of industries involving NORM means that no standard numerical value that may act as a reference level for all of them. We must select a proper reference level according to the characteristics of the exposure situation, with attention to actual and potential exposure pathways, individual dose distribution, and the prospect for optimization. Generally, this annual dosage should be below a few mSv, or slightly above that, but should rarely exceed 10 mSv, and that only when required by the circumstances involved.

In Section 4.2.2, which is about "Waste" the ICRP describes disposal methods for NORM waste. It indicates that the method for disposal should reflect the type and level of hazard that the waste poses, as determined by considering both the radioactive and nonradioactive pollutants present. We recommend a graded approach that considers the level of radioactivity and the volume of waste. The ICRP recommends that waste with high concentrations of radionuclides should be disposed of in a manner consistent with the management of radioactive waste, while other waste may be treated as industrial or hazardous and be disposed of appropriately in near-surface landfills.

Section 4.3 "Protection of the Environment" details the optimization process. It states that this process should assess environmental protections, including the protection of nonhuman species.

6.4.2 Conclusion

ICRP concludes that NORM present in the industrial process is a significant issue for radiological protection. It recognizes that the question of its proper management has been of concern for decades, and involves ethical considerations related to justice and equity in industries that have significant economic, environmental, and human impacts. Overall, the drafted guideline is generic to apply to all industries involved with NORM; it is not specifically designed for the oil and gas industry.

While doses of radiological exposure in industries involving NORM are variable, they can nonetheless be comparable, and sometimes greater than, other human activities where systems for radiological protection are already applied. Industries involving NORM are licensed, but frequently not for radiological purposes. Despite the long history of these industries, a concern with radiological protection has only recently been understood as necessary and developed accordingly. As such, they typically have a poor awareness of radiological protection. This awareness can and should be developed to implement a set of radiological protection procedures.

The ICRP, therefore, recommends greater control of industries involving NORM. They must implement systems of protection, which incorporate principles of optimization and justification, and dosage criteria. Stakeholder involvement from workers and the public in these decision processes is also key. The ICRP's proposals also require further clarification and investigation through scientific review to ensure reliable guidance that able to provide adequate protection against radiation.

6.5 Conclusion

Over the past few years, the world has witnessed a rise in the production of hydrocarbons to meet a global increase in energy demand. Since radioactive materials are found, geochemically, in hydrocarbon-containing reservoirs, and as a result of the increase in the oil and gas production to meet global energy demands, production of radioactive waste is also increasing. Existing research indicates that these hazardous radioactive wastes pose a serious threat to workers' health, society, and the environment. Current disposal methods constitute not only an environmental concern but also a public health hazard. The environmental consequences that associate with the processing of oil and gas, including radiological risks, are highly contentious and are furthermore becoming politicized because many countries around the world rely, to a large extent, on oil and gas as the major drivers of their economies.

A major point of impasse is the fact that state-controlled oil companies are not fully aware of the environmental dangers associated with the radioactive waste that forms during the extraction and production of oil and gas.

Companies further show a lack of enthusiasm for revealing their strategies and specific details related to radiological protection and for waste disposal methods. We can attribute this lack of temerity to a lack of knowledge and the lack of dedicated safety standards and regulation. On the other, they can attribute it to the economic and political interests that often dominate social concerns raised regarding environmental or worker protections. These factors motivate some oil and gas companies to conceal information regarding radiation protection and radioactive waste dumping in some countries.

This chapter has highlighted how the issues of radiation protection and radioactive waste disposal have been approached in the oil and gas industry, and what improvements can be made to existing safety standards and regulations. It also outlines what role international atomic agencies currently play in regulating and legislating radiation protection and radioactive waste disposal. Furthermore, it posits the need for a scientific approach to examining the efficiency and efficacy of current standards and regulations, with attention to the controversies and inconsistencies that exist in the characterization of nuclear radioactive materials and their waste management in the oil and gas industry, as well as the variation between the actual practices of state-owned companies and theoretical and regulatory guidelines.

This chapter has outlined the role of well-known international atomic and radiation agencies in regulation and legislation. Such regulatory and legislative reports include the IAEA's Safety Report no. 34 "Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry; Guidelines for the Management of Naturally Occurring Radioactive Material (NORM) in the Oil and Gas Industry" (2003), the IOGP's Report no. 412 "Guidelines for the management of Naturally Occurring Radioactive Material (NORM) in the Oil & Gas Industry" (2008), and the ICRP's drafted "Radiological Protection from Naturally Occurring Radioactive Material (NORM) in Industrial Processes" (2019).

The IAEA is dedicated to developing standards and guidelines to protect workers, the general public, and the environment from radiological issues arising from nuclear energy. It not only regulates the nuclear industry but also all those attendant industries that are involved with or affected by radiation risk. Oil and gas are one such industry, and constitutes the subject of its 34th Report Series, which is described above. The report seeks to foster a mutual understanding between regulatory bodies and the oil and gas industry, as well as within that industry itself to promote radiation protection and responsible management of radioactive waste. The report outlines the best practices of the industry and provides practical guidance for radiation projection.

Overall, this guideline is generic and based on the best industrial practices, rather than on scientific data or justifications. While such genericism can offer a useful framework to implement appropriate safety measures, there remains an urgent need for systematic and thorough investigations drawn from scientific, quantitative methods. These investigations must address both radiation protections for workers during the extraction and production of oil and gas, as well as appropriate and effectual radioactive waste management processes. Investigations must, particularly, address the fact that often the radioactive wastes generated by the oil and gas industry exceed the exemption levels set by the IAEA. Furthermore, they must address those present methods of radioactive waste disposal in the oil and gas industry lack oversight from a dedicated nuclear regulatory body for the industry and therefore, fail to provide adequate protection for workers, the environment, and communities.

Moreover, the IOGP constitutes a leading association within the petroleum industry. It is a global forum for that industry and seeks to achieve best practices in the service of health, safety, environmental stewardship, as well as in social responsibility, and engineering and operations. It has played an essential role in the development of guidelines that facilitate these aims, but here again, its guidelines and recommendations have been based on the best-known practices and not on scientific approaches.

The IOGP's Guideline Report no. 412 is concise, comprising only 42 pages. It constitutes, therefore, only a succinct, collective guideline that can operate as a road map for the industry, rather than as an extensive model that is able to address radiation protection and radiological waste management from a scientific perspective or offer robust science-based solutions. Accordingly, it may not be sufficient to devise practices for industry-specific processes for radiation protection and radiological waste management. Instead, it provides a functional framework for action that requires integration with other sources and further research.

Finally, the ICRP is an independent, international, nongovernmental organization, whose mission is to provide recommendations and guidance on radiation protection. They consult the guidelines and recommendations in many industries concerned with radiological issues and protections. Their recommendations on dose limits are particularly influential. Accordingly, the ICRP has developed a new guidance publication for "Radiological Protection from Naturally Occurring Radioactive Material (NORM) in Industrial Processes," (2019) and has recently released a drafted report to the public for consultation. The proposed new guidance has been designed to generically address radiological protection issues for industries involving NORM and is not specific to any one particular industry. The report is notable for being the first to address the protection of nonhuman species as part of an environmental assessment and to offer guidelines on this aspect of environmental hazard and impact. It comprises of five chapters.

The ICRP has, in its proposed new guidance, offered some significant and contradicting conclusions. It stated that NORM produced and exposed during industrial processes may be an issue from a radiological protection point of view; this is in contradistinction in another place where it has indicated that NORM merely constitutes background radiation and poses no risk. It also recognizes that these are sizeable industries that play significant roles in their local economies; therefore, fiscal concerns related to industry practice may have far-reaching effects. Accordingly, it recognizes that the way to address radiological protection in industries involving NORM, and that economic and health concerns have been a concern for some decades.

Nonetheless, it concludes that is a matter of justice and equity, key ethical values to consider when addressing radiological protection, that we limit radiological and other chemical hazards. Doses from industries involving NORM are variable, but they can be comparable to, or greater than, those arising from other human activities wherein systems of radiological protection are already applied. Addressing this is not only a health concern but also an ethical one.

Furthermore, the ICRP indicates that industries involving NORM are generally licensed, although in most cases not for radiological purposes. They should, therefore, be able to apply a set for radiological protection procedures. However, their experience is limited in this field. Despite industries being active for decades, concerns about radiological protection are relatively recent, and industries generally have poor awareness of radiological protection. Such radiological awareness needs to be fostered and mandated. Thus, the ICRP recommends that industries involving NORM need to be controlled. A system of protection, which incorporates the principles of justification and optimization in deciding upon protections, as well as corresponding dose criteria and requisites, should, they conclude, be applied. The involvement of the relevant stakeholders in decision-making processes is also crucial.

Overall, their drafted guideline is generically designed for all industries involved with NORM and is not specific to the oil and gas industry. Furthermore, it contains many controversial conclusions that have not been adequately tested through scientific inquiry. Accordingly, this report still requires further scientific review. Specifically, dose limit and ALARP recommendations need addressing as they are a subject of great scientific debate in the scientific community especially as they concern the oil and gas industry. Whereas, they always associate radiological issues in this industry with random variables, as well as they are always time function variables. We must verify the conclusions through detailed scientific assessment, and consider via quantitative risk assessment, and dynamic modeling.

A new scientific approach is required to generate a paradigm shift in guidelines and regulations formulation. New, reliable guidelines, regulations, and policies must be based on the physicochemical characteristics of radioactive materials generated from the oil and gas industry that can differentiate between NORM and TENORM, rather than merely on what have historically been best industry practices or conservative assumptions. New measures to protect the workers, public, and the environment must be mandatory and should not be left optional, nor up to the subjective interpretation of the industry itself. Policies must be designed for the oil and gas industry within a legal framework and made subject to monitoring by an independent radiation protection authority. The international atomic agencies must work toward this goal to control radiological pollution and contaminants from the oil and gas industry, as well as other industries, and to establish security for communities, future generations, and the environment.

References

AP1, 1989. A National Survey on Naturally Occurring Radioactive Materials (NORM) in Petroleum Producing and Gas Processing Facilities. API, Dallas, Texas.

EPA, 2019. Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). and available from: https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm. (Accessed 18 January 2019).

Gazineu, M.H.P., Araujo, A.A., Brandao, Y.B., Hazin, C.A., Godoy, J.M.D.O., 2005. Radioactivity concentration in liquid and solid phases of scale and sludge generated in the petroleum industry. J. Environ. Radioact. 81, 47–54.

Health Canada, 2013. Canadian Guidelines for the Management of Naturally Occurring Radioactive Materials (NORM). and available from: https://www.canada.ca/content/dam/hc-sc/migration/hc-sc/ewh-semt/alt_formats/pdf/pubs/contaminants/norm-mrn/norm-mrn-eng.pdf. (Accessed 16 January 2019).

IAEA, 2003. Safety Report no. 34, 'Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry: Guidelines for the Management of Naturally Occurring Radioactive Material (NORM) in the Oil and Gas Industry. and available from: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1171_web.pdf. (Accessed 14 January 2019).

ICRP, 2019. Drafted Report on 'Radiological Protection from Naturally Occurring Radioactive Material (NORM) in Industrial Processes. and available from: http://www.icrp.

org/docs/Protection%20of%20the%20Environment%20under%20Different%20Exposure%20Situations%20(for%20consultation).pdf. (Accessed 12 January 2019).
International Energy Agency, 2019. Global Energy Demand Grew by 2.1% in 2017, and Carbon Emissions Rose for the First Time since 2014. and available from: https://www.iea.org/newsroom/news/2018/march/global-energy-demand-grew-by-21-in-2017-and-carbon-emissions-rose-for-the-firs.html. (Accessed 21 January 2019).
IOGP, 2008. Report no. 412. 'Guidelines for the Management of Naturally Occurring Radioactive Material (NORM) in the Oil & Gas Industry. and available from: https://www.rp-alba.com/resources/412.pdf. (Accessed 10 January 2019).
Neff, J., Lee, K., Deblois, E., 2011. Produced water: Overview of composition, fates, and effects. In: Produced Water. Springer Science & Business Media, pp. 1–52 ISBN: 1461400465, 9781461400462.
Rood, A.D., White, G.J., Kendrick, D.T., 1998. Measurement of Rn-222 flux, Rn-222 emanation and R-226 Ra-228 concentration from injection well pipe scale. Health Phys. 75, 187–192.
Sperelakis, N., 2001. Cell Physiology Sourcebook: A Molecular Approach. Elsevier, pp. 1–1235.
The UK Government, 2016. UK Strategy for the Management of Solid Low-Level Waste from the Nuclear Industry. and available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/497114/NI_LLW_Strategy_Final.pdf. (Accessed 14 January 2019).

CHAPTER SEVEN

The importance of public participation in legislation of TENORM risks management in the oil and gas industry

Chapter Outline

7.1 Introduction

Since the 18th century, several modern and postmodern states have emerged. Even though some of these states appear to be democratic, they are authoritarian by nature, leading to an increase in emerging market governments that are not content with regulating markets but also wish to dominate them. Promoting state-corporate activity is a significant source of wealth generating a significant return on the investments of the state.

Nuclear Radioactive Materials in the Oil and Gas Industry
https://doi.org/10.1016/B978-0-12-816825-7.00007-8

When measured by the reserves they control, the biggest energy companies worldwide are either fully or partly owned and are operated by the government. Government-operated companies, commonly called state-owned companies (SOEs), control about 75% of the world's crude oil production.

Apparently, the state-controlled oil companies are not fully aware of the environmental dangers associated with radioactive waste coproduced along with the extraction and production of the hydrocarbons. Furthermore, the same corporations are rarely enthusiastic in revealing their plans or strategies for the management of radioactive wastes that are produced daily in massive quantities. The attribution of such behaviors is based on the political and economic interests that may trump and dominate social concerns that are projected regarding the environmental consequences. This could reveal why the inadequate disposal methods used to get rid of radioactive waste issues in the oil and gas industries are subtle and concealed from the public. Therefore, the radiological issue becomes a serious public issue.

Unfortunately, there is a lack of public participation in the formulation of safety laws and policies in the oil and gas industry. At the same time, the technological risks associated with the production of oil and gas is increasingly politicized and highly contentious. While this is also due in part to a lack of public knowledge about these risks, it is also the result of government efforts to maintain the highest level of state income to ensure continuity of power at the expense of the public interest. These efforts have destabilized trust in political systems (Fig. 7.1).

The significance of trust and the link between national participation and the dynamics of the political systems have serious implications regarding technological risks, particularly in the oil and gas industry, which is recognized as the biggest economic sector both globally and locally. It is important to further investigate from legal and technical perspectives to what extent the current radiological risk management system can protect workers in the oil and gas industry, the public, and the environment from radiological exposure.

7.2 An overview of radioactive wastes in the oil and gas industry

Scholars such as Al-Farsi (2008) have reported that the discovery of radioactivity associated with the extraction and production of oil and gas goes back more than 100 years. Radioactive wastes are hazardous substances that are comprised of radionuclides belonging to the Uranium and Thorium

Fig. 7.1 Political conflicts and public distrust.

series. These materials are nuclear constituents according to the nuclear sciences as well as the International Atomic Energy Agency. These radioactive materials produce different types of radiations, such as alpha, beta, and gamma emissions or in forms of discharging harmful gases into the atmosphere, such as Radon. Exposures to these radiations are likely to cause chronic cancerous illnesses, and this could be one of the causes of the spread of cancer in the era of oil and gas.

Despite these facts, unfortunately, some of the associated regulations and industries producing radiological pollution are having an ambiguous understanding about the characterization of these materials or have a tendency of avoiding describing them as nuclear materials again for political and economic reasons. This is because most countries in the world rely exclusively on oil and gas production to drive their economies.

Therefore, the environmental dangers that arise from the disposal of nuclear radioactive wastes in the oil and gas industry have been gradually politicized over time. It comes because of the powerful influence that facilitates the economic benefits by dominating the political ecology. This is scientifically called the philosophy of utilitarianism. For instance, the United States-North Dakota Department of Health Division of Waste Management strives to persuade the public that technologically enhanced radioactive materials emanating from the oil and gas industry are not inherently bad or hazardous (NDDOH, 2015).

According to Janssen et al. (1998), radiation emissions from the nonnuclear industries are as significant as the discharge from nuclear production. It is estimated that it is potentially three times more harmful than the emissions from the nuclear industries. Consequently, radiation wastes produced from extractions and refining of oil and gas present a grave peril to both the individuals and the environment.

Currently, most organizations and legislations have characterized radioactive materials produced from oil and gas industries as naturally occurring radioactive materials (NORMs) with lower risks. While these materials are scientifically characterized as nuclear wastes since radiation occurs from unstable atoms to get rid of its excess energy in the form of energy or particles emissions, as well as such materials belong to uranium and thorium series decays that have been classified by IAEA as nuclear materials.

Thus, exposure to these materials may pose a significant danger and may differ from various perspectives based on cell responses and level of radioactivity received, as well as the duration of exposure. This could be one of the reasons for the misunderstanding in looking into this specific matter from a regulatory point of view.

For instance, there are no dedicated political ecology policies in Canada governmental or provincial levels that regulate technologically enhanced radioactive wastes produced from a nuclear perspective. The available policy instruments for both the federal, provincial, and municipal, such as The Government of Canada's Radioactive Wastes Policy Framework 1996, which was developed by the Federal Provincial Territorial Radiation Protection Committee together with the Nuclear Safety and Control Act (NSCA) (1997). Its associated regulations are primarily comprised of acts, guidelines, and regularity measures, which are designed to regulate management, handling, and disposal for generic radioactive wastes for certain industries, such as nuclear facilities, mills, uranium mines, and hospital usage (CNSC, 2017a).

Besides the federal policies, still, provincial regulations can either refer to it or to their own regulations. However, it is expected that conflicts and inconsistencies could still arise due to the overall availability of different regulations or general guidelines that are not purposely designed for the oil and gas industry. This leaves it open for different interpretations and therefore making industries to become a self-regulation organization. The primary reason is that they were initially designed for nuclear facilities, mills, and uranium mines.

This may lead to a secondary conclusion that the currently available policy instruments are technically and scientifically not adequate to regulate and manage nuclear radioactive wastes. This is because waste from the oil and gas industry is not properly characterized under nuclear waste. The large volume of radioactive wastes generated daily by the industry lack safe disposal methods that can accommodate such huge volumes of nuclear radioactive wastes of mixed different levels of radioactivity concentrations.

An example of inconsistency that may arise if we are trying to apply the current regulations is that according to the Canadian Nuclear Safety Commission (CNSC), NORMs are "exempted from the application of the Nuclear Safety and Control Act and its regulations except when these materials are associated with the development, production or use of nuclear energy or when the specific activity is beyond 70 Bq/g" (CNSC, 2017b). This means radioactive waste produced from the oil and gas industry fall under the Nuclear Safety and Control Act (1997), because they meet the following conditions, which are:

1. Radioactive wastes produced from the oil and gas industry are characterized scientifically as nuclear materials.
2. Moreover, while many organizations and industry characterized them as NORMs, it has been reported in many oilfields and academic studies that the activity concentration of these radioactive wastes produced from the oil and gas industry can reach thousands of Becquerel per gram.

Tab Cuthill general Manager of NORM Services at SECURE Energy Services website, mentioned that the activity concentration levels of oilfield radioactive waste in Western Canadian Sedimentary Basin of Ra226 from Treater Waste found to be more than 600 Bq/g, while for Pb 210 from LPG Waste greater than 17,000 Bq/g (ESAA, 2017). This fact is not only in Canada, but it has been reported in many different oil and gas producing countries around the world. For instance, the US Environmental Protection Agency (US EPA) reported in 1993 that the activity concentration of contaminated radioactive sludge waste produced from the US oilfield reached 25,000 Bq/g.

Hence, there exists an urgent need for developing critical bylaws devoted to limiting and controlling risks of nuclear radioactive waste generated from the oil and gas industry.

7.3 Concerns associated with nuclear radioactive wastes coproduced with oil and gas

According to the US Energy Information Administration-EIA (2017), the regular production of world liquid fuel was estimated to be 99.51 million barrels per day in the fourth quarter of 2017. Massive production of this nature is accompanied by the production of enormous levels of hazardous nuclear radioactive wastes dissolved in the produced formation water. Virtually, formation water production is 10 times the amount of the crude oil production (usually, production of a barrel of crude oil is accompanied by the production of ten barrels of contaminated produced water).

Besides the production of the contaminated produced water, the oil and gas industry also produces thousands of nuclear radioactive materials in the form of scales and sludges. The oil and gas industry usually disposed of radioactive waste directly into the environment. Strand (1999) categorized the current and frequently used disposal methods of radioactive waste disposal in the oil and gas industry into three main elimination categories that are:

- Marine disposal
- Terrestrial disposal
- Injection of wastes into geological formations.

The disposal procedures are extensively employed by several onshore and offshore corporations. For instance, many European countries dispose of their hazardous wastes from offshore drilling and production activities directly into the ocean. While the onshore operations dispose of their hazardous nuclear radioactive wastes in farmlands or evaporation ponds or injecting them into geological formations. This method plays a major role in enhancing the concentration of the existing naturally occurring nuclear radioactive materials and converting them into technologically enhanced naturally nuclear radioactive materials.

In Canada, majority of available federal, governmental or even provincial policies, regulations that are inspired by some important boards such as The Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB), the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB), and the National Energy Board (NEB) are used to regulate the discharge of contaminated produced water during oil and gas production for the Canadian offshore oil and gas industry.

These regulations request operating companies to check and to confirm if the concentration of oil and gas residual in produced water is within limits or not. However, never ask them to check and measure radioactivity concentrations. This may lead to a preliminary conclusion that available governmental or provincial policies regulating nuclear radioactive wastes disposal into the environment by the oil and gas industry are not available and the available ones are not designed for this issue and are not effective or efficient in preventing and protecting against radiological pollution arising.

Therefore, the absence of reliable and effective legislation and regulations aimed at the disposal of radioactive waste in the oil and gas industry is a global issue that threatens the environment and poses a serious health hazard.

7.4 An overview of legislative inconsistencies and political conflicts concerning nuclear radioactive wastes

Some of the related legislation, as well as the industries producing TENORM, tend to avoid anything related to the word "nuclear." TENORM are present in the natural nuclear isotopes produced by radioactive decay from thorium-232 and uranium-238 series, which are abundant in rocks containing oil and gas. In the oil and gas industry, they are enhanced technologically due to the physical and chemical processes used to enhance oil and gas production, which is known by enhanced oil recovery technologies—EORT (Kolb and Wajcik, 1985; Baried et al., 1996; Jonkers et al., 1997; O'Brien and Cooper, 1998; ALNabhani et al., 2015).

Technologically enhanced naturally occurring nuclear radioactive materials are the major source of radiation exposure for the public and the environment. This could happen either through direct exposure pathways or through ingestion and inhalation pathways from contaminated water and soil. In fact, TENORM are highly important as enriched nuclear material generated in the nuclear industry, which may be an indication of why oil and gas companies use the same methods as those used in the nuclear industry to dispose of TENORM waste. The methods of nuclear waste disposal include land spreading and deep injection disposal methods.

According to Janssen et al. (1998), radiation doses' emissions from nonnuclear industries are as important as the emissions from nuclear industries. He also stated that the maximum doses of emissions from nonnuclear industries (such as the oil and gas industry) are greater than the emissions from nuclear industries by more than three orders of magnitude.

The reluctance of TENORM industries to be associated in any way with the term "nuclear" could be attributed to economic and political reasons. Legislation related to nuclear issues is another important reason. Due to the importance of having detailed and safety legislation to accommodate large amounts of waste treatment, storage, and disposal, this eventually becomes both a financial and administrative burden, which governments try to avoid. In addition, the radiological risk from TENORM associated with oil and gas production threatens the health and safety of workers, the public, and the environment.

Therefore, governments are often reluctant to acknowledge to workers involved in the oil and gas industry that they may be exposed to radiological risk or to share their policies regarding radioactive material waste disposal methods and cost-cutting plans with the public, because workers and the public will oppose them.

A glance at the oil and gas industry in the province of Alberta is considered a key component of Canada economy compared to any other province in Canada, largely due to its oil refining industries that contribute around 80% of Canada's oil. Canada has been ranked as the third largest oil reserves, the fourth largest oil exporter, and the fifth largest oil producer in the world. The massive daily production of oil and gas is associated with the massive production of radioactive wastes of different level of activity concentrations that are disposed of directly into the environment.

It is important to investigate if the policies are designed to regulate the disposal of radioactive waste into the environment have been effective or not in addressing the above-mentioned concern or providing enough protection against the effect of pollution from the oil and gas industry. Overall, the provincial government of Alberta, including the CNSC, attempt to ensure that radioactive waste disposal is carried out in a safe, comprehensive, environmentally sound, and in an integrated manner. It develops the policy that regulates and oversees the producers and owners to ensure compliance with the legal requirements by meeting their operational responsibilities.

In this context, the environmental protection policy framework used by the provincial government of Alberta is in line with the federal and provincial standards such as Canadian Nuclear Laboratories (CNL) and Nuclear Waste Management Organization (NWMO) in defining the long-term management and safe handling arrangements that are also distinctively designed for certain categories of high-level radioactive wastes, such as nuclear industry waste, milling waste, uranium mining waste, and nuclear medical waste that fall under the nuclear waste regulations.

However, no program has been specifically designed to manage nuclear radioactive waste generated from the oil and gas industry and instead these wastes are not properly classified or defined. Moreover, the provincial government of Alberta incorporated in its environmental protection policies that low-intermediate radioactive waste producers and owners are responsible for the funding, organization, transporting and management of disposal as well as other facilities that are required for generated wastes (CNSC, 2017).

From the perspective of nuclear waste management, the Alberta government indicted in 2009 that its policies related to nuclear radioactive management must meet federal and provincial standards and regulations such as Nuclear Safety and Control Act also designed to regulate the disposal, storage, and management of nuclear radioactive wastes like the CNSC.

While the radioactive waste generated from oil and gas industry meet above condition, they are not explicitly or implicitly considered under nuclear radioactive waste regulation or act and instead, this has led to arguments whether waste from oil and gas industry should be classified as hazardous waste or not. It seems surprising in Alberta that any waste regulated under the federal NSCA is not defined as "hazardous waste." The provincial waste management policy in Alberta is governed primarily under section 9 of the Environmental Protection and Enhancement Act (EPEA) requiring the approval for harmful waste disposal, for the collection, transportation, generation or disposal of any harmful wastes with current practices of oilfield waste management. This act allows the producer to be responsible for his waste' handling and management according to the disposal of the hazardous waste code of practice.

Thus, these inconsistencies raise unanswered questions whether the radioactive and hazardous waste produced by the oil and gas industry are potentially regulated and considered as ordinary waste under the Alberta EPEA. While scientifically, oil and gas radioactive waste is supposed to be regulated under nuclear radioactive waste regulation.

Since there is no decisive classification for the radioactive waste coproduced during oil and gas extraction and production, this leaves the door wide open for personal interpretation that makes us to be in imminent danger. This is also obvious even with the industries that classified oilfield wastes as NORMs; still available policies are general and ambiguous. For instance, while investigating the Directive 058: Oilfield Waste Management Requirements for the Upstream Petroleum Industry (2006) issued by Alberta Energy Regulator (AER), it stated under section 32.2 that "Naturally Occurring Radioactive Materials: NORMs are not within the scope of the Atomic Energy Control Act administered by the AECB. Jurisdiction for the control of NORM rests with the individual provinces. The options are basic in nature and do not give specific criteria for the handling treatment or disposal methods for the NORM material" (AER, 2006).

Another example of policies inconsistences seen clearly in the Province of Alberta's Radiation Protection Act that was revised in 2000. This act regulating radiation exposure risks in general and stated in clause 12 (1)

"The owner of radiation equipment that produces ionizing radiation shall ensure that 1. (a) Exposure of persons to ionizing radiation is kept as low as is reasonably achievable" (Alberta Radiation Protection Act. of 2000, 2017). While scientifically, ALARA is a debatable issue because it invokes the doctrine of utilitarian philosophy, which states that the best behavior is the behavior that achieves maximum increase in benefits even if there is little damage as well as that ALARP associated with high levels of uncertainties to identify and prove a low, reasonable, and safe radiological exposure limit because available international safety standards failed to standardize a certain safe exposure limit due to the fact that each dual's living cells have different responses to different radiation levels according to American National Research Center (USNRC, 2003).

This leads to a more fundamental conclusion that available policy instruments are not appropriate to regulate and manage nuclear radioactive wastes emanating from the oil and gas industry due to inconsistency and ambiguity.

Another area of inconsistency to be discussed is the issues of the exploration of oil and gas in the Niger-delta region of Nigeria that is well known for its abundant oil and gas (Aniefiok et al., 2016). Over the last 55 years, approximately 1182 exploration wells have been drilled to date in the Delta Basin, and approximately 400 oil and gas fields of different sizes have been developed. Avwiri and Ononugbo (2011) assessed the NORM content encountered during hydrocarbon exploration and production in Ogba/Egbema/Ndoni fields and concluded that NORM has been enhanced technologically in the oil-bearing community because of the adoption of new technologies to enhance oil and gas recovery.

In this context, each stage of petroleum exploration, development and production, decommissioning and rehabilitation, and transportation and distribution operations often result in significant environmental impacts because of the release of huge quantities of nuclear radioactive waste to the environment. In principle, the Niger Delta region in Nigeria is mainly governed by three types of licences that could be easily obtained, which are: the Oil Prospecting License (OPL), Petroleum Exploration License (OEL), and Oil Mining Lease (OML). These licenses allow national and international oil exploration and production companies operating in Nigeria to exercise their activities freely. Because of this and in addition to unsafe nuclear radioactive waste disposal by the oil and gas industry, several environmental impacts have been seen clearly in the Niger Delta region, such as forest and soil disturbance following geological and seismic surveys, deforestation for road construction, tank farms, pits and pipelines, exploratory drilling, development and production drilling, and construction of treatment facilities.

In addition to the environmental damage associated with noncompliance with sustainable development policies and Multilateral Environmental Agreements (MEAs), there are several cumulative impacts associated with oil exploration and production activities in both the onshore and offshore fields of the Delta region including direct disposal of nuclear radioactive waste generated from oil and gas industry into the environment. Accordingly, current waste disposal methods adopted by the oil and gas industry in Nigeria have resulted in environmental pollution and potential risk to the atmosphere, soils, sediments, surface and groundwater, the marine environment, and the terrestrial ecosystems of the delta's host communities.

The main sources of environmental pollution in the Niger Delta region include oil spills, pipeline explosion, gas evacuation, drilling muds, oily and toxic sludge, sabotage of oil facilities (including illegal oil bunkering and artisanal refining), oil well blowouts, oil dumps, and other operational releases. It is true that the export of petroleum resources has contributed immensely to the Nigerian economy over the last 55 years. However, the past and the present oil exploration and production have undermined important human rights, such as the provision of enough protection to their health and environment. This is due to the lack of reliable legislation designed for the oil and gas industry including regulation of the nuclear radioactive waste disposal methods currently used by the oil and gas industry.

On the other hand, if we look at the history of British politics, the legislative and decision-making processes in relation to risks associated with nuclear radioactive waste have been full of contradictions and often opposed by the public. Nuclear radioactive waste became an object of concern in 1975 as public knowledge began to grow over the operation of Wind scale and the possibility of Britain becoming a global nuclear dump for the processing of 4000 tons of Japanese nuclear waste.

By the end of the 1970s, nuclear waste had become a source of political conflict in Britain. In 1979, the pronuclear government of the United Kingdom continued disposing of nuclear radioactive waste into the sea, even under political pressure. At first, participation in the debates concerning the wind scale inquiry was only limited to experts, but when nuclear waste moved from being a generic issue to the specific question of finding disposal locations for the nuclear radioactive wastes, protests dumping policies emerged from environmental groups and local communities.

As more and more people participated in the protests, the balance of power shifted away from the government and the nuclear industry. Thus, the protests ensured that eventually, decision-making regarding waste management met the demands of the public. In 1981, the local communities succeeded in shutting down the High-Level Waste borehole drilling program, a major success for the protestors. Later, in 1983, protestors in various countries again succeeded in stopping industries in Britain from dumping nuclear waste into the sea.

William Waldegrave argued against this decision in Parliament and emphasized that the government made its policy to dump nuclear waste at sea because there was no evidence of the harmful effects of dumping wastes into the sea. He insisted that a clear national interest was available to ensure that the difficulties would be overcome. However, by the end of August 1983, the British government abandoned its dumping plan, as Belgium and Switzerland had done (The observer Newspaper issue, 28 August, 1983). Later, in May 1988, the UK Energy Secretary announced the decision of the government to stop dumping waste into the sea (Hansard, 1988). Despite this announcement, the government wanted to continue disposing of large items arising from operations of sea disposal.

In the United States, political opposition concerning nuclear waste disposal developed when policies of waste management moved to site-specific proposals in greenfield locations. Controversy typically occurs during the process of selecting the sites (or host states) for nuclear waste disposal. After the sites of waste disposal are identified, the level of opposition to these decisions intensifies. The TENORM situation is a political quagmire that is difficult to extricate ourselves from. The government authorities try to convince the public that TENORM is not as harmful as nuclear radiation exposure by separating the radiation standards for NORM/TENORM from the radiation standards of the nuclear industries. And indeed, the lack of consistency in the laws and policies regarding radiation is due to the lack of consistency in the safety standards and guidelines used. This inconsistency can result in misinterpretation of radiological risk as politicians wish to avoid opposition from the public.

Some developed countries adopting radiation legislation into their system still have inconsistencies in their laws and policies. The Nuclear Regulatory Commission (USNRC) commissioner Dicus (1998) states that the United States has not adopted the latest International Conference for Pattern Recognition (ICPR) recommendations, nor are their policies consistent due to the conflicting standards in several of their federal agencies. He also adds that there is conflict among the different statutory approaches resulting in radiation protection requirements, which resembles a patchwork quilt. In addition, he states that the present situation does not serve the public or promote confidence toward scientists or the US policy-makers.

Moreover, the presence of many agencies that deal with the protection of workers and the public from radiation in the United States also contributed to inconsistencies in the regulations and policies. These include the National Council on Radiation Protection and Measurements (NCRP), USNRC, Department of Energy (DOE), US EPA, and Conference of Radiation Control Program Directors (CRCPD) of state governments. According to the Committee of the National Research Council, the differences between the US EPA guidelines for TENORM and the same guidelines that were developed by other organizations are essentially based on the differences in the policy judgments of risk management and not on technical and scientific information (the US National Research Council, 1999).

Furthermore, the presence of many agencies would lead to a diversity of standards and guidelines and thus to inconsistencies in the regulations and policies. For instance, in their joint study, the National Radiological Protection Board (NRPB), based in the United Kingdom, and the Centre d'études sur l'évaluation de la protection dans le Domaine nucléaire (CEPN), based in France, concluded that it was inappropriate to choose a nuclide reference level and apply this as a reference level for all materials.

In short, legislation related to nuclear issues, including TENORM, could not be established based on the available standards which are themselves inconsistent with each other. For instance, a certain nuclide varies from one material to another (Penfold et al., 1997). The law as it now does not incorporate the more recent International Basic Safety Standards, and this is another reason that might explain the inconsistencies in the regulations and policies (Nyanda and Muhogora, 1997).

7.5 Challenges faced by the policy-makers in regulating radiological risks

The available estimates involving exposure to radiation are overly conservative. Research indicates that medical factors are more often absent and assumptions too conservative. In addition, many radiation pathways may not be considered in the risk assessments, as they are very complex or cannot be easily quantified. Medical opinions are rarely employed in the outcomes of the risk assessments, as has been explained in the previous chapter. The risk assessment results, therefore, do not reflect real situations, as they are purely hypothetical.

Unfortunately, some industries and governments create their policies and laws based on these risk assessment outcomes and by adopting risk management principles, such as "precautionary principles" (PP) or "as low as reasonably practicable" (ALARP). These approaches could have tremendous legal implications based on the suspicions leading to debates in the medical, engineering, and legal communities on what quantitative basis risk is considered low, safe, reasonable, and practicable.

Conversely, the oil and gas industry in many countries has developed labor and insurance laws to protect workers from injuries and accidents. However, the main concern is that NORM-related issues are either not covered at all in such laws, or subject to only partial investigation, making it difficult to distinguish the difference between NORM and TENORM. Therefore, the number of lawsuits alleging bodily injury from exposure to TENORM has increased due to the lack of clear governmental regulations and laws to control TENORM and their potential exposure hazards.

Litigation, in turn, may generate disputes between insurers and policyholders over whether standard-form liability policies were meant to provide coverage for such claims. Many available companies come to realize later that their insurance policies do not provide coverage for the resulting losses related to TENORM exposure, as it is extremely difficult to prove the consequences of TENORM such as cancer, which may only appear much later in life. The lack of reliable regulations and laws is detrimental to any development of measures to protect against radiation; there is no conclusive answer as to the validity of the ALARP or PP hypothesis from a radiological point of view, because it is not known at this time whether the effects of exposure to low-level radiation may increase cancer risk according to recent research and epidemiological studies.

As correctly pointed out by ICRP chairman Roger Clarke, "there are no prospects that the existence of a low-dose threshold for tumor induction could be proved or disproved conclusively .... Because of the continuing lack of definitive scientific evidence, a new approach to protection should be considered" (Clarke, 1999).

All this evidence supports the conclusion that laws are urgently needed to regulate the treatment and management of nuclear-producing substances, mainly from the oil and gas industry, which produce large quantities of TENORM daily along with oil and gas production. However, the public must participate effectively in the legislative process, not only for themselves but also for future generations and the protection of the environment. The time has come to establish a framework for smart and effective laws and regulations that will enable the government to protect the public and workers in the oil and gas industries from radiological risk due to exposure to TENORM. And this is needed even though doses of radiation are low (Graham et al., 1999; Burkart, 1999).

In relation to this, the health, safety, and environmental policy and sustainability are looking forward to optimizing the balance of benefits that accrue to the society from economic activities with the damage caused by technological risk and pollution (Munasinghe, 2001). The primary responsibility of the policy-makers is to consider health, safety, and environmental factors in the plans of economic development with health, safety, and environmental policy instruments. This helps to minimize the risks that threaten human existence as well as the environment.

The instruments can be categorized into three major classifications: (1) economic instruments, such as health, safety, and environment taxes; (2) regulatory instruments, such as health, safety, and environment licenses that can be purchased or sold under specific legal frameworks; and (3) legal instruments, such as legal health, safety, and environment liabilities. Considering the current practices and existing policies, unfortunately, the reports indicate that the nuclear radioactive wastes produced by the oil and gas industry are subject to partial investigation or not fully addressed from nuclear, health, environmental, and legal perspectives.

This could be attributed to many reasons again, such as political and economic reasons or to lack of knowledge and understanding. From the political and economic perspective, SOEs always strive to boost the production of oil and gas as the fundamental economic source for the state. This gives influence and dominance of the political power over ecological or health policy. Accordingly, those that are under partial investigation might be at the initial stages of policy cycle models of policy evaluation of policy formulation. While inconsistencies and conflicts in the current policy instruments could be attributed to the lack of knowledge and understanding. Consequently, there are challenges experienced in the formulation of adequate and efficient political-ecology and health policies that are dedicated to nuclear radioactive wastes from the oil and gas industry and capable of providing enough protection to the people and environment.

Some of these challenges include but are not limited to the following questions: Will the political ecology and health policy approach conform to a sustainable development strategy? Are the of America, Canada, Nigeria, the United Kingdom, and all other oil producing countries ready to sacrifice its primary economy source for the protection of people and the environment?

Furthermore, and in relation to the discussion above of the policy instruments, the main risk factors of TENORM identified in the oil and gas industry can be used as a foundation for developing legislation and regulations associated with public health and the environment, are as follows:

(1) Regulations and legislative acts specifically designed to regulate and govern TENORM issues in the oil and gas industry are lacking.

(2) Workers involved in oil and gas activities, from upstream to downstream, are at great risk of being exposed to significantly elevated doses of radiation from TENORM under adverse conditions ("occupational radiological exposure"). This includes workers performing drilling and associated services, such as work over, fluid filtration, coring, hydraulic fracturing, fishing and milling, perforation, logging, and wire-line services, as well as flow-line maintenance crews, workshop maintenance crew members, workers at refineries and gas power plants, and workers at TENORM waste disposal facilities.

(3) Current TENORM waste disposal methods used in the oil and gas industry are completely unsafe and not always based on scientific evaluations or radiological risk assessments from either engineering or medical perspectives. These disposal methods contribute to serious radiological contamination and pollution, affecting humans, the atmosphere, water aquifers, plants, and animals.

(4) TENORM from drilling activities in the form of drilling cuttings or suspended particles in drilling fluid are disposed of in an uncontrolled manner in unlined or unfenced waste bits at the drilling site, normally left untreated and exposed to many contamination pathways (e.g., groundwater contamination, plant, and food contamination).

(5) The risk associated with unsafe transportation, storage, handling, and treatment of TENORM wastes can pose a threat to the public and the environment.

(6) The fate and transport pathways of TENORM in the oil and gas industry and its biological effects on human, animal, and plants can pose a serious risk. Low doses of TENORM exposure can still cause carcinogenic diseases.

(7) The release of TENORM during drilling activities, well blowouts, or contaminated equipment maintenance leads to environmental and occupational radiological risks.

(8) Reinjection of TENORM waste and contaminated water produced in the geological formations enhances radioactive concentrations, which may migrate and contaminate groundwater.
(9) Recycling and disposal of equipment contaminated with TENORM can pose certain risks.

7.6 Political institutional reform and trust reconstruction in technological risk management

Even though the intricacies of politics often introduce conflicts in the management of technological risk, it is essential to consider public participation in risk management policy-making. This path runs in two antithetical directions (Fiorino, 1989). One advances toward involving the public in policy-making related to technological risk management. This approach reflects a commendable level of mutual trust between the government and the public. A sterling example is Switzerland, which boasts a straightforward form of democracy throughout its political decision-making process.

The other approach leads to a more centralized control by the government and truncated public participation. These approaches thus entail two different levels of trust between the government and the public. For instance, the French citizens have great trust in their government because of its minute control over health and safety issues. By contrast, Americans commingle their high level of perceived risk with a notable distrust of the government, science, as well as industry, but they still believe to some extent that they can control certain risks. As a result, American citizen groups barely have the freedom to intervene or question administrative proceedings, expert governmental agencies, and judgments, and force policy changes through litigation (Jasanoff, 1986).

Political scientists assert that in an environment of reinforced distrust, the French approach, which restricts policy formulation and implementation, is beneficial (Morone and Woodhouse, 1989) because French lawmakers look up to the scientific elite to shepherd them in policy matters (Jasper, 1990). "Perhaps no other political system provides as large a role for people to exercise technocratic power on the basis of technical training and certification" (Jasper, 1990). On the other hand, America has adopted a different approach to democracy that is often not up to the task of involving citizens in policy-making related to risk management strategies, especially for technological risks such as those associated with nuclear radioactive waste policies.

The failed attempt by the Congress to strip Nevada of its right to issue environmental and safety permits for nuclear waste studies at Yucca Mountain is a good example of government resistance to citizens' appeals (Batt, 1992). Given that the French method is not likely to be accepted in the United States, restoration of trust may require a degree of openness and involvement with the public that goes far beyond public relations and "two-way communication," and extends to levels of power-sharing and public participation in risk management decision-making that have rarely been seen; even this, however, is no guarantee of success (Flynn et al., 1992; Bord, 1988; Nelkin and Pollak, 1979). Trust and belief cannot be gained overnight; various foundations must be set over time to achieve transparency and public involvement.

The disappointing outcome of the proposed nuclear waste repository in Nevada is an indication of the situation in America. To enhance more democracy in policy-making, it is vital to orchestrate means to work effectively in situations where we cannot depend on trust (Kasperson et al., 1992). After numerous past experiences in technological risk management, Americans have made long strides to improve the current process. Although vast amounts of money, resources, and time have been used for scientific studies intended to identify and minimize technological risks, Americans have not fully succeeded in learning how to manage the hazards identified by science.

Jackson et al. (1990) admirably highlight the challenge concerning nuclear waste disposal and thus make a significant contribution to tackling several risks. Thus, a highly sophisticated and complex engineering system is necessary for the safe storage of colossal quantities that may reach 100 thousand tons of radioactive nuclear waste that may emit radiation for over thousands of years. There has also been an acknowledgment of the political requirements that would have to be met to design and implement such a solution. While numerous resources have been used to develop complex and sophisticated technologies, the equally sophisticated political processes and institutions that require a dependable and conscious strategy for nuclear radioactive waste management have not been developed.

The history of high-level radioactive waste management reveals repeated failures to recognize the need for political institutional reform and reconstruction. Comprehending the main reasons behind political conflicts and realizing the need to encourage public participation in both technological risk-management processes and legislative decision-making are important first steps toward mitigating the technological risk of TENORM exposure in the oil and gas industry as well as maintaining a strong economy with a safe and healthy community.

7.7 Public participation is a legal right guaranteed by the legislator

In the 1970s, public participation in the legislative process emerged as a major concern regarding the decisions that were made about the management of technical risks. Proponents argued that tabling recommendations for greater public participation with regards to the radiological risk associated with TENORM from the oil and gas industry into law would help reduce current the ignorance exhibited by the government bureaucracy. They claimed that this would have a domino effect, in that the government would be expected to promote conflict resolution and be more responsive to concerns of the public, which in turn would help legitimize its policies and significantly increase the chances of successfully implementing them (Rosenbaum, 1976; ACIR, 1979; Langton, 1978).

Critics often emphasized the diminished governmental power brought about by such policies, describing them as detrimental to the states' decision-making processes. Skeptics also worry that citizens may not behave in a responsible manner, especially given their lack of decision-making experience related to such high-caliber policies (Aberbach and Rockman, 1978; Cupps, 1977; Berry et al., 1989).

Therefore, the discussion with the public should take place on significant high-risk issues, especially those pertaining to risky technologies such as workers being exposed to nuclear radioactive materials in the oil and gas industry, consisting of hazardous radioactive nuclear wastes, the role of EORTs and hydraulic fracturing in enhancing the activity concentrations of TENORM, the current nuclear radioactive waste disposal methods adopted by the oil and gas industry. The dilemma persists when policymakers must decide whether to involve the public in decision-making on such complex and controversial matters related to the economy, the environment, and the well-being of society (Rosenbaum, 1983).

Conversely, disregarding public participation in matters as important as nuclear radioactive hazard waste management more often leads to importunate opposition. Such political stalemates are most probably due to authoritarian regimes. Sweden, the Netherlands, and Austria have shown that active programs of public involvement can be designed and that people's understanding of technical issues can be improved, even when approval of the policies sought by governments is not assured (Nelkin, 1977).

Recent findings indicate that meliorated communication of risk information is an important variable in increasing public understanding of the issues as well as engendering trust and confidence in risk policy decision-making (Kasperson, 1986; US National Research Council, 1989). Strategies should be enacted for wider public participation as one of the principles of government transparency to mitigate crucial and sensitive issues, such as radiological risks, which can affect the public and future generations. Democratic principles should be used in policy-making, particularly on nuclear radiological risks to achieve certain objectives. These objectives include achieving synergy between the public and the government, encouraging technical review by a qualified panel of policy actors, considering, public fear to gain public support in the policy implementation process.

The government can apply several techniques to involve the public in such sensitive matters. Public participation in decision-making on issues affecting the public and future generations is primarily a legal right. The public has the right to exercise this right either directly or through their representatives, regardless of the extent of their knowledge about technical issues, as is the case with numerous legal rights guaranteed to the public by the legislator in areas where citizens surpass lack of knowledge of legal and legislative matters.

7.8 Public participation approach

Because different processes of extraction and exploration of oil and gas carry different risks, their regulation is not a straightforward matter. For instance, in the United States, decisions affecting the outcomes of contentious issues are made within the hierarchy of the local, state, and federal governments. These decisions are not always well coordinated or harmonized or in consistency with other regulations.

The resulting convolution presents challenges in strategic planning for the government, citizens, environmentalists, and industry interests. The structure of the government department or agency that makes decisions in this area represents another challenge, which spearheads the process of policy formulation. Furthermore, various institutions that share similar risk management regulations associated with oil and gas extraction may repudiate their own existing regulations, as explained earlier. In Canada for instance, policy issues are similarly complex, facing municipal, provincial, and federal government challenges, which may result in inconsistency in some cases. Canada regions benefit at the expense of local jurisdictions, where negative effects are most significant across several government layers (Council of Canadian Academies, 2014).

In relation to the subsurface rights, in the United States, the decision to allow exploitation and exploration is made by landowners rightfully owning the subsurface rights. While, in Canada, subsurface rights belong to the Crown, which grants provincial governments control over development and regulatory processes, such as the issuing of exploration licenses. However, it should be noted that Canada's First Nations title and treaty rights may transcend provincial and federal jurisdictions, adding another level of complexity to the Canadian context.

New technologies have emerged and developed very rapidly in the oil and gas industry. This has led to increased uncertainty about the impact of such technologies on the environment, public health, and the economy (Theodori et al., 2014). In addition, governments are often under pressure from the public to either ban harmful technologies in the oil and gas extraction process or develop and implement various policies guaranteeing environmental protection as well as risk-free surroundings for communities around the production and extraction sites.

Researchers such as Small et al. (2014) have argued that new governance models and enhanced public participation in the policy development process, coupled with independent scientific research, could help governments address the perceived risks and benefits of technologies, resulting in stronger and more widely accepted policies and regulations. (These technologies include EORTs, which help enhance oil and gas production while also enhancing the radioactivity concentration of naturally nuclear radioactive materials present in oil and gas formations, and hydraulic fracturing technology, which plays a key role in the fate and transport model of TENORM.)

Both scientific and technical experts should be consulted to formulate appropriate TENORM policies. Further, the policy should be divided into the following three categories: a literature review on TENORM in the full life cycle of oil and gas production and regulation, which calls for more research into policy implications; social studies focusing on public perceptions of the radiological risks of TENORM and community awareness and responses; and finally, empirical studies highlighting specific safety, health, and environmental impacts of TENORM.

Policies are discussed and debated in polemical forums, such as gray literature and conclusive studies on the nuclear radioactive consequences. However, these studies are often impugned and the concerns ignored by politicians on the grounds of insufficient substantiation of the long-term consequences of technological risks, such as radiological TENORM risk and hydraulic fracturing risks (Council of Canadian Academies, 2014).

Despite the insufficient support in the literature and the associated uncertainty about technological risks and its consequences in different energy industries, public participatory approaches to policy development have been applied in various issues involving risks as a result of technology adoption and have shown excellent results and success. These include strategic environmental assessments (Gauthier et al., 2011), energy efficiency and renewable energy strategies (Adams et al., 2011; Ngar-yin Mah and Hills, 2014).

Different approaches to public participatory development can be used in different political regimes, such as multicriterion decision-making approaches (Greening and Bernow, 2004) and a postnormal science (PNS), which is a form of evidence-based decision-making (Turnpenny et al., 2009). Although these approaches differ, they all enhance public participation (Turnpenny et al., 2009). And when the public becomes more informed, a direct domino effect ensues as citizens are given an avenue to voice their concerns on technological risks.

Turnpenny et al. (2009) described how the policy-making of unconventional oil and gas development is highly intricate. It may be addressed by participatory policy-making processes with all involved parties contributing to the solution. Unfortunately, it is important to sometimes observe that the government is bound to make decisions that do not necessarily address citizens' concerns in the absence of public participatory laws. This is obvious when the government's main concern is to obtain "community permission" to continue trading oil and gas in the areas; regardless of the importance of considering potential technological risks during policy-making as many cases have been around the world.

Eventually, the development of oil and gas in any province will result in risks to the environment and human health. Thus, the government must rethink its policies and consider public participation in formulating risk policy to mitigate technological risks, particularly radiological risks and other technological risks arising in the oil and gas production and extraction industry. For example, successful, methodical, and proficient public participation in risk policy-making can be achieved via a volunteer committee of the public. This system comprises academic and technical experts from public nominations, without any governmental interposition.

The government should allow anyone to participate in the panel of their choice, without being subject to any restrictions. The public community panel then appoints a technical consultant to facilitate the panel's works and a project administrator to coordinate the panel's review. The panel's sole activities are to conduct public consultations on the possible exposure to

TENORM and their presence in oil and gas extraction as well as production including treatments and disposal. The panel should also conduct a literature review on the health, safety, and socioeconomic impacts of TENORM exposure through different pathways to workers involved in the oil and gas industry and to the public.

The final findings and recommendations of the community panel must be shared, discussed, and agreed upon with the public or their nominated representatives. The outcome of this panel and recommendations from the public are subsequently brought to the government's attention. Then both the public and the government must agree on laws and regulations relating to the optimal utilization of oil and gas resources without jeopardizing public health, safety, or the environment.

7.8.1 Academic and technical advisory community panel

The public panel includes of the following categories of expertise: hydrogeology, geology, political science, geochemistry, chemistry, environmental management, economics, public health, water quality management, waste treatment and management, oil and gas engineering, climate science, environmental psychology, community engagement, knowledge of aboriginal wisdom, law, quantitative risk assessment and management, and nuclear physics/chemistry, if found. Furthermore, the public panel consists of technical and academic advisors such as geologists, petrophysicists, chemists, petroleum engineers, production engineers, HSE advisors, radiological physicians, lawyers, and economists. Since most of these academic experts and technical personnel who are employed by the government are originally from the same community; therefore, they are entitled to nominations as they are members of the public according to translucent democracy.

7.8.2 Public engagement methodology

The adoption of a public engagement policy strategy is a very helpful tool to overcome the issue of mistrust between the various actors. Adoption of this strategy has shown an increasing number of cases with successful outcomes (Rayner, 2010; Ricci et al., 2010; Adams et al., 2011). First, the development of a public engagement strategy shall include but is not limited to understanding and promotion of public engagement through diverse mechanisms with different levels of participation.

Second, engagement is required ranging from the simple provision of information to active deliberation to ensure that a heterogeneous public with different strata of knowledge and interests is involved. Third, the process must be socially inclusive, accessible, and informative. Fourth, the process should include issues that people perceive as relevant to everyday life, such as cancer due to TENORM exposure; TENORM disposal methods that could contaminate water, soil, and food resources; radiological risk to a family member working in the oil and gas industry; and environmental damage and the radiological effects of TENORM on future generations. Finally, the process must be made more transparent and open to the public.

7.8.3 Scope of work

State-of-the-art assessments of the range of impacts of TENORM risks from the oil and gas industry and its associated technologies with respect to the health and safety fears of workers and the public are not adequate for drafting policies. This is due to the lack of concrete evidence to substantiate a final decision. Thus, supplementary research is required to identify hazards that are catastrophic and those that require high levels of monitoring, risk mitigation, and regulation. As in other industries, TENORM from the oil and gas industry and associated activities can both benefit and harm the community, the general population, and individuals. Based on the TENORM carcinogenic risk analysis, there is a need to incorporate a comprehensive program of safety, health, and environmental monitoring alongside strict managerial regulations and enforcement in radiology policy-making.

Management practices of drinking water and soil quality should be elucidated with specific reference to potential contaminants arising from radioactive waste disposal methods including surface disposal, underground injection disposal, and hydraulic fracturing technologies that help create easy pathways for TENORM to reach water resources. Other enhanced oil recovery methods and their associated technologies should be used in the description of management practices. Similarly, a policy on water resource protection and management should be considered as part of the TENORM risk management policy. Well, integrity including good design, construction, operation procedures, completion type, geological formation structure, casing quality, cementing quality, hydraulic fracturing, chemical types, and volume is essential in understanding some of the long-term risks of TENORM migration and leakage pathways between different geological formations.

The deficiency of long-term data on good integrity and the ineffectiveness of current management practices raise serious concerns about the destruction and pollution of underground infrastructure and natural resources. This emphasizes the need for effective, dynamic, and long-term water and soil quality monitoring plans as well as the local modeling of risks. To better assess TENORM emissions that enter the atmosphere from oil and gas fields and processing facilities, as well as their effects during the full life cycle of production, systematic air quality measures need to be undertaken. This would further our understanding of consequences for human health and the climate, serving as a direct early warning system for any radiological emissions posing a threat to the public.

Certain countries have adopted the Radiation Monitoring Network and Early Warning System (RMN&EWS). However, there are important questions as to the rationale for using these RMN&EWS to set the safe radiological limit. The scientific, medical, and engineering communities are still divided on the safe limits of exposure to radiation, especially exposure to low limits that may eventually cause cancer. Furthermore, there are significant variations in determining the safety limit among the safety standards themselves.

In summary, the radiological emergency monitoring system serves two main purposes: first, it warns of any sudden rise in radiation; second, it provides an overview of the radiation and contamination levels. While this system may alert us to a nuclear radiological accident, it also provides the required data on the radiation levels before an accident, allowing us to assess the environmental impact after an accident occurs. But RMN&EWS safety is still not the optimal solution to prevent radiological risk exposure.

It functions only as an ordinary safety-warning barrier, which may fail due to several technical and physical reasons. Consequently, given the persistent effects of radiological exposure, it is imperative that the government set up emergency responses, plans, and precautionary principles in case of any nuclear radioactive accident that is known to escalate rapidly.

7.9 Conclusions

Greater public participation in technological risk policy legislation is usually regarded as a sign of a healthy and lively democracy. This study highlights the importance of public participation in conferring legitimacy on public institutions and remedying the "truncated democracy" syndrome. Public participation has been the straw that breaks the camel's back, making nations as powerful as the United Kingdom and the United States heed public demands to change their nuclear radioactive policy, in the management policies of radioactive wastes, given the serious risks to health, the environment, and natural resources, and the economy.

Political conflicts and legislative inconsistencies hamper the management of nuclear radioactive risk. This is considered a characteristic problem of a "truncated democracy." This thesis thus proposes a framework for engaging public participation, which together with government legislation can ensure workers' safety, public health, and the environment. A systematic approach is presented to maximize the efficiency of public engagement in the process of policy-making and decision-making via an independent voluntary community panel comprising academic and technical experts with multidisciplinary expertise.

These experts can examine the scientific and technical evidence and related legal issues to mitigate radiological risks associated with TENORM from the oil and gas industry. The main duties of this panel would be to carry out state-of-the-art assessments of the range of impacts of TENORM risk from the oil and gas industry and its associated technologies in terms of the health and safety risks to workers and the public.

In conclusion, it is a prerequisite of a mature and healthy democracy that the public is engaged in policy-making directed at mitigating crucial and sensitive issues. Therefore, supporters of deliberative democracy must endeavor to convince political regimes and legislatures to engage the public in decision-making related to nuclear radiological policy to minimize radiological risks at the local and international levels.

Unfortunately, some political regimes wish to develop a strong nuclear program toward nonpeaceful purposes, may find TENORM coproduced from the oil and gas industry as excellent, abundant, and cost-effective sources. Therefore, public participation in the legislative process that aims to mitigate technological risks associated with the nuclear radioactive material is the optimal strategy to achieve much-needed protections and avoid any misuse of political power.

References

Aberbach, J.D., Rockman, B.A., 1978. Administrators' beliefs about the role of the public: the case of American federal executives. West. Polit. Q. 31 (December), 502–522.

ACIR–Advisory Commission on Intergovernmental Relations, 1979. Citizen Participation in the American Federal System. http://www.library.unt.edu/gpo/acir/Reports/brief/B-3.pdf. (Retrieved 10.12.15).

Adams, M., Wheeler, D., Woolston, G., 2011. A participatory approach to sustainable energy strategy development in a carbon-intensive jurisdiction: case of Nova Scotia. Energy Policy 39, 2550–2559.

Alberta Energy Regulator–AER, 2006. Oilfield Waste Management Requirements for the Upstream Petroleum Industry.
Alberta Radiation Protection Act. of 2000, 2017. R2. The Province of Alberta. 1-15. Available from: (Retrieved 22, 09, 2017).
Al-Farsi, A., 2008. Radiological Aspects of Petroleum Exploration and Production in the Sultanate of Oman (Doctoral thesis). http://eprints.qut.edu.au/29817/1/Afkar_Al-Farsi_Thesis.pdf. Retrieved 28, 9,2017.
ALNabhani, K., Khan, F., Yang, M., 2015. Technologically enhanced naturally occurring radioactive materials in oil and gas production: a silent killer. Process Saf. Environ. Prot. https://doi.org/10.1016/j.psep.2015.09.014.
Aniefiok, E.I., Usenobong, F.U., Margaret, U.I., Idongesit, O.I., Udo, J.I., 2016. Petroleum industry in Nigeria: environmental issues, National Environmental Legislation and Implementation of International Environmental Law. Am. J. Environ. Prot. 4 (1), 21–37.
Avwiri, G.O., Ononugbo, C.P., 2011. Assessment of the Naturally Occurring Radioactive Material (NORM) Content of Hydrocarbon Exploration and Production Activities in Ogba/Egbema/Ndoni Oil/Gas Field, Rivers State, Nigeria. pp. 572–580.
Baried, R.D., Merrl, G.B., Klein, R.B., Rogers, V.C., Nilson, K.K., 1996. Management and Disposal Alternatives for Norm Wastes in Oil Production and Gas Plant Equipment. American Petroleum Institute, pp. 1-1–5-18.
Batt, T., 1992. Nevada claims victory in Yucca deal. Las Vegas Rev. J., 1A–3A.
Berry, J.M., Portney, K.E., Thomson, K., 1989. Conflict, alienation and delay: is citizen participation poison? In: Paper presented at the Annual Meeting of the Midwest Political Science Association, Chicago.
Bord, R.J., 1988. The low-level radioactive waste crisis. Is more citizen participation the answer? In: Burns, M.A. (Ed.), Low-Level Radioactive Waste Regulation. Science.
Burkart, W., 1999. Ethics and science in radiation protection, SSI news. Swedish Radiat. Protect. Inst. Newslett. 7, 1.
CNSC (Canadian Nuclear Safety Commission), 2017a. Low- and Intermediate-Level Radioactive Waste. Available from: http://nuclearsafety.gc.ca/eng/waste/low-and-intermediate-waste/index.cfm, Retrieved on 11.10.2017.
CNSC (Canadian Nuclear Safety Commission), 2017b. Naturally Occurring Radioactive Material (NORM). Available from: http://nuclearsafety.gc.ca/eng/resources/fact-sheets/naturally-occurring-radioactive-material.cfm. Retrieved on 11.10.2017.
Clarke, R., 1999. Control of low-level radiation exposure: time for a change? J. Radiol. Prot. 2 (1), 107–115.
Council of Canadian Academies, Ottawa, 2014. Environmental impacts of shale gas extraction in Canada: The Expert Panelon Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction.
Cupps, D.S., 1977. Emerging problems of citizen participation. Public Adm. Rev. 37, 478–487.
Dicus, G.J., 24 April, 1998, Paper No 5, 98-13 1998. Why We Need to Harmonize Radiation Protection Legislation. Presented at the 1998 "Women in nuclear" Global Annual Meeting, Taipei, Taiwan.
Environmental Services Association of Alberta-ESAA, 2017. NORM Waste Management. Retrieved on Oct 15, 2017 and available from: http://www.esaa.org/wp-content/uploads/2015/10/15-Cuthill.pdf.
Fiorino, D., 1989. Technical and democratic values in risk analysis. Risk Anal. (9), 293–299.
Flynn, J., Kasperson, R., Kunreuther, H., Slovic, P., 1992. Time to rethink nuclear waste storage. Issues Sci. Technol. (8), 42–48.
Gauthier, M., Simard, L., Waaub, J., 2011. Public participation in strategic environmental assessment (SEA): critical review and the Quebec (Canada) approach. Environ. Impact Assess. Rev. 31 (1), 48–60.

Graham, J., Higson, D.J., Mitchel, R.E.J., Kobayashi, S., 1999. France, 25thOctober 1998; reprinted in the J Aust Radiation Protect Soc (16)1999. Low doses of ionising radiation incurred at low dose rates. In: Report of the International Nuclear Societies Council's Task Group on Low Doses, presented at a Special Session of the ENC'98 World Nuclear Congress held in Nice, pp. 32–47.
Greening, L.A., Bernow, S., 2004. Design of coordinated energyand environmental policies: use of multi-criteriadecision-making. Energy Policy 32 (6), 721–735.
Hansard–Great Britain-Parliament, 1988. Radioactive Waste(Disposal). Official Record 26 May 1988, Col. 233. HMSO, London.
Janssen, M.P.M., Blaauboer, R.O., Pruppers, M.J.M., 1998. Geographical distribution of radiation risks in the Netherlands. Health Phys. 74 (6), 677–686.
Jasanoff, S., 1986. Risk Management and Political Culture. Russell Sage Foundation, New York.
Jasper, J.M., 1990. Nuclear Politics: Energy and the State in the United States, Sweden, and France. Princeton University Press, Princeton, NJ.
Jackson, R.B., Vengosh, A., Carey, J.W., Davies, R.J., Darrah, T.H., O'Sullivan, F., Pétron Jacob, G., 1990. Site Unseen: The Politicsof Siting a Nuclear Waste Repository. University of Pittsburgh, Pittsburgh, PA.
Jonkers, G., Hartog, F.A., Knaepen, W.A.J., Lancee, P.F.J., 1997. Characterization of NORM in the oil and gas production (E&P)industry. In: Proceedings of International Symposium on Radiological Problems With Natural Radioactivity in the Non-nuclear Industry, Amsterdam, September 8–10, 1997, pp. 23–47.
Kasperson, R.E., Golding, D., Tuler, S., 1992. Social distrust as afactor in siting hazardous facilities and communicating risks. J. Soc. Issues 48, 161–187.
Kasperson, R.E., 1986. Six propositions on public participation and their relevance for risk communication. Risk Anal. 6, 275–281.
Kolb, W.A., Wajcik, M., 1985. Enhanced radioactivity due to natural oil and gas production and related radiological problems. Sci. Total Environ. 45), 77–84.
Langton, S. (Ed.), 1978. Citizen Participation in America. Lexington Books, Lexington, MA.
Morone, J.F., Woodhouse, E.J., 1989. The Demise of Nuclear Energy? Lessons for a Democratic Control of Technology. Yale University, New Haven, CT.
Munasinghe, M., 2001. Sustainable development and climate change: applying the sustainomics transdisciplinary meta-framework. Int. J. Glob. Environ. Issues 1 (1), 13–55.
Nelkin, D., Pollak, M., 1979. Public participation in technological decisions: reality or grand illusion? Technol. Rev., 55–64.
Nelkin, D., 1977. Technological Decisions and Democracy: European Experiments in Public Participation. Sage, Beverly Hills, CA.
Ngar-yin Mah, D., Hills, P., 2014. Participatory governance for energy policy-making: a case study of the UK nuclear consultation in 2007. Energy Policy 74), 340–351.
North Dakota Department of Health-Division NDDOH, 2015. Transcript of Public Hearings related to TENORM Rule Revisions in Williston, Bismarck, and Fargo, North Dakota. Division of Waste Management., pp. 1–60.
Nuclear Safety and Control Act. S.C, 1997. C. 9. Minister of Justice. Canada. (2017).
Nyanda, A.M., Muhogora, W.E., 1997. Regulatory control of low level radiation exposure in Tanzania: low doses of ionizing radiation. In: Biological effects and regulatory control. Contributed Papers. International Conference held in Seville, Spain, 17–21 November 1997, IAEA-TECDOC-976, pp. 308–311.
O'Brien, R.S., Cooper, M.B., 1998. Technologically enhanced naturally occurring radioactive material (NORM): path way analysis and radiological impact. Appl. Radiat. Isot. 49.

Penfold, J.S.S., Mobbs, S.F., Degrange, J.P., Schneider, T., 1997. Establishment of reference levels for regulatory control of workplaces where materials are processed which contain enhanced levels of naturally-occurring radionuclides. Radiation Protection 107. Office for Official Publications of the European Communities, Luxembourg.
Rayner, S., 2010. Trust and the transformation of energy systems. Energy Policy 38 (6), 2617–2623.
Ricci, M., Bellaby, P., Flynn, R., 2010. Engaging the public on paths to sustainable energy: who has to trust whom? Energy Policy 38 (6), 2633–2640.
Rosenbaum, W.A., 1983. The politics of public participation inhazardous waste management. In: Lester, J.P., Bowman, A.O.M. (Eds.), The Politics of Hazardous Waste Management. Duke University Press, Durham, NC.
Rosenbaum, W.A., 1976. The paradoxes of public participation. Adm. Soc. (8), 355–383.
Small, M.J., Stern, P.C., Bomberg, E., Christopherson, S.M., Goldstein, B.D., Israel, A.L., Jackson, R.B., Krupnick, A., Mauter, M.S., Nash, J., North, D.W., Olmstead, S.M., Prackash, A., Rabe, B., Richardson, N., Tierney, S., Webler, T., Wong-Parodi, G., Zielinska, B., 2014. Risks and risk governance inunconventional shale gas development. Environ. Sci. Technol. 48, 8289–8297.
Strand, T., 1999. Handling and disposal of norm in the oil and gas industry. In: WM'99 Conference, February 28-March 4, 1999.
The observer Newspaper issue, 28 August, 1983.
Theodori, G.L., Luloff, A.E., Willits, F.K., Burnett, D.B., 2014. Hydraulic fracturing and the management, disposal, andreuse of frac flow back waters: views from the public in the Marcellus Shale. Energy Res. Soc. Sci. (2), 66–74.
Turnpenny, J., Lorenzoni, I., Jones, M., 2009. Noisy and definitelynot normal: responding to wicked issues in the environment, energy and health. Environ. Sci. Policy 12 (3), 347–358.
US Energy Information Administration-EIA, 2017. Short-Term Energy Outlook. Available from: https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf. Retrieved 03, 10, 2017.
US Environmental Protection Agency (US EPA), 1993. Produced Water Radioactivity Study. Office of water and Office of Science and Technology, Washington, DC, USA.
USNRC–US-National Research Council, 1989. Improving Risk Communication. National Academy Press, Washington, DC.
USNRC–US-National Research Council, 1999. Evaluation of Guideline for Exposure to Technologically Enhanced Naturally Occurring Radioactive Materials. National Academy Press, Washington.
USNRC, 2003. Reactor Concepts Manual: Biological Effects of Radiation. USNRC Technical Training Center.

Further reading

Environmental Protection and Enhancement Act. 2000, 2017. C.E-12. Province of Alberta., pp. 1–256.

CHAPTER EIGHT

Conclusions and recommendations

This book attempts to investigate the available literature and identify current knowledge and technology gaps associated with the presence of TENORM in the oil and gas industry. We have identified three main gabs from the available studies we are addressing in this book, and they are: (1) workers in the oil and gas industry face a great risk of being exposed to various levels of radioactivity throughout the oil and gas extraction and production life cycles; (2) high volumes of TENORM waste are generated daily from the petroleum industry and have become a serious concern as another source of radiation exposure to workers, the general public, and the environment; and (3) the lack of a uniform international safety standard, inconsistencies, and conflicts in existing regulations and legislation designed to manage TENORM risks and the inability of these measures to provide enough protection for public health and the environment.

The main goal of this book is to provide a road map for further researches on key gaps it identifies in measures put in place to protect public health and the environment from the radiological risks posed by TENORM in the oil and gas industry. To achieve that goal, this book presents a new approach of dynamic modeling and quantitative risk assessment of TENORM occupational exposure in the oil and gas industry using SMART approach, which integrates SHIPP (system hazard identification, prediction, and prevention) methodology and rational theory (SMART approach). The SHIPP methodology is a methodological framework used to identify, evaluate, and model processes of potential TENORM occupational exposure accidents. The rational theory is used to model accident causation behavior that usually contributes to its occurrence based on the logical, inductive, and probabilistic analysis. The basic premise of the rational theory is that an accident occurrence is a result of joint and conditional behavior among different parameters.

This book also presents an analysis of current TENORM waste disposal methods used that are completely unsafe and unsupported by scientific evaluations or radiological risk assessments from an engineering or a biological

https://doi.org/10.1016/B978-0-12-816825-7.00008-X

perspective. These disposal methods contribute to serious radiological contamination and pollution that affect humans, the atmosphere, water aquifers, plants, and animals. To assess their effectiveness, we evaluated a real scenario-based risk assessment of common TENORM waste disposal methods and simulated based on a transport and fate model using RESRAD version 6.5. The results of the scenario-based risk assessment were compared with those obtained using a similar simulated scenario constructed from a literature review and medical opinion.

Finally, this book highlights the issue of the lack of consistency of safety standards related to radiological risks posed by TENORM in the oil and gas industry. It has investigated the main reasons that underlie political conflicts in the reservations about regulating technological risks such as nuclear and radiological issues, particularly in the oil and gas industry. There exists a real need for a public participatory approach in the formulation of technological risk-management processes as an important step toward enhancing nuclear awareness. The legislative decision making is an important first step toward mitigating the technological risks of TENORM exposure in the oil and gas industry as well as maintaining a strong economy. TENORM exposure is a vital public issue as it concerns workers' safety and public health. Hence, this book provides a framework for engaging public participation, which together with government legislation can promote awareness related to public health and environmental safety and aimed to strike a balance between the interests of the authorities and the interests of the public.

Chapter 1 discusses that the continued oil and gas, accidents, and disasters have sounded the alarm, and there is an urgent need of a new approach explaining safety during oil and gas extraction and production processes based on the academic researches to improve safety awareness. Therefore, Chapter 1 provides an overview of the nature of the oil and gas industry including operational and occupational safety during oil and gas extraction and production activities in onshore/offshore.

Available reports revealed that oil and gas operation activities are very risky and have a serious potential to harm people, to cause damage to the environment or loss to assets, and to adversely impact the industry reputation. Despite all the effort from the oil and gas industry to prevent accidents, operational accidents and occupational injuries are still existing and keep posing a major threat with social, environmental, and economic consequences. This could attribute to the adoption of the classical risk assessment and management by the oil and gas industry, the lack of adoption of advanced safety engineering studies around quantitative risk assessment and dynamic accident modeling, and cost-cutting plans that are widely implemented in the oil and gas industry which undermine the safety of people and the environment. Chapter 1 argues that understanding the nature of oil and gas operation will help to understand how workers in the oil and gas industry are at high potential risk of being exposed to known and unknown hazardous risks in the oil and gas industry.

Chapter 1 also outlines that the oil and gas industry has focused on its history on making safety its top priority. However, the industry still needs to do a lot to improve safety culture and system and one of the key things is the adoption of the scientifically based solution, quantitative and dynamic approaches for such complicated and integrated systems. Scientific studies and available statistics show that the main causes of accidents in the oil and gas industry are usually:

1. 88% human errors.
2. 10% equipment failure and workplace design.
3. 2% errors unforeseen risks.

Chapter 1 concludes that to some extent, some of the oil and gas industry has made great strides in strengthening occupational and operational safety measures by applying the highest safety standards, regulations, advance training, personal protective equipment, design improvement, and many other precautionary measures. However, all of these have not been able to prevent occupational or operational accidents and disasters. This could be because of not shedding the light on the lack of studies and understanding, human errors, and unforeseen risks that are the main factors behind the continuity of the accidents and the inability of current qualitative methodologies that are not necessarily based on the scientific evaluation currently used by the industry to anticipate unforeseen risks, or to address, analyze human errors, and quantify them.

For example, if the human errors were not behind them, then the machines will either continue to work safely according to what they have programmed or will stop due to mechanical defects, but the main danger lies in the wrong human decisions as well as the inability to predict unforeseen risks that usually end up into a disaster. If all the incidents in the oil and gas industry, both large and small, were reviewed and investigated, the investigation reports will reveal that the main causes were human error and the inability to predict the unforeseen risks due to lack of knowledge and understanding. Thus, the important question is that why are all the safety systems in the industry not able to prevent or reduce the frequency of accidents occurrences? The simple answer is that the risk assessment methods used in their safety systems are classical and qualitative approaches and not necessarily based on the scientific evaluation to predict the risks at a very early stage.

Chapter 1 insists that the most viable solution to mitigate and control continual accidents in the oil and gas industry should focus on developing adequate safety measures that will prevent operational and occupational risks at early stage. This can be achieved by adopting a scientific-based approach that provides a systematic platform and comprehensive dynamic risk assessment framework management based on the safety barrier performance evaluation and dynamic updating of abnormal events in the system and its subsystems. Thus, frequently, mitigation of all types of accidents including occupational accidents can be achieved early by providing the appropriate safety measures and barriers that are effectively and dynamically maintained. This situation could be improved significantly by predicting, controlling, and mitigating exposure at the source, and by emphasizing the prevention of incidents to achieve an inherently safer design to maximize safety.

Moreover, Chapter 1 recommends the importance that the oil and gas industry to consider in their safety and risk management system effective scientifically based solutions to conduct studies on human behavior from the psychological perspective. It is necessary to promote the development of this effort because occupational accidents are still happening, and this will have negative impacts on the society. Future studies should be carried out using advanced dynamic modeling and quantitative risk assessments, which involve contributions from academic and technical experts who should play active roles in the oil and gas health, safety, and environment (HSE) management system.

Chapter 2 reviews the literature that discussed the development stages of the concept of "Naturally Occurring Radioactive Materials" (NORM) in oil and gas production since the beginning of the 19th century to the present day. It further explains how the scientific and technological development used in processes associated with the enhancement of oil and gas recovery enhances NORM'S concentration and develops technologically enhanced naturally occurring radioactive materials (TENORM). It redefines TENORM and how they are enhanced and classified as nuclear materials from technical and scientific perspectives. It also explains how spectral gamma ray logging technology helps to prove that NORM is used as an indication of oil and gas presence.

Chapter 2 also reveals that there is a strong relationship between the presence of hydrocarbons and radioactive materials, which will rethink the interpretation of the theory of oil and gas formation based on the logical scientific explanations. Chapter 2 provides a better understanding of TENORM geochemistry and their forms found during the extraction and production of oil and gas that pose serious health and environmental risks. It makes a strong argument for the importance of TENORM risk assessment and management process through safety approaches. Chapter 2 also sheds light on modes of exposure in the oil and gas industry and the biological and health effects of radiation exposure. Finally, Chapter 2 indicates that the presence of TENORM in the industry has been known for over a century, but they do not assess its impacts on HSE. Despite several decades of extensive research and studies addressing the presence of TENORM in the oil and gas industry, the knowledge and technological gaps remain in addressing scientifically the potential health, safety, and environmental concerns of how to safely manage their exposure. The main technical gaps have not been explored, or addressed in the available literature regarding TENORM issues and have been outlined at the end of the chapter, and they are:

1. Knowledge gaps
   - Inability to scientifically differentiate between NORM and TENORM.
   - Lack of scientific knowledge about the fundamental concepts and theories of TENORM in the oil and gas industry.
   - The absence of legislation and the lack of consistency of safety standards related to radiological risks posed by TENORM in the oil and gas industry.
   - Historical database of TENORM.
2. Technical gaps
   - Technical evaluation of TENORM geochemistry.
   - Consideration of consequences of hazardous chemical agents associated with TENORM.
   - Dynamic accident modeling and quantitative risk assessment and management for radiological exposure, radioactive waste disposal methods.
   - Comprehensive TENORM exposure pathways survey in all oil and gas drilling, production, processing, and refining, filling stations facilities, workshops, and equipment, as many of them were not surveyed nor assessed yet.
   - Laboratory investigation of the consequences and impacts of TENORM exposure and their biological effects on public health and the environment.

- Lack of scientific-based TENORM waste disposal and management solutions.
- Utilization and recycling of nuclear radioactive materials and wastes associated with TENORM to generate energy.
- Radiological exposure pathways and fate and transport modeling of radioactive waste disposal methods currently used in the oil and gas industry.

Chapter 3 addresses risk assessment and management of TENORM waste disposal options in the oil and gas industry through presenting scenario-based risk assessments of disposal methods commonly used for technologically enhanced naturally occurring nuclear radioactive materials (TENORM) wastes in the oil and gas industry. These wastes fall into four main categories: hard scales, sludge, drill cuttings, and contaminated produced water which contains different types of soluble and insoluble radionuclides with activity concentrations levels that are ranging from low to high level. These wastes belong to uranium-238 and thorium-232 decay series that are likely to be enhanced technologically because of physical and chemical processes associated with enhanced oil and gas recovery technologies. Furthermore, Chapter 3 outlines that the production of oil and gas has increased greatly to satisfy growing demands worldwide for energy and according to many scientific studies, which have revealed that oil and gas production usually accompanied by a massive production of radioactive materials because black shale is known to constitute the most important accessible reservoir of organic compounds of hydrocarbons and the main source of the uranium. This has led to increasing the volume of generated TENORM wastes in the light of daily global production which poses a radiological risk to workers, the public, and the environment in both short and long term. Chapter 3 reveals that serious concern arises as to how to dispose of these massive daily produced wastes in a safer way as compared to the practices currently used that are not systematically based on the scientific evaluations or radiological risk assessments from both engineering and biological perspectives. Also worrisome are the adverse effects of radiological pollution from TENORM waste disposal methods and potential sources affecting workers, the public, food, water resources, soil, and the environment. Chapter 3 considers TENORM waste in the petroleum industry has become a serious concern as a potential issue of radiation and environment pollution.

Chapter 3 emphasizes that the risk of being exposed to TENORM wastes must, therefore, be identified and controlled to protect workers, the public, and the environment. Accordingly, the chapter presents an analysis of TENORM waste disposal options and risk assessment methods commonly used and assesses their effectiveness through presenting an integrated fate and transport model and exposure pathways supported with plausible scenarios to show how contaminants can migrate through the geosphere and biosphere, reaching the environment, animals, and humans. In this context, a real case scenario of TENORM wastes disposed of in an evaporation pond was simulated using RESRAD (Version 6.5) where real data that are dynamically updated were used as input parameters to evaluate the potential radiological doses and increased carcinogenic risk. The simulated results and findings have been validated by comparing the results obtained from similar simulated scenarios constructed from some literature review. Following findings have been concluded in Chapter 3, which are:

- The current TENORM waste disposal alternatives were not necessarily based on the scientific evaluations or radiological risk assessments from both engineering and biological perspectives.
- In most cases, the judgment that radioactive waste disposal methods have been considered to be safe was based on the low-risk values obtained from risk assessments, which are not necessarily 100% accurate because they are not necessarily based on the quantitative and dynamic fate and transport evaluations or not consider the biological effects in their conclusions. The low numerical values obtained from such risk assessments could be substantially based on the uncertainty in each parameter estimation, input assumption, and the final computation of risk factors. Thus, the accuracy of conclusions based on a single deterministic value may be subject to uncertainty that may arise from the following factors:
  - Inaccurate input data or assumptions, or default input made by the simulator, or simulator quality.
  - Some parameters may not be considered or may be inaccurately assumed in the model due to its continual change as a function of time and of the inability of the simulation program to dynamically update these variables as a real-time function. For example, a continuous feed of TENORM waste causes changes in radionuclide concentrations and source term concentrations, yet the input assumptions are of a conservative nature.
  - Dose assessment limitation due to site characterization of progeny radionuclides and the status assumptions of equilibrium/disequilibrium/ingrowth for each sample.
  - Each sample may contain a series of at least 12 radionuclides some of which emit alpha or beta, and others gamma. This makes it hard to quantify the number of radionuclides and their progenies in the

sample; such as radon gas. Consequently, analysis reports of TENORM samples vary from laboratory to laboratory, yielding different figures of final doses and excess risk. It is highly recommended to first segregate the sample contents and use real-time standard measurement tools that can quantify each radionuclide and its progenies amounts.

- Efficiency of measurement tools and data processing.
- To derive single radionuclide and dose-based acceptance criteria, some of the modeling simulators require an understanding of the physical, chemical, biological, geological, and geochemical factors/inputs parameters applicable to the selected exposure scenario(s) to be incorporated in a radiological risk assessment simulator. Additional understanding of the status of equilibrium is necessary to accurately perform a doses/risks assessment in support of doses/risks-based acceptance criteria. Historical information about the site processes/or, selection of appropriate analyses to identify key decay series radionuclide and a comprehensive review of the characterization data are needed to understand the equilibrium status of the present decay series.
- The biological effect should not be generalized or characterized to be similar for all people exposed to different levels of radiation. Not all living cells in the same body are equally sensitive to radiation, therefore, different cell systems in different individuals have different sensitivities to radiation according to the US National Research Council. Many other factors such as differences in genetic structure, medical history, age, and gender type are factors that have a great impact on the biological effects of radiation exposure.

Chapter 3 recommends that to eliminate or minimize the above uncertainties, the use of real-time input data as it has a dramatic impact on results. This is clearly demonstrated by comparing the results of doses and excess carcinogenic risk obtained from the risk assessment of TENORM wastes disposed of in evaporation ponds based on a real scenario (case study 1), with the outcome from similar risk assessments obtained from the literature reviews described in the case studies 2 and 3. A simulation risk assessment program needs to be developed with the capability of dynamic updating of risk factors and other time function variables. It is strongly recommended to integrate important biological parameters in the same simulation program that directly affect life risks, such as medical history, age, gender, current, or historical doses effects versus biological response.

Given the above-mentioned limitations, Chapter 3 argues that the results of risk radiological assessment still indicate that excess carcinogenic risk is caused by exposure to TENORM waste disposal in the oil and gas industry. The comparison of the estimated doses provides a preliminary indication of the relative risks associated with each TENORM waste disposal method. However, the performance of TENORM waste disposal methods and radiological risks to workers, the public, and the environment using radiological risk assessments should not be evaluated exclusively based on the risk value itself, or by comparing the estimated doses with existing or proposed regulatory standards associated with uncertainty and inconsistency where there is no commonly agreed standard about a precise characterization of a safe low radiological dose as well as some are still arguing whether to consider dose limit for radiological exposure in the oil and gas industry as occupational or public dose limit as some guidelines recommended.

Finally, Chapter 3 recommends that the proposed approach related to TENORM waste disposal management can be used as a guideline or model to evaluate the performance and the effectiveness of current and future disposal methods in the oil and gas industry and more researches are urgently required to further investigate safer TENORM waste disposal methods from the perspectives of environmental and human health protection.

Chapter 4 reveals that there is a significant lack of available information regarding dynamic modeling, and quantitative risk assessment of TENORM occupational exposure and most of the available studies so far, have been designed to measure the radioactivity concentrations levels at different oil and gas stream. These studies found that the level of radioactivity concentration can range from low to extremely high levels.

Accordingly, the findings and the measurements have sounded the alarm that many workers in the oil and gas industry, as well as the public, are at the risk of being exposed to different levels of radiation doses. These doses range from low to extremely high levels of radiation under adverse conditions and often exceed the currently acceptable occupational exposure limits for workers exposed to these materials. Unfortunately, these limits have been found to be inconsistent in many available safety standards from one country to another. Chapter 4 argues, according to many laboratories and epidemiological studies available, that regardless of the level of exposure, chronic cancer is the ultimate and eventual consequence of radiation exposure. It is worth mentioning that; it is possible to mitigate accidents involving radiological exposure at an early stage through preventative methodologies, including effective introduction and maintenance of appropriate safety measures and barriers to reducing risk and life-threatening situations. Radiological poisoning from TENORM is cumulative from chronic exposure and thus difficult to identify, especially in the early stages. It can take many years to manifest negative health symptoms. Periodic medical checkups could combat the danger of radiation exposure for cancer and other negative effects, but this is a neglected practice in the oil and gas industry. Chapter 4 introduces one of the effective safety measures to mitigate radiological exposure risks in the oil and gas industry, which is a dynamic accident modeling and risk assessment management of radiological occupational exposure in the oil and gas industry using the SMART approach. This approach integrates SHIPP (system hazard identification, prediction, and prevention) methodology and rational theory (SMART approach). The SHIPP methodology is a generic framework used to identify, evaluate, and model processes of potential TENORM occupational exposure accidents. The rational theory is used to model accident causation behavior that usually contributes to its occurrence based on a logical, inductive, and probabilistic analysis. The basic premise of the rational theory is that an accident occurrence results from joint and conditional behavior among different parameters. The application of the proposed approach was illustrated in Chapter 4 through a scenario of possible occupational exposure at different oil and gas activities including upstream, midstream, and downstream. Overall, the proposed approach provides an integrated framework for dynamic prediction and TENORM occupational exposure risk information update. The outcome of this approach would help to monitor radiation exposure risk dynamically, support the development of effective safety and protective measures, and minimize radiological occupational risks due to its ability to: (i) identify the interaction between systems and their subsystems, as well as the source of TENORM and their distributions in oil and gas extraction and production processes; (ii) identify and analyze all possible TENORM occupational exposure scenarios; (iii) model all possible different occupational radiation exposure scenarios based on the performance of safety barriers using Monte Carlo simulation; (iv) predict and update the failure probabilities of the identified safety barriers; and (v) enable proactive management of TENORM risks using either adaptive risk management techniques or precautionary principle techniques.

Chapter 4 reveals that the dynamic TENORM occupational exposure accident modeling and quantitative risk assessment in the oil and gas industry using the SMART approach was based on the evaluation of the performance of five identified sequential safety prevention barriers and their subelements. These barriers have been assigned by professional academic experts and they are: (1) the Early Detection Safety Prevention Barrier (EDSPB); (2) the Isolation Integrity Safety Prevention Barrier (IISPB); (3) the Personal

Protection Equipment and Exposure Duration Safety Prevention Barrier (PPE&EDSPB); and (4) the Emergency Management Safety in Prevention Barrier (EMSPB). These safety barriers were found to be sufficient to provide enough protection for workers from being exposed to radiological risks. Unfortunately, the five identified sequential safety prevention barriers are mostly absent in many oilfields because of reasons that attribute to the lack of knowledge and understanding, political and economic reasons (because oil and gas industry is considered the most important source of economy for many countries), the lack of radiation exposure accident modeling, and risk assessment studies.

Chapter 4 reveals in the analysis and discussion section that the testing the validation of the dynamic accident modeling and quantitative risk assessment for the radiological exposure in the oil and gas industry using the SMART approach was coupled with a probabilistic methodology for 2272 workers involved at different oil and gas streams. Model validation on three important phases was based comprising; (1) safety barriers' performance analyses and evaluation of five identified sequential safety prevention barriers and their subelements; (2) model prediction and updating; and (3) consequences occurrence probability updating.

The results obtained from this model provided both qualitative and quantitative information about TENORM occupational exposure risk in the oil and gas industry. These results indicated that the posterior probability values for the identified safety barrier failures have drastically increased within the 10-year period, as a result, of system degradation. Chapter 4 reveals that such degradation could be attributed to many factors, the most important being a dearth of dynamic and quantitative radiological risk assessment studies related to TENORM risks in the oil and gas industry. The lack of the dedicated radiation protection legislation for the oil and gas industry, and the fact that many of vital industries that are producing nuclear radioactive materials are reluctant to admit the presence of radiological risks in their operations and avoid any association with the word "nuclear," which is a clear admission that the workers are exposed to radiation risks despite previous studies that confirm nuclear radioactive materials are coproduced with oil and gas production and can range from low to extremely high levels. Moreover, and due to the lack of knowledge, some industries consider exposure to TENORM as same as exposure to low dose and therefore, is safe while this issue is a debating issue in the scientific community while the medical community considers it unsafe according to many recent epidemiological and laboratory studies in relation to the biological effects as a result of the exposure to low-energy doses. Moreover, the implementation cost-cutting philosophy that is commonly used in the oil and gas industry is a potential barrier for acknowledgement and action concerning TENORM risks and inhibits safety barrier improvement. Consequently, no action yet has been taken by the industry to introduce or bolster safety barriers. As a result, the system will continue to degrade.

Based on the obtained results, Chapter 4 concluded that it is apparent that there is an urgent need to develop appropriate safety measures for protection against radiation exposure during the extraction and production of oil and gas. It is equally important to find an effective scientifically based solution to minimize the large production of the volume of radiological nuclear materials created during oil and gas production in the form of radioactive waste that usually disposed of directly into the environment and not based systematically on scientific evaluations or radiological risk assessments from both engineering and biological perspectives. Also worrisome are the adverse effects of radiological pollution from TENORM waste disposal methods and the potential sources affecting workers, the public, food, water resources, soil, and the environment. Therefore, there is an urgent need for more studies in relation to dynamic accident modeling and quantitative risk assessment based on a SMART approach to establishing a successful and thorough TENORM management system to provide enough protection against radiological risks from this neglected field.

Chapter 5 reveals that results from different worldwide field surveys, well-logging data, coring, and drilling cuttings samples confirm enhanced nuclear radioactive materials that belong to uranium and thorium series in the oil and gas production where different levels of radioactivity concentration were recorded that vary in a range from low to high levels. They have also reported that a huge volume of nuclear radioactive waste is produced annually by the oil and gas industry along with oil and gas production. Moreover, many other studies took different measurements of nuclear radioactivity at various stages of oil and gas extraction and production processes. All these studies have confirmed the existence of uranium, thorium, and number of important minerals in the geological formation that contain hydrocarbons. However, these natural sources of energy are not utilized so far and instead, unfortunately, are currently being disposed of as waste directly into the environment causing serious threats to the environment, the public, and future generations. Accordingly, Chapter 5 sheds the light on this issue and presents some important scientific recommendations that emphasized on the importance of how to recover the abundant deposits of natural uranium, thorium, and many other elements that are available in geological formation hosting hydrocarbons. And how to get the benefit of producing them with oil and gas production and exploiting them as another source of energy. Scientific and practical proofs have been presented in Chapter 5 to explain how uranium, thorium, and many other valuable minerals are economically feasible to be extracted and produced along with the oil and gas extraction and production processes rather than dumping them as wasted energy directly into the environment that eventually causes a radiological issue.

Chapter 5 outlines that from an economic point of view, uranium and other nuclear materials can be extracted from the reservoir that contain hydrocarbons and from other geological formations through exploiting the same process currently used for oil and gas extraction and production processes, which are identical to the process used for in situ uranium recovery in the modern uranium mining industry in terms of exploration survey, drilling procedures, gathering and separation processes, and enhancement recovery technology including lixiviant, injection, and production wells. This new integrated technology to recover both oil and uranium is called In Situ Oil and Uranium Recovery Technology. This new technology will play a significant role in numerous peaceful applications of atomic energy by providing the raw nuclear materials that can be used for nuclear power generation, or as radiotracers, and many other safer applications.

Chapter 5 summarizes five important advantages that can be gained from the adoption of In Situ Oil and Uranium Recovery Technology in the oil and gas industry, which are: (1) besides oil and gas production from the oilfields, a new source of nuclear energy raw materials including uranium and thorium can produce a vital tributary that can be used on the peaceful applications of the atomic energy; (2) huge cost saving since exploration, extraction, and production process and other ancillary enhanced oil recovery technique are already existing, and they will use the same for extracting uranium, thorium, oil and gas, and other valuable minerals. The only thing required in the existing facilities is the uranium separation facility to be attached to the existing oil and gas gathering and production stations in the oilfield; (3) less environmental footprints and pollutions; (4) processing and converting of huge volumes of radioactive waste that are daily generated from the oil and gas industry into energy will permanently help to get rid of current nuclear radioactive waste disposal methods used by the oil and gas industry that pose a serious threat to the public health, environment, and future generations; and (5) minimize radiological risk.

Chapter 5 reveals that the adoption of the In Situ Oil and Uranium Recovery Technology in the oil and gas industry may take some time as it will be subject to more studies and researches. Therefore, an urgent solution is required to provide scientific solutions to protect people working in the oil and gas industry from being exposed to radiological risk. Thus, five sequential and interconnected safety barriers for radiation prevention have been introduced as crucial in providing enough protection against occupational nuclear radiological exposure risks during the oil and gas extraction and production processes, which are: (1) EDSPB; (2) IISPB; (3) PPE&EDSPB; (4) Emergency Management Safety Prevention Barrier (EMSPB); and (5) Management and Organization Safety Prevention Barrier (M&OSPB). More attention has been paid in this chapter for leaded shield personal protection equipment (LPPE), which should be made of a composition of a strong, lightweight, leaded layer, or any other similar materials which is known to be the best shielding material against gamma radiation because of its high electron density. Such material need to be blended with other safe and lightweight material that has high electron density to increase the overall number of electron clouds, as well as this composition, can be also mixed with polyethene C_2H_4 polymers that contain more hydrogen atoms. Fast emitted particles or energies will be slowed by collision with hydrogen atoms, which will be able to absorb high emitted energy such as gamma radiation, fast neutrons. These polymers are known for having high linear energy transfer and therefore, can absorb and scatter the emitted radiation or energy. When this composition is used as a shield, then gamma electromagnetic wave other emitted particles that are trying to penetrate this fabric will first collide with the high density of electron clouds, and then their energy will be absorbed and scattered by the hydrogen atoms of the polyethylene C_2H_4. LPPE must be used by all workers involved in different aspects of oil and gas extraction and production activities, including drilling crew members, work-over crew members, well services and intervention crew members, workshop technicians, flow line crew members, workers in production, gathering stations, and refineries or petrochemical or other related industries relying on hydrocarbon products that contains nuclear radioactive materials.

On the other hand, Chapter 5 outlines that the adoption of the In Situ Oil and Uranium Recovery Technology in the petroleum industry may take some time since more studies and researches are required. Since then, it is crucial to have a scientifically based solution able to treat the huge amount of daily produced nuclear radioactive wastes during production processes, which is a major concern that poses serious risks to the environment, the lives of the people, and future generations. Therefore, a novel of Thermo-chemi-nuclear Conversion Technology (TCT) has been introduced to treat different forms of nuclear radiological waste produced. Not only that, this technology is designed to manage nuclear wastes along with household, sewage, industrial effluent, and hazardous wastes, and eventually convert them into fuel and renewable energy. Chapter 5 describes the main processes of the TCT that comprises of: (1) waste feed and handling; (2) thermo-chemi-nuclear treatment; (3) cooling and condensation; and (4) energy generation. Chapter 5 describes the working principle of the TCT, in which nuclear radioactive waste, contaminated formation water, scale, sludge, and many other types of waste such as contaminated scraps, contaminated soils, garbage, household waste, construction waste, and sewage waste are processed in two different processes, which are gasification process, and chemical and nuclear treatment process. These wastes are converted into syngas and subsequently cooled and refined into a clean renewable synthesis fuel. On the other hand, the radioactive waste is segregated according to their types and sent to nuclear facilities for further treatment or undergo series of nuclear transmutation reactions in a nuclear reactor that contains particle accelerators in which energetic subatomic particles are bombarded toward a target nucleus according to the common modes of nuclear decay reactions and eventually be converted into a stabilized atom. This way the treated materials can be used safely later for any industrial application as road construction materials, for example, or it can be further enhanced to generate more energy according to the "principle of energy production from the radioactivity" so that it can be used to generate electricity.

As it has been mentioned earlier that, the available studies indicate that there is inadequate awareness of the oil and gas industry worldwide about the issue of worker protection from radiological risks, and about the proper disposal of radioactive wastes into the environment. Accordingly, scientists and experts fear that workers involved in the production and maintenance stages of the oil and gas industry, as well as the general public and the environment, are at risk of being exposed to different levels of radiation levels. Thus, Chapter 6 investigates the role of international atomic agencies in regulating and legislation of radiation protection and the management of radioactive waste as well as attempts to reveal answers to some important questions. For example, it explores if available guidelines and regulations provide adequate protection for workers, the environment, and communities against radiological issues caused by the oil and gas industry. It also attempts to address if the available regulations and guidelines are based on the scientific details and justifications and if they offer generic guidelines that alert industry workers to potential harm and provide a general caution, or they are offering detailed scientific recommendations based on characterizing the nature of the radioactive materials and radiation exposure pathways in the oil and gas industry.

Furthermore, Chapter 6 also investigates if the fact recommendations for radioactive waste disposal methods specific to the oil and gas industry are efficient and clear or vague and subject to interpretation. As well as if the fact and the guidance in these reports are optional, or mandatory, or leave the decision to the industries themselves to choose which policies and guidelines they wish to implement. Finally, it examines if there is an urgent need a further science-based investigation to manage these issues adequately or not.

Chapter 6 highlights how the issues of radiation protection and radioactive waste disposal have been approached in the oil and gas industry, and what improvements can be made to existing safety standards and regulations. It also outlines what role international atomic agencies currently play in regulating and legislating radiation protection and radioactive waste disposal in the oil and gas industry. Furthermore, it posits the need for a scientific approach to examining the efficiency and efficacy of current standards and regulations, with attention to the controversies and inconsistencies that exist in the characterization of nuclear radioactive materials and their waste. It has been found that there is a variation between the theoretical and regulatory guidelines and the actual practices of state-owned companies (SOEs), which are not fully aware of the environmental dangers associated with the radioactive waste that forms during the extraction and production and this is due to the lack of knowledge, science-based justifications, or due to economic and political reasons.

Chapter 6 outlines the role of some of the well-known international atomic agencies in regulation and legislation. Such regulatory and legislative reports include the IAEA's Safety Report no. 34 "Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry; Guidelines for the Management of Naturally Occurring Radioactive Material (NORM) in the Oil and Gas Industry" (2003), the IOGP's Report no. 412 "Guidelines for the management of Naturally Occurring Radioactive Material (NORM) in the oil and gas industry" (2008), and the ICRP's recently released drafted report to the public for consultation "Radiological Protection from Naturally Occurring Radioactive Material (NORM) in Industrial Processes" (2019).

The IAEA's Safety Report no. 34 consists of seven sections alongside four appendices. Overall these sections outline the best practices of the industry and provide practical guidance for radiation projection. The IAEA's Safety Report no. 34 is very general and based on the best industrial practices that only provide advisory options for controlling radiological risks in the oil and gas industry rather than mandatory preventative measures. This could be obvious, for example, in Section 5.5.4 "Practical radiation protection measures" the requirements mentioned in the BSS for safety and radiation protection through the implementation of ALARA principles to keep radiation doses as low as reasonably achievable, whereas ALARA principles are themselves a controversial issue in the scientific community because they are associated with uncertainty elements. Implementing this philosophy is, however, challenging, due to economic and social factors, as well as the fact that the exposure that occurs due to external and internal contamination require different practical measures and solutions. In this vein, Section 5.5.4.1 offers set measures to limit external radiation exposure, which are: (i) reduce the duration of any mandatory external exposure; (ii) ensure distance between accumulated NORM and possibly exposed people; and (iii) maintain shielding material between NORM and possibly exposed people. While it is scientifically important to recognize that these measures are only possible in those areas that have known radiation variables and characteristics. That is, they are only applicable in controlled environments. These measures are not viable in cases of random radiological variables and exposure such as the case of different activities in the oil and gas industry.

In another occasion, The IAEA's Safety Report No. 34 outlines very briefly in Section 5.6.5 the common disposal methods used in the oil and gas industry. In describing disposal procedures for solid and liquid NORM within the industry. While the described disposal procedures and disposal methods mentioned by IAEA are not necessarily in line with the best international practices based on the sound scientific evaluation. Even the IAEA has stated that previously regulatory safety review, as well as oversight and protection, were not thoroughly considered and enforced. In this context, the IAEA's Safety Report No. 34 Lamentably, indicates that NORM waste may be disposed of as nonradioactive (normal) waste in consonance with the criteria for the clearance of NORM waste, which can be found in Clearance Levels for Radionuclides in Solid Materials: Application of Exemption Principles (IAEATECDOC-855, Vienna—1996). Many scholarly studies have revealed that nuclear radioactive wastes produced by many oil and gas industries were exceeding the exemption limits set by IAEA and are often disposed of as nonradioactive wastes. This arises due to both limited knowledge on the part of the industry, as well as due to a lack of scrutiny by regulatory bodies and authorities. Furthermore, in Section 5.6.5.2, the IAEA states that risk assessment is a key component in selecting NORM waste disposal methods. While this assessment can be qualitative or quantitative, many industries, such as in the United States, focus on qualitative risk in selecting a disposal method. This type of qualitative risk assessment often relies on historical data and assumptions that may not be appropriate in the presence of a scientific revolution. It introduces, therefore, a significant element of inaccuracy and unreliability. Risk assessment alone is not a substantial basis for the selection of an appropriate disposal method as many other factors require consideration. These factors include efficiency, as well as mathematical fate and transport model, exposure pathway modeling, radioactive waste characteristics such as the radionuclides types, radioactivity concentrations, the physical and chemical forms, and half-life of the dominant radionuclide. There are also significant site-specific factors, which include climate, geology, and groundwater and surface water characteristics. These have a notable effect on the feasibility of any NORM waste disposal method and procedures that must be included in the decision-making process.

On the other hand, the recommendations mentioned in Appendix I of Safety Report 34 discusses monitoring radiation in the workplace, including both general principles for monitoring radiation and different types of instruments for the job that leaves the door open for the industry to interpret for itself on which instruments are most applicable to radiation protection. While the selection of the appropriate instrument or the reference level depends on many factors such as exposure conditions, dose rates, and biological effects that are also associated with uncertainty. Accordingly, there is an urgent need for systematic and thorough investigations that should be drawn from scientific, quantitative methods. These investigations must address both radiation protection for workers during the extraction and production of oil and gas, as well as appropriate and effectual radioactive waste management processes based on the scientific evaluation rather than best practice. Investigations must, particularly, address the fact that often the wastes generated exceed the exemption levels set by the IAEA. Furthermore, present methods of radioactive waste disposal in the oil and gas industry lack oversight from a dedicated regulatory body for the industry, and therefore, fail to provide adequate protection for workers, the environment, and communities.

While the IOGP's Guideline Report No. 412 is brief, it only comprises 42 pages. It constitutes only a succinct, collective guideline that can operate as a road map for the industry, rather than as an extensive model that is able to address radiation protection and radiological waste management from a scientific perspective or offer robust science-based solutions. It presents scientifically controversial conclusions in many places in this report. For example, in Sections 1.6 and 1.7 provided controversial and general conclusions in relation to the health effects of exposure to NORM. For example, it notes that "the health effects associated with exposure to ionizing irradiation vary depending on the total amount of energy absorbed, the time period, the dose rate and the particular organ exposed." And, moreover, "chronic exposure to NORM above exposure limits for the general public or following inadequate safety precautions are typically delayed effects such as the development of certain forms of cancer." To a large extent, this is true, but there are many other important factors that play an important role in this regard and need to be carefully considered. It is, therefore, important to further medically study the biological effects of NORM exposure. However, the IOGP presents some scientifically controversial conclusions within the section, suggesting that medical surveillance operates as a nonspecific and imperfect tool and that exposure to low doses may be considered safe. The IOGP, therefore, places emphasis on source control and dose monitoring, and undervalues the place of medical surveillance in understanding and controlling the effects of radiation exposure—a place that has been established through decades of scientific research that has likewise proven that even exposure to low doses of radiation can cause damage to DNA and therefore, poses a serious health risk.

Section 1.7 turns to the environment and examines "Environmental Problems Associated with NORM." However, these problems are reduced to a mere three lines: "Handling, storage, transportation and the use of NORM-contaminated equipment or waste media without controls can lead to the spread of NORM contamination, and result in contamination of areas of land, resulting in potential exposure of the public." This brief summary lacks appropriately detailed or scientific discussion of disposal methods for radioactive waste and associated risk assessments and further ignores safe handling methods, storage, and discussion of transportation, which are all paramount environmental concerns. It also fails to produce scientifically based solutions for minimizing environmental impacts in any transparent or practicable way. It also fails to produce scientifically based solutions for minimizing environmental impacts in any transparent or practicable way.

Accordingly and based on what has been provided in Section 1.7 of the IOGP's Guideline Report No. 412, it may not be sufficient for the industry to perform well in relation to radiation protection and radiological waste management. Instead, it provides a functional framework for action that requires integration with other sources and further research.

On the other hand, the newly ICRP's proposed guidance on industry assessments of radiological hazard and attendant protections comprises five chapters. It is generically designed for all industries involved with NORM and is not specific to the oil and gas industry. Furthermore, as of yet, it contains many controversial conclusions that have not been adequately tested through scientific inquiry.

In this vein, ICRP offered some controversial conclusions within Chapter 3 of its proposed guideline. For example, it states that "doses resulting from the process in which NORM is concentrated are expected to remain relatively low whatever the circumstances," and implicitly indicating that such exposure poses no health risks, which is somewhat at odds with their prior conclusions and other scholarly studies that prove the opposite. This is a generalized and preemptive conclusion that has not been substantiated by biological, epidemiological, or laboratory studies. Many available scholarly studies have demonstrated that even low doses of radiation can damage DNA and, thus, have a biological effect. Accordingly, the issue of low-dose exposure requires further scientific investigation, as do various factors related to its proper management before this type of conclusion can be made. This is not the only controversial claim presented in Chapter 3. Elsewhere, the ICRP suggests that occupational dose limits need not apply to workers who are not considered occupationally exposed. That is, that dose limits do not apply in situations where NORM is present without intentional purpose, and rather exists as a natural fact. However, NORM may have health and safety effects whether or not said exposure is extrinsic or adventitious. In Publication 126, which draws from Publication 65 (2014), it indicated that those workers who are not considered occupationally exposed should be treated in the same manner as members of the public. However, elsewhere in that same guideline, it indicated that the exposure of said workers should nonetheless be considered.

Another area where the report generates potential contention is in its principles for decision making. We should base the principles for decision-making procedures for radiation protection on justification, optimization, and limitation. These principles state that it shall introduce no practices unless they yield a positive net benefit. They also demand that exposures be maintained at levels that are as low as reasonably achievable, that individual doses not exceed the limits recommended for the circumstances by the Commission, and that consideration is given to economics and social responsibility. Despite being well intentioned, however, these three principles remain a controversial issue within the scientific communities due to their necessary and attendant elements of uncertainty. A special concern is the scientific, quantitative analysis of what constitutes low, reasonably achievable, and safe.

Accordingly, this report still requires further scientific review. Specifically, dose limits and ALARP or ALARA recommendations need to be further addressed as they are a subject of a great scientific debate in the scientific community especially as they concern the oil and gas industry. Whereas, radiological issues in this particular industry are always associated with random variables, as well as they are always time function variables. Accordingly, conclusions must be further verified through detailed scientific assessment, as well as considered via quantitative risk assessment, and dynamic modeling.

Chapter 6 presents an important conclusion that the available guidelines and regulations often act as a guiding source for managing similar approaches in relation to the management of NORM from different industries and trying to standardize the same procedures to make it implemented in all industries producing radioactive materials in a convenient manner and not mandatory. Available guidelines and regulations are also unable to differentiate scientifically between NORM and TENORM, which makes a major scientific difference and a major risk in the process of drafting guidelines and regulations according to the associated risk level and characteristics. Furthermore, the currently used guidelines and regulations do not form any type of mandatory management principles rather it only recommends and explains the various controls that are regulated according to various working practices. They lack scientific justifications, compulsory, and detailed instructions for industry-specific practices, as well as quantitative information on risk assessment. They, furthermore, consider the radiation levels associated with the oil and gas industry to be low, and not in excess of background radiation, therefore, they pose no risk. Despite numerous scientific studies that indicate elevated levels of radioactivity concentrations, and extremely high levels of radiation, in many industries around the world. Accordingly, these guidelines offer incomplete information and exist only as a starting point that needs further development to become reliable and more effective in providing the required protection for workers, public, and the environment. It is important that public and industry to be engaged with different stakeholders and authorities to create feasible and reliable regulation that can provide the required level of protection and management. Such regulation must be mandatory and controlled by nuclear commissions authorities otherwise this makes industries to act as self-regulators in controlling and managing exposed radiation and radioactive waste the way that meets their capabilities and limited awareness.

Finally, Chapter 7 argues that the biggest energy companies worldwide are either fully or partly owned and are operated by the government. Government-operated companies, commonly called SOEs, control about 75% of the world's crude oil production. Apparently, the state-controlled oil companies are not fully aware of the environmental dangers associated with radioactive waste coproduced along with extraction and production of the hydrocarbons. Furthermore, the same corporations are rarely enthusiastic in revealing their plans or strategies for the management of radioactive wastes that are produced daily in massive quantities. They base the attribution of such behaviors on the lack of knowledge and understanding as well as political and economic interests that may trump and dominate social concerns that are projected regarding the environmental consequences. This could reveal why the inadequate disposal methods used to get rid of radioactive wastes issues in the oil and gas industries are subtle and concealed from the public. Therefore, the radiological issue becomes a serious public issue.

Unfortunately, the technological risks such as radiological risks associated with the production of oil and gas are increasingly politicized and highly contentious. While this is also due in part to a lack of public knowledge about these risks, it is also the result of government efforts to maintain the highest level of state income to ensure continuity of power at the expense of the public interest in the absence of the mandatory safety standards, guidelines, and regulations that are based on the scientific justification and are especially designed for the oil and gas industry in relation to radiation protection and radioactive waste management. As a result, there is a lack of public participation in the formulation of safety laws and policies in the oil and gas industry. At the same time, these efforts have destabilized trust in political systems and reduced levels of nuclear awareness.

The significance of trust and the link between national participation and the dynamics of the political systems have serious implications regarding technological risks, particularly in the oil and gas industry, which is recognized as the biggest economic sector both globally and locally. It is important to further investigate from legal and technical perspectives to what extent the current radiological risk management system can protect the workers, the public, and the environment from radiological exposure. Furthermore, there is also a risk to the public through radiological pathways that contaminate soil, water, and food sources due to the current disposal methods of radioactive materials that are either stored near the surface or underground. Incidentally, these disposal sites are later developed into residential sites, industrial sites, or commercial premises that can amplify the radiological risk to us and our grandchildren and their descendants. Radiological risks from the oil and gas industry threaten public health and the environment and are thus a matter of public concern that requires their participation in this public issue to increase their awareness. Accordingly, Chapter 7 focuses on the relationship between the legislation and politics related to radiological issues in the oil and gas industry, and the laws associated with this industry that are inadequate to provide enough protection to both human health and the environment from the radiological risks.

Chapter 7 addresses the political conflict in regarding nuclear radioactive waste management and outlines some examples of governments that put their political and economic interests as top priorities and at the expenses of the protection of their people and environment. Greater public participation in technological risk policy legislation is usually regarded as a sign of a healthy and lively democracy. This study highlights the importance of public participation in conferring legitimacy on public institutions and remedying the "truncated democracy" syndrome. Public participation has been the straw that breaks the camel's back, making nations as powerful as the UK and the US heed public demands to change their nuclear radioactive policy, in the management policies of radioactive wastes, given the serious risks to health, the environment, and natural resources and the economy.

Political conflicts and legislative inconsistencies hamper the management of technological risks such as nuclear radioactive risk. This is considered a characteristic problem of a "truncated democracy." Thus, Chapter 7 reveals that according to many available pieces of literature usually technological risks and its consequences in different energy industries are associated with uncertainty. Therefore, public participatory approaches to policy development have been applied in various sectors that have shown excellent results and success according to some scholarly studies. These include strategic environmental assessments, energy efficiency, and renewable energy strategies.

Different approaches to public participatory development can be used in different political regimes, such as multicriterion decision-making approaches and a postnormal science (PNS), which is a form of evidence-based decision making. Such approaches enhance public participation. And when the public becomes more informed, a direct domino effect ensues as citizens are given an avenue to voice their concerns on technological risks. Accordingly, Chapter 7, thus proposes a framework for engaging public participation, which together with government legislation can ensure workers' safety, public health, and the environment. A systematic approach is presented to maximize the efficiency of public engagement in the process of policy making and decision making via an independent voluntary community panel comprising academic and technical experts with multidisciplinary expertise. These experts can examine the scientific and technical evidence and related legal issues to mitigate radiological risks associated with TENORM from the oil and gas industry. The main duties of this panel would be to carry out state-of-the-art assessments of the range of impacts of TENORM risk from the oil and gas industry and its associated technologies in terms of the health and safety risks issues that people perceive as relevant to everyday life, such as cancer due to TENORM exposure; TENORM disposal methods that could contaminate water, soil, and food resources; radiological risk to a family member working in the oil and gas industry; and environmental damage and the radiological effects of TENORM on future generations.

Chapter 7 finally insists that it is a prerequisite of a mature and healthy democracy that the public is engaged in policy making directed at mitigating crucial and sensitive issues. Therefore, supporters of deliberative democracy must endeavor to convince political regimes and legislatures to engage the public in decision making related to nuclear radiological policy to minimize radiological risks at the local and international levels.

Glossary of Terms

Absorbed dose The concentration of ionizing radiation deposited in or absorbed by a mass unit of tissue, often measured in rads in the non-SI system, or in the gray (Gy) in the SI system, which is defined as 1 J of energy absorbed per kilogram of matter. It is used to assess the potential for biochemical changes in specific tissues.

Accident An event that happens unintentionally and unexpectedly, typically causing damage to humans, property, or the environment.

Accident modeling A technique used to analyze why and how an accident occurs by modeling it in a scenario. It is used to predict and to characterize accidents.

ALARP An acronym standing for "as low as reasonably practicable." Also associated with **ALARA** or "as low as reasonably achievable." It is a term often used in risk assessment and risk management.

Appraisal well A vertical or deviated **well** drilled in order to assess the viability of a hydrocarbon reservoir prior to commercial production.

Atom The smallest unit of ordinary matter and comprises of the nucleus. The nucleus is comprised of positively charged protons and, typically, a similar number of neutrons, which have no electrical charge that prevent the repulsive forces between protons. Protons and neutrons are referred to as "nucleons." There are electrons orbiting around the nucleus and they are negatively charged. When the number of protons and electrons are equal, the atom is said to be electrically neutral, whereas if it has a greater or lesser number of protons, it is said to be positively or negatively charged, accordingly.

Bayesian updating theorem A mathematical inference used to update the posterior probability of a hypothesis that was based on prior knowledge, as more evidence or information becomes available.

Biological effects of radiation The harmful biological outcomes that result from exposure to ionizing radiation, whether to human beings or other living organisms. If cells fail to repair themselves, those cellular effects can include transformation, mutation, chromosome aberration, or cell death; alternation in or delay or increase of cell division; and genetic transmission of cell changes to nascent cells.

Chronic exposure A state of continuous or long-term exposure to or contact with radioactive materials or other toxic substances.

Conditional probability The likelihood that an event (Event B) will occur, given the knowledge that another event (Event A) has already occurred. The probability of Event B occurring is conditional on Event A's occurrence.

Decay chain A series of radioactive decays of different radioactive decay products, referred to as a sequential series of radioactive transformations of unstable atoms to become stable ones.

Deductive reasoning A process of formal reasoning wherein a concordance of premises leads to a specific and logically certain conclusion. If the premises are true, and the principles of deductive reasoning are used, the conclusion must also be true.

Dynamic modeling Is a dynamical process that describes the dynamic change in the behavior and interaction of system components. It describes the behavior of a system over time.

Effective dose Represents the stochastic risk to the whole body from of nonuniform exposure to radiation. Its unit of measurement is the Sievert (Sv) in the SI system.

Enhanced oil recovery technology (EORT) Technologies used to increase the amount of oil that can be extracted from a reservoir. Usually this entails injecting a substance into an injection well in order to increase depleted pressure and reduce the oil's viscosity in the reservoir.

Equivalent dose A dose amount (H) represents the stochastic effects and used to assess the expected biological damage from an absorbed dose of radiation, considering that different types of radiation having different effects. The unit of measure is the Sievert (Sv) in the SI system.

Exploration well A borehole that is drilled in order to determine the presence of oil or gas.

Exposure pathway The avenues through which persons, animals, plants, or environments can be exposed to a hazardous substance. The primary exposure pathways are: inhalation, ingestion, and direct contact.

Failure probability The likelihood that a system or system component will fail at a given time.

Floating production storage and offloading (FPSO) unit A floating vessel or platform used in the offshore oil and gas industry for producing, processing, and storing hydrocarbons.

Formation water or produced water Naturally occurring water in the pores of a rock, or water that is pumped into a geological formation containing hydrocarbon in order to increase formation pressure or to sweep oil that remains between pores.

Gamma radiation Electromagnetic energy (photons) emitted by some radionuclides as a product of radioactive decay. Gamma photons constitute the most energetic photons on the electromagnetic spectrum.

Gasification A thermochemical process that converts carbon-containing materials into a synthetic gas. These materials can include waste and biomass. The resultant gas can be used to produce electricity, as well as chemicals, fuels, and fertilizers.

Geochemistry A discipline that applies the principles and tools of chemistry to major geological systems in order to assess their chemical composition and attendant chemical reactions. It describes the chemical activity that takes place within the earth's crust.

Half-life The time taken for half of the atoms comprising a radioactive material to disintegrate during radiological decay.

Hazard A potential source of danger that can cause injury to humans, or damage property or the environment.

HEMP An acronym standing for "hazard and effect management process." In instances where there is a failure in controls, HEMP is one of the primary tools employed by the oil and gas industry to mitigate risks in the workplace, as well as to manage equipment, properties, and environments.

Human error An action, either intentional or unintentional, that does not adhere correctly to policy or procedure, and that may lead to consequences such as injury, harm, or loss. It is considered the foremost contributing factor in industry disasters and accidents.

Hypothetical scenario A conjectural circumstance that is proposed in order to introduce a logical constant. Such scenarios can be used to identify missing data or plan responses.

Inductive reasoning A process of reasoning wherein multiple premises that are viewed as true are combined to supply evidence for a conclusion. The conclusion of an inductive argument is typically general, and probable rather than certain.

Inorganic basis theory or metallic theory A theory that states that the origin of petroleum is inorganic. It holds that petroleum was formed by water composed of unsaturated hydrocarbons reacting with deposits of metal carbides at high temperatures, resulting in the formation of acetylene that then condensed to heavier hydrocarbons.

In situ recovery (ISR) A process in mining that entails drilling boreholes in a formation and injecting a lixiviant solution in order to dissolve minerals that naturally occur in a solid state in order to recover other minerals, such as uranium.

Ionic exchange A reversible chemical process in which a reaction is typically used for softening or demineralizing water, purifying chemicals, or separating substances. It entails a reversible interchange of one kind of ion in an insoluble solid with another of the like kind in a surrounding solution.

Ionizing radiation The process through which an atom is charged or ionized. This occurs when radiation has enough energy to remove tightly bound electrons from the orbit of an atom.

Isotopes Atoms that have an equal number of protons and electrons and, hence, the same atomic number, but a different number of neutrons. This means that isotopes which have different atomic mass and physical properties, but will have the same chemical properties.

Joint probability The likelihood of two independent events occurring at the same time.

Legislation The process of enacting laws or a collective body of laws.

Linear no-threshold (LNT) model A model used in radiation protection to quantitatively describe radiation exposure and risk, that is, dose and effects. The model shows a linear proportional relationship between dose and effects with no threshold; cancer risk increases with dose. Nonetheless, low dosages still pose a risk of adverse effects.

Lixiviant A liquid medium, such as a groundwater solution that is mixed with oxygen, used to extract a desired metal from a formation. It is used in hydrometallurgy.

Marginal probability The probability of a single, random event occurring, not conditional upon and irrespective to the occurrence of other events.

Modes of radiation exposure The two principle modes of exposure to ionizing radiation are external and internal exposure. External exposure occurs through direct skin contact. While, the internal exposure occurs through inhalation, ingestion, or other activity whereby a radionuclide enters the bloodstream.

Morbidity The rate or incidence of a specified disease in a population. Morbidity may be age or gender specific.

Mortality The age or rate at which people perish due to a specific cause or several combined causes.

Multiple-criteria decision-making (MCDM) or multiple-criteria decision analysis (MCDA) A process that entails the evaluation of multiple and conflicting criteria during decision-making. These criteria can conclude quality, cost, and risk.

Nuclear The energy produced by the nucleus of an atom when it is divided, decays, or joins another nucleus.

Nuclear Safety Commission A governmental agency in charge of regulating the use and safety of nuclear energy and materials.

Occupational safety The protection of employee health and well-being in the workplace.

Onshore and offshore drilling Drilling processes for the extraction of natural resources, typically oil and gas. Onshore drilling entails drilling under the earth's surface, while offshore drilling entails drilling under the seabed.

Organic basis theory A theory that states oil and gas are formed from the remains of formerly living organisms, especially marine organisms. These organisms mixed over time with sand and minerals to form sedimentary rock in the high-temperature environments that arise when the earth's crust moves due to volcanic activity. Due to this volcanic activity the rock forms layers, which produce organic residue containing hydrogen and carbon.

Political That which is related to the governance or public affairs of a nation, including circumstances wherein an organization acts in the interests of a state power.

Political system The formal and legal institutions that constitute a state or government.

Pollution The introduction of contaminants into an environment, often leading to adverse changes, harm, damage, or loss to the people, assets, and the environment.

Posteriori knowledge Knowledge that requires evidence to be proven.

Posterior probability A revised calculation of the likelihood of an event occurrence. It is calculated by using Bayesian updating theorem to update a prior probability.

Postnormal science (PNS) A novel approach developed in the 1990s by Silvio Funtowicz and Jerone R. Ravetz, it is a scientific approach used in cases where "facts are uncertain, values in dispute, stakes high and decisions are required urgently" until the debated issue become scientifically proved.

Prior knowledge Knowledge that is already available based on experience or historical data. Prior knowledge may be accurate or inaccurate. Such knowledge may be self-evident and therefore not require proof.

Prior probability A term used in Bayesian statistical inference, which is the likelihood of an event's occurrence, based on previously available data (historical data).

Probability A branch of mathematics that entails calculating the likelihood that an event will occur. Probability is expressed as a number between 0 (will never occur) and 1 (will always occur).

Producing well A borehole that is drilled and is found to produce oil or gas.

Prompt fission neutrons logging A process that entails a pulsed source of neutrons flux, emitting about 108 neutrons per second. This accelerates deuterium ions into a tritium. The neutrons flux target geological formations and collide with U-253, which leads to the slow-neutron-induced fission of U-235 into the formation. Epithermal neutrons and thermal neutrons that return from the formation following fission are counted separately in an epithermal/thermal neutron detector. This detector indicates the percentage ratio of U-235, the ratio of epithermal to thermal neutrons being directly proportional to that percentage.

Qualitative risk assessment A process that qualitatively characterizes the level of risk associated with a particular hazard or activity by assessing the probability of injury and the severity of the associated consequences, typically by drawing from historical data. Risk matrix is an example of this type of assessment.

Quantitative risk assessment A process that entails a numerical estimate of the probability of the risk or the defined risk that will result from a particular hazard. It is sometimes referred to as probabilistic risk assessment (PRA).

Radiation The emission of energy as electromagnetic waves such as gamma radiation or as particles, such as alpha and beta particle, through a material medium or through space.

Radiation protection or radiological protection A practice that has been defined by the International Atomic Energy Agency (IAEA Safety Glossary—draft 2016 revision) as "The protection of people from harmful effects of exposure to ionizing radiation, and the means for achieving this." The IAEA also states. "The accepted understanding of the term radiation protection is restricted to protection of people," while some organizations such as ICRP extends the definition to include the protection of non-human species or the protection of the environment.

Radioactive decay (nuclear decay or nuclear radiation radioactivity) The process wherein an unstable atomic nucleus stabilizes by emitting excess energy in the form of radiation, such as alpha and beta particles, or electromagnetic waves, such as gamma radiations.

Radioactive waste Any material whether it is liquid, gas, or solid, that contains a radioactive nuclear substance and is produced via nuclear power generation, nuclear fission, or nuclear technology or from other applications such as the oil and gas industry, mining, and research and medicine.

Radioactivity concentration The amount of activity per unit mass or volume of material wherein radionuclides are essentially distributed uniformly. In the SI system it is measured in becquerel per gram (Bq/g), where Bq is the number of radioactive transformations that occur in a particular radioactive isotope per second.

Radionuclide An atom with excess nuclear energy, making it unstable. When a radionuclide decays it emits nuclear radiation.

Rational reasoning theory A systemic process that entails logical, inductive, and probabilistic analysis. It is used in risk management and to rationally appraise active and passive factors within a system and subsystems that can contribute to an accident through investigating the performance of identified safety prevention barriers.

Redox Refers to a "reduction-oxidation reaction," a type of chemical reaction wherein a change occurs in the oxidation state of atoms. Oxidation refers to the loss of electrons by a molecule, atom, or ion, and an increase in oxidation state, while reduction refers to a gain of electrons by a molecule, atom, or ion, and decrease in oxidation state. It is a type of complementary reaction.

Regulations Rules or orders issued by a government, a regulatory agency, or an executive authority that have the force of law.

Risk The likelihood of occurrence of unwanted events such as injury or harm, often as a result of exposure to hazards that may result in various levels of consequences.

Risk assessment A systematic process that entails hazard identification and an evaluation of the risks involved in a certain activity, alongside an appraisal of potential consequences. This process can be either qualitative or quantitative.

Safety Reasonable protection from the risk of harm or injury, or loss or damage that can inflict on property or people or environment, whether it is accidental or deliberate. It judges risk acceptability.

Safety prevention barriers Physical or nonphysical barriers used in the prevention, mitigation, and control of accidents or other undesirable events.

Secular equilibrium A situation wherein the production rate of a radioactive isotope is equal to its decay rate, resulting in a constant quantity. This occurs when the half-life of the daughter radionuclide is much shorter than that of the parent radionuclide.

Seismic survey A process that involves using a seismograph and induced shock wave reflections in order to determine rock patterns and investigating geological and geophysical properties of the geological formation.

Spectral gamma-ray logging A method of characterizing and evaluating the rock or sediment in a borehole or drilled hole by measuring its naturally occurring gamma radiation.

State-owned enterprise (SOE) A legal entity that engages in commercial activities on behalf of a government. It can be owned either partially or fully by that government.

Total organic carbon (TOC) A critical parameter that is calculated to determine and evaluate the quality of an oil and gas reservoir of any source rock. Carbons, including kerogen, bitumen, and hydrocarbons, are typically present in all organic components of rock.

Uncertainty Refers to situations that involve imperfect or incomplete knowledge, sometimes due to unknown variables. Uncertainty can arise for subjective or objective reasons.

Uranium A chemical element with atomic number 92. Its most common isotopes are U-238, with 146 neutrons, and which accounts for about 99.3% of uranium, and U-235, which is the only naturally occurring fissile isotope and has 145 neutrons. It accounts for about 0.7% of uranium. U-238 can be used to produce a fissile isotope of plutonium and has a half-life of 4.5 billion years.

Well completion The process of preparing a well for production or injection.

Well logging A technique that is widely used in the oil and gas industry of making a detailed record of the geologic formations penetrated by a borehole in order to identify, quantify, and evaluate oil and gas reservoir.

Work over services The process of performing major maintenance or a completion operation on a well. It involves invasive techniques including wireline, coiled tubing, or snubbing.

APPENDIX A

Morbidity and mortality risk coefficients for external exposure[1]

Nuclide	Morbidity (l/year)/(pCi/g)	Mortality (l/year)/(pCi/g)
Ac-227 + D	1.47E − 06	9.99E − 07
Ag-108m + D	7.19E − 06	4.90E − 06
Ag-110m + D	1.30E − 05	8.84E − 06
Al-26	1.33E − 05	9.03E − 06
Am-241	2.76E − 08	1.86E − 08
Am-243 + D	6.35E − 07	4.32E − 07
Au-195	1.38E − 07	9.35E − 08
Ba-133	1.44E − 06	9.77E − 07
Bi-207	7.08E − 06	4.82E − 06
C-14	7.83E − 12	5.21E − 12
Ca-41	0.00E + 00	0.00E + 00
Ca-45	3.96E − 11	2.66E − 11
Cd-109	8.73E − 09	5.79E − 09
Ce-141	2.27E − 07	1.54E − 07
Ce-144 + D	2.41E − 07	1.65E − 07
Cf-252	NA[a]	NA
Cl-36	1.74E − 09	1.19E − 09
Cm-243	4.19E − 07	2.85E − 07
Cm-244	4.85E − 11	2.87E − 11
Cm-245	2.38E − 07	1.62E − 07
Cm-246	4.57E − 11	2.72E − 11
Cm-247 + D	1.36E − 06	9.27E − 07
Cm-248	NA	NA
Co-57	3.55E − 07	2.42E − 07
Co-60	1.24E − 05	8.44E − 06
Cs-134	7.10E − 06	4.83E − 06
Cs-135	2.36E − 11	1.58E − 11

Continued

[1] US Environmental Protection Agency (US EPA). (1997a) Exposure Factors Handbook. EPA/600/P-95/002F.

Nuclide	Morbidity (l/year)/(pCi/g)	Mortality (l/year)/(pCi/g)
Cs-137 + D	2.55E − 06	1.73E − 06
Eu-152	5.30E − 06	3.61E − 06
Eu-154	5.83E − 06	3.97E − 06
Eu-155	1.24E − 07	8.43E − 08
Fe-55	0.00E + 00	0.00E + 00
Fe-59	5.83E − 06	3.97E − 06
Gd-152	0.00E + 00	0.00E + 00
Gd-153	1.62E − 07	1.09E − 07
Ge-68 + D	4.17E − 06	2.84E − 06
H-3	0.00E + 00	0.00E + 00
I-125	7.24E − 09	4.54E − 09
I-129	6.10E − 09	3.90E − 09
Ir-192	3.40E − 06	2.31E − 06
K-40	7.97E − 07	5.44E − 07
Mn-54	3.89E − 06	2.65E − 06
Na-22	1.03E − 05	7.03E − 06
Nb-93m	3.83E − 11	2.21E − 11
Nb-94	7.29E − 06	4.96E − 06
Nb-95	3.53E − 06	2.41E − 06
Ni-59	0.00E + 00	0.00E + 00
Ni-63	0.00E + 00	0.00E + 00
Np-237 + D	7.96E − 07	5.41E − 07
Pa-231	1.39E − 07	9.45E − 08
Pb-210 + D[b]	4.17E − 09	2.88E − 09
Pm-147	3.21E − 11	2.16E − 11
Po-210	3.95E − 11	2.69E − 11
Pu-238	7.22E − 11	4.53E − 11
Pu-239	2.00E − 10	1.34E − 10
Pu-240	6.98E − 11	4.39E − 11
Pu-241 + D	1.33E − 11	2.56E − 07
Pu-242	6.25E − 11	3.95E − 11
Pu-244	NA	NA
Ra-226 + D	8.49E − 06	5.79E − 06
Ra-228 + D	4.53E − 06	3.08E − 06
Ru-106 + D	9.66E − 07	6.59E − 07
S-35	8.77E − 12	5.84E − 12
Sb-124	8.89E − 06	6.05E − 06
Sb-125[b]	1.81E − 06	1.24E − 06
Sc-46	9.63E − 06	6.56E − 06
Se-75	1.45E − 06	9.82E − 07
Se-79	1.10E − 11	7.30E − 12
Sm-147	0.00E + 00	0.00E + 00

Continued

Nuclide	Morbidity (l/year)/(pCi/g)	Mortality (l/year)/(pCi/g)
Sm-151	3.60E−13	2.11E−13
Sn-113	2.02E−08	1.37E−08
Sr-85	2.20E−06	1.49E−06
Sr-89	7.19E−09	5.10E−09
Sr-90+D	1.96E−08	1.39E−08
Ta-182	6.04E−06	4.11E−06
Tc-99	8.14E−11	5.48E−11
Tc-125m	6.98E−09	4.40E−09
Th-228+D	7.79E−06	5.31E−06
Th-229+D	1.17E−06	7.97E−07
Th-230	8.18E−10	5.53E−10
Th-232	3.42E−10	2.30E−10
Tl-204	2.76E−09	1.88E−09
U-232	5.98E−10	4.03E−10
U-233	9.82E−10	6.66E−10
U-234	2.52E−10	1.68E−10
U-235+D	5.43E−07	3.69E−07
U-236	1.25E−10	8.21E−11
U-238+D	8.66E−08	7.01E−08
Zn-65	2.81E−06	1.91E−06
Zr-93	0.00E+00	0.00E+00
Zr-95	3.40E−06	2.31E−06

[a] NA: Not available.
[b] Pb-210+D and Sb-125 values listed are for a cutoffs half-life of 30 days.

Morbidity and mortality risk coefficients for inhalation

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
Ac-227 + D	F	5.00E-04	1.01E-07	8.24E-08
	M	5.00E-04	1.33E-07	1.21E-07
	S	5.00E-04	2.13E-07	2.02E-07
Ag-108m + D	F	5.00E-04	2.10E-11	1.51E-11
	M	5.00E-02	2.67E-11	2.15E-11
	S	1.00E-02	1.04E-10	8.95E-11
Ag-110m + D	F	5.00E-02	2.02E-11	1.44E-11
	M	5.00E-02	2.83E-11	2.30E-11
	S	1.00E-02	4.51E-11	3.81E-11
Al-26	F	1.00E-02	4.00E-11	2.77E-11
	M	1.00E-02	6.92E-11	5.85E-11
	S	1.00E-02	2.90E-10	2.60E-10
Am-241	F	5.00E-04	3.77E-08	2.95E-08
	M	5.00E-04	2.81E-08	2.44E-08
	S	5.00E-04	3.54E-08	3.34E-08
Am-243 + D	F	5.00E-04	3.70E-08	2.92E-08
	M	5.00E-04	2.71E-08	2.34E-08
	S	5.00E-04	3.37E-08	3.17E-08
Au-195	F	1.00E-01	2.95E-13	1.74E-13
	M	1.00E-01	4.11E-12	3.67E-12
	S	1.00E-01	6.48E-12	5.85E-12
Ba-133	F	2.00E-01	6.25E-12	4.55E-12
	M	1.00E-01	1.16E-11	9.88E-12
	S	1.00E-02	3.25E-11	2.86E-11
Bi-207	F	5.00E-02	2.08E-12	1.24E-12
	M	5.00E-02	2.10E-11	1.78E-11
	S	5.00E-02	1.10E-10	9.62E-11
C-14 (particulates)	F	1.00E+00	6.22E-13	4.26E-13
	M	1.00E-01	7.07E-12	6.51E-12
	S	1.00E-02	1.69E-11	1.59E-11
C-14 (monoxide)	G	1.00E+00	3.36E-15	2.27E-15

Continued

Nuclide	Type	f_1	Morbidity (1/pCi)	Mortality (1/pCi)
C-14 (dioxide)	G	1.00E+00	1.99E-14	1.36E-14
Ca-41	F	3.00E-01	2.75E-13	2.58E-13
	M	1.00E-01	2.09E-13	1.90E-13
	S	1.00E-02	5.07E-13	4.70E-13
Ca-45	F	3.00E-01	1.20E-12	9.92E-13
	M	1.00E-01	9.40E-12	8.70E-12
	S	1.00E-01	1.28-11	1.19E-11
Cd-109	F	5.00E-02	1.48E-11	1.05E-11
	M	5.00E-02	1.77E-11	1.52E-11
	S	5.00E-02	2.19E-11	2.01E-l1
Ce-141	F	5.00E-04	2.37E-12	1.82E-12
	M	5.00E-04	1.14E-11	1.02E-11
	S	5.00E-04	1.35E-11	1.22E-11
Ce-144+D	F	5.00E-04	8.36E-11	7.22E-11
	M	5.00E-04	1.10E-10	9.81E-11
	S	5.00E-04	1.80E-10	1.66E-10
Cf-252	F	5.00E-04	NA[c]	NA
	M	5.00E-04	NA	NA
	S	5.00E-04	NA	NA
Cl-36	F	1.00E+00	1.32E-12	8.77E-13
	M	5.00E+00	2.30E-11	234E-11
	S	1.00E+00	1.01E-10	9.55E-11
Cm-243	F	5.00E-04	3.03E-08	2.41E-08
	M	5.00E-04	2.69E-08	2.38E-08
	S	5.00E-04	3.67E-08	3.47E-08
Cm-244	F	5.00E-04	2.63E-08	2.10E-08
	M	5.00E-04	2.53E-08	2.26E-08
	S	5.00E-04	3.56E-08	3.36E-08
Cm-245	F	5.00E-04	3.81E-08	2.98E-08
	M	5.00E-04	2.78E-08	2.40E-08
	S	5.00E-04	3.45E-08	3.26E-08
Cm-246	F	5.00E-04	3.77E-08	2.95E-08
	M	5.00E-04	2.77E-08	2.39E-08
	S	5.00E-04	3.46E-08	3.26E-08
Cm-247+D	F	5.00E-04	3.49E-08	2.74E-08
	M	5.00E-04	2.50E-08	2.16E-08
	S	5.00E-04	3.09E-08	2.91E-08
Cm-248	F	5.00E-04	NA	NA
	M	5.00E-04	NA	NA
	S	5.00E-04	NA	NA
Co-57	F	1.00E-01	6.96E-13	4.63E-13
	M	1.00E-01	2.09E-12	1.76E-12
	S	1.00E-02	3.74E-12	3.23E-12

Continued

Nuclide	Type	f_1	Morbidity (1/pCi)	Mortality (1/pCi)
Co-96	F	1.00E-01	1.71E-11	1.17E-11
	M	1.00E-01	3.58E-11	2.97E-11
	S	1.00E-02	1.01E-10	8.58E-11
Cs-134	F	1.00E+00	1.65E-11	1.13E-11
	M	1.00E-01	3.09E-11	2.61E-11
	S	1.00E-02	6.99E-11	6.14E-11
Cs-135	F	1.00E+00	1.86E-12	1.26E-12
	M	1.00E-01	1.04E-11	9.55E-12
	S	1.00E-02	2.49E-11	2.33E-11
Cs-137+D	F	1.00E+00	1.19E-11	8.10E-12
	M	1.00E-01	3.30E-11	2.89E-11
	S	1.00E-01	1.12E-10	1.02E-10
Eu-152	F	5.00E-04	1.90E-10	1.52E-10
	M	5.00E-04	9.10E-11	7.47E-11
	S	5.00E-04	9.07E-11	7.96E-11
Eu-154	F	5.00E-04	2.11E-10	1.74E-10
	M	5.00E-04	1.15E-10	9.81E-11
	S	5.00E-04	1.41E-10	1.27E-10
Eu-155	F	5.00E-04	1.91E-11	1.66E-11
	M	5.00E-04	1.48E-11	1.33E-11
	S	5.00E-04	1.88E-11	1.73E-11
Fe-55	F	1.00E-01	1.48E-12	1.22E-12
	M	1.00E-01	7.99E-13	6.70E-13
	S	1.00E-02	6.48E-13	5.88E-13
Fe-59	F	1.00E-01	7.96E-12	5.66E-12
	M	1.00E-01	1.33E-11	1.14E-11
	S	1.00E-02	1.47E-11	1.29E-11
Gd-152	F	5.00E-04	9.10E-09	7.99E-09
	M	5.00E-04	5.33E-09	4.81E-09
	S	5.00E-04	8.58E-09	8.14E-09
Gd-153	F	5.00E-04	4.63E-12	3.81E-12
	M	5.00E-04	6.55E-12	5.81E-12
	S	5.00E-04	8.58E-12	7.73E-12
Ge-68+D	F	1.00E+00	2.94E-12	1.67E-12
	M	1.00E+00	4.90E-11	4.49E-11
	S	1.00E+00	1.08E-10	1.00E-10
H-3 (particulates)	F	1.00E+00	1.95E-14	1.34E-14
	M	1.00E-01	1.99E-13	1.69E-13
	S	1.00E-02	8.51E-13	7.84E-13
H-3 (water vapor)	V	1.00E+00	5.62E-14	3.85E-14
H-3 (elemental)	G	1.00E+00	5.62E-18	3.85E-18
H-3 (organic)	G	1.00E+00	1.28E-13	8.77E-14

Continued

Nuclide	Type	f_1	Morbidity (1/pCi)	Mortality (1/pCi)
I-125 (particulates)	F	1.00E+00	1.06E-11	1.10E-12
	M	1.00E-01	3.22E-12	1.08E-12
	S	1.00E-02	1.49E-12	1.20E-12
I-125 (vapor)	V	1.00E+00	2.77E-11	2.87E-12
I-125 (methyl iodide)	V	1.00E+00	2.16E-11	2.23E-12
I-129 (particulates)	F	1.00E+00	6.07E-11	6.22E-12
	M	1.00E-01	2.83E-11	9.62E-12
	S	1.00E-02	2.56E-11	2.21E-11
I-129 (vapor)	V	1.00E+00	1.60E-10	1.64E-11
I-129 (methyl iodide)	V	1.00E+00	1.24E-10	1.27E-11
Ir-192	F	1.00E-02	7.14E-12	4.85E-12
	M	1.00E-02	1.92E-11	1.67E-11
	S	1.00E-02	2.41E-11	2.15E-11
K-40	F	1.00E+00	1.03E-11	6.55E-12
	M	1.00E+00	5.00E-11	4.44E-11
	S	1.00E+00	2.22E-10	2.08E-10
Mn-54	F	1.00E-01	2.79E-12	1.97E-12
	M	1.00E-01	5.88E-12	4.66E-12
	S	1.00E-01	1.21E-11	9.88E-12
Na-22	F	1.00E+00	3.89E-12	2.67E-12
	M	1.00E+00	3.50E-11	3.06E-11
	S	1.00E+00	9.73E-11	8.55E-11
Nb-93m	F	1.00E-02	7.07E-13	5.11E-13
	M	1.00E-02	1.90E-12	1.66E-12
	S	1.00E-02	5.66E-12	5.25E-12
Nb-94	F	1.00E-02	2.01E-11	1.44E-11
	M	1.00E-02	3.77E-11	3.20E-11
	S	1.00E-02	1.35E-10	1.18E-10
Nb-95	F	1.00E-02	1.89E-12	1.31E-12
	M	1.00E-02	5.44E-12	4.66E-12
	S	1.00E-02	6.44E-12	5.55E-12
Ni-59	F	5.00E-02	5.74E-13	3.89E-13
	M	5.00E-02	4.66E-13	3.60E-13
	S	1.00E-02	1.27E-12	1.17E-12
Ni-63	F	5.00E-02	1.38E-12	9.32E-13
	M	5.00E-02	1.64E-12	1.36E-12
	S	1.00E-02	3.74E-12	3.46E-12
Np-237+D	F	5.00E-04	1.75E-08	1.29E-08
	M	5.00E-04	1.77E-08	1.55E-08
	S	5.00E-04	2.87E-08	2.71E-08
Pa-231	F	5.00E-04	7.62E-08	5.62E-08
	M	5.00E-04	4.07E-08	3.27E-08
	S	5.00E-04	4.55E-08	4.26E-08

Continued

Nuclide	Type	f_1	Morbidity (1/pCi)	Mortality (1/pCi)
Pb-210 +D[d]	F	2.00E-01	9.18E-10	6.76E-10
	M	1.00E-01	2.80E-08	2.83E-09
	S	1.00E-02	1.63E-08	1.55E-08
Pm-147	F	5.00E-04	9.10E-12	8.44E-12
	M	5.00E-04	1.16E-11	1.07E-11
	S	5.00E-04	1.61E-11	1.50E-11
Po-210	F	1.00E-01	9.95E-10	7.29E-10
	M	1.00E-01	1.08E-08	1.02E-08
	S	1.00E-02	1.45E-08	1.37E-08
Pu-238	F	5.00E-04	5.22E-08	4.40E-08
	M	5.00E-04	3.36E-08	2.97E-08
	S	1.00E-05	3.55E-08	3.35E-08
Pu-239	F	5.00E-04	5.51E-08	4.66E-08
	M	5.00E-04	3.33E-08	2.94E-08
	S	1.00E-05	3.32E-08	3.13E-08
Pu-240	F	5.00E-04	5.55E-08	4.66E-08
	M	5.00E-04	3.33E-08	2.94E-08
	S	1.00E-05	3.32E-08	3.13E-08
Pu-241 +D	F	5.00E-04	8.66E-10	7.33E-10
	M	5.00E-04	3.34E-10	2.84E-10
	S	1.00E-05	1.41E-10	1.30E-10
Pu-242	F	5.00E-04	5.25E-08	4.40E-08
	M	5.00E-04	3.13E-08	2.76E-08
	S	1.00E-05	3.09E-08	2.92E-08
Pu-244	F	5.00E-04	NA	NA
	M	5.00E-04	NA	NA
	S	1.00E-05	NA	NA
Ra-226 +D	F	2.00E-01	4.38E-10	3.15E-10
	M	1.00E-01	1.15E-08	1.09E-08
	S	1.00E-02	2.82E-08	2.68E-08
Ra-228 +D	F	2.00E-01	1.22E-09	8.75E-10
	M	1.00E-01	5.21E-09	4.69E-09
	S	1.00E-02	4.37E-08	4.15E-08
Ru-106 +D	F	5.00E-02	3.48E-11	2.27E-11
	M	5.00E-02	1.02E-10	8.95E-11
	S	1.00E-02	2.23E-10	2.06E-10
Ru-106 (vapor)	V	5.00E-02	5.51E-11	8.62E-11
S-35 (inorganic)	F	8.00E-01	2.32E-13	1.45E-13
	M	1.00E-01	5.03E-12	4.63E-12
	S	1.00E-02	6.55E-12	6.03E-12
S-35 (dioxide)	V	8.00E-01	4.96E-13	3.19E-13
S-35 (carbon disulfide)	V	8.00E-01	2.90E-12	1.96E-12

Continued

Nuclide	Type	f_1	Morbidity (1/pCi)	Mortality (1/pCi)
Sb-124	F	1.00E-01	4.81E-12	3.16E-12
	M	1.00E-02	2.43E-11	2.09E-11
	S	1.00E-02	3.20E-11	2.79E-11
Sb-125[d]	F	1.00E-01	3.85E-12	2.78E-12
	M	1.00E-02	1.66E-11	1.48E-11
	S	1.00E-02	4.00E-11	3.60E-11
Sc-46	F	1.00E-04	1.89E-11	1.40E-11
	M	1.00E-04	2.16E-11	1.82E-11
	S	1.00E-04	2.47E-11	2.14E-11
Se-75	F	8.00E-01	3.77E-12	2.66E-12
	M	1.00E-01	4.03E-12	3.29E-12
	S	1.00E-02	5.00E-12	4.26E-12
Se-79	F	8.00E-01	3.33E-12	2.33E-12
	M	1.00E-01	9.25E-12	8.33E-12
	S	1.00E-02	1.99E-11	1.87E-11
Sm-147	F	5.00E-04	1.26E-08	1.13E-08
	M	5.00E-04	6.88E-09	6.25E-09
	S	5.00E-04	9.29E-09	8.81E-09
Sm-151	F	5.00E-04	9.18E-12	8.55E-12
	M	5.00E-04	4.88E-12	4.55E-12
	S	5.00E-04	4.88E-12	4.55E-12
Sn-113	F	2.00E-02	2.35E-12	1.54E-12
	M	2.00E-02	1.00E-11	8.73E-12
	S	2.00E-02	1.45E-11	1.30E-11
Sr-85	F	3.00E-01	1.47E-12	1.03E-12
	M	1.00E-01	2.56E-12	2.05E-12
	S	1.00E-02	3.23E-12	2.65E-12
Sr-89	F	3.00E-01	4.00E-12	2.81E-12
	M	1.00E-01	2.34E-11	2.04E-11
	S	1.00E-02	3.02E-11	2.67E-11
Sr-90 +D	F	3.00E-01	4.69E-11	4.21E-11
	M	1.00E-01	1.13E-10	1.04E-10
	S	1.00E-02	4.34E-10	4.06E-10
Ta-182	F	1.00E-03	7.62E-12	5.11E-12
	M	1.00E-03	2.77E-11	2.44E-11
	S	1.00E-03	3.74E-11	3.35E-11
Tc-99	F	8.00E-01	1.16E-12	6.88E-13
	M	1.00E-01	1.41E-11	1.29E-11
	S	1.00E-02	3.81E-11	3.58E-11
Te-125m (particulates)	F	3.00E-01	1.43E-12	9.40E-13
	M	1.00E-01	1.17E-11	1.07E-11
	S	1.00E-02	1.45E-11	1.34E-11

Continued

Nuclide	Type	f_1	Morbidity (1/pCi)	Mortality (1/pCi)
Te-125m (vapor)	V	3.00E-01	3.77E-12	2.55E-12
Th-228+D	F	5.00E-04	2.24E-08	1.64E-08
	M	5.00E-04	9.19E-08	8.57E-08
	S	5.00E-04	1.44E-07	1.37E-07
Th-229+D	F	5.00E-04	1.01E-07	7.63E-08
	M	5.00E-04	1.34E-07	1.20E-07
	S	5.00E-04	2.30E-07	2.17E-07
Th-230	F	5.00E-04	3.40E-08	2.48E-08
	M	5.00E-04	2.35E-08	1.95E-08
	S	5.00E-04	2.85E-08	2.68E-08
Th-232	F	5.00E-04	4.14E-08	2.99E-08
	M	5.00E-04	2.39E-08	1.92E-08
	S	5.00E-04	4.33E-08	4.07E-08
Tl-204	F	1.00E+00	2.45E-12	1.48E-12
	M	1.00E+00	2.27E-11	2.07E-11
	S	1.00E+00	6.07E-11	5.66E-11
U-232	F	2.00E-02	3.69E-09	2.63E-09
	M	2.00E-02	1.95E-08	1.80E-08
	S	2.00E-03	9.25E-08	8.77E-08
U-233	F	2.00E-02	6.44E-10	4.55E-10
	M	2.00E-02	1.16E-08	1.10E-08
	S	2.00E-03	2.83E-08	2.69E-08
U-234	F	2.00E-02	6.29E-10	4.44E-10
	M	2.00E-02	1.14E-08	1.07E-08
	S	2.00E-03	2.78E-08	2.64E-08
U-235+D	F	2.00E-02	5.89E-10	4.15E-10
	M	2.00E-02	1.01E-08	9.51E-09
	S	2.00E-03	2.51E-08	2.38E-08
U-236	F	2.00E-02	5.96E-10	4.18E-10
	M	2.00E-02	1.05E-08	9.92E-09
	S	2.00E-03	2.58E-08	2.45E-08
U-238+D	F	2.00E-02	5.78E-10	4.10E-10
	M	2.00E-02	9.35E-09	8.83E-09
	S	2.00E-03	2.37E-08	2.25E-08
Zn-65	F	5.00E-01	7.59E-12	5.22E-12
	M	1.00E-01	5.81E-12	4.44E-12
	S	1.00E-02	7.47E-12	6.14E-12
Zr-93	F	2.00E-03	1.52E-11	1.41E-11
	M	2.00E-03	7.29E-12	6.70E-12
	S	2.00E-03	6.07E-12	5.66E-12

Continued

Nuclide	Type	f_1	Morbidity (1/pCi)	Mortality (1/pCi)
Zr-95	F	2.00E-03	6.55E-12	4.92E-12
	M	2.00E-03	1.65E-11	1.45E-11
	S	2.00E-03	2.11E-11	1.87E-11

[a] Separate risk coefficient for particulate aerosols of type F, type M, and type S representing fast, medium, and slow absorption to blood, respectively. The risk coefficients are also provided for tritium, sulfur, nickel, ruthenium, iodine, and tellurium in a vapor form and for tritium and carbon in a gaseous form.
[b] The gastrointestinal uptake (f_1) values are for an adult and represent the fraction of a radionuclide reaching the stomach that would be absorbed to blood without radiological decay during passage through the gastrointestinal tract.
[c] NA: Not Available.
[d] Pb-210+D[d] and Sb-125[d] values listed are for a cut-offs half-life of 30 days.
US Environmental Protection Agency (US EPA) (1997a). Exposure Factors Handbook. EPA/600/P-95/002F.

Index

Note: Page numbers followed by *f* indicate figures and *t* indicate tables.

F

G

H

I

K

L

M

NUCLEAR RADIOACTIVE

MATERIALS IN THE OIL AND GAS INDUSTRY

Khalid Al Nabhani | Faisal Khan

Solid scientific platform revealing important scientific theories supported with real scenarios from both academic and professional perspectives

Nuclear Radioactive Materials in the Oil and Gas Industry comprehensively introduces TENORMs generated from various types of oil and gas processes and their associated adverse human health effects, discusses effective TENORM waste management strategies, and develops a quantitative risk analysis framework for TENORM exposure assessment. It thoroughly investigates and identifies current knowledge and technical gaps associated with the presence of TENORM in the oil and gas industry and addresses the three main gaps identified from the available studies: (1) workers in the industry face a great risk of being exposed to radioactivity; (2) high volumes of TENORM waste are generated daily and have become a serious concern as another source of radiation exposure; (3) the lack of a uniform international safety regulations designed to manage risks and their inability to provide enough protection for public health and the environment.

Nuclear Radioactive Materials in the Oil and Gas Industry offers researchers, scientists, and graduate and undergraduate students a comprehensive and well-researched reference starting with fundamental concepts, problem identification, and solutions development. This book is an ideal comprehensive guideline for professionals involved to the oil and gas industry and nuclear industry who are concerned about radiological issues.

Key Features

- Demystifies NORM and TENORM concepts and redefines TENORM from technical and nuclear scientific perspectives
- Addresses statistically representative data of quantitative risk assessment and dynamic accident modeling
- Stresses the need for legislation and consistency of safety standards related to radiological risks posed by TENORM on health and environment

Khalid Al Nabhani holds a Ph.D. in risk assessment and management of TENORM in the oil and gas industry. He has more than 16 years of rich and diverse experience in the oil and gas industry. He has published five important scientific papers about TENORM.

Faisal Khan is recipient of President Outstanding Research Award of 2012-2013 and 2013-2014, the CSChE National Award on Process Safety Management of 2014, and Society of Petroleum Engineer award for his contribution in health, safety, and risk engineering. He has authored seven books and over 300 research articles in peer-reviewed journals and conferences on safety, risk, and reliability engineering.

ISBN 978-0-12-816825-7

9 780128 168257

ELSEVIER

elsevier.com/books-and-journals