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Risk Assessment and Management of Technologically Enhanced Naturally Occurring Nuclear Radioactive Material in the Oil and Gas Industry

by

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Key words

NORM, TENORM, nuclear, radiological, radionuclide, geochemistry, Uranium, Thorium risk assessment, accident modelling, inhalation, fate and transport, doses, cancer, RESRAD, SMART, SHIPP, technical, knowledge, gaps, scenario, rational, politics, inconsistencies, legislation, public participation, safety, health, oil and gas, occupational, dynamic, barriers, exposures, waste, disposal, environment, shale, gamma, cancer, pathway, upstream, downstream, reactor, gasification Thermo-chemi-nuclear.

Abstract

There is inadequate awareness in the oil and gas industry worldwide about the issue of worker protection from Technologically Enhanced Naturally Occurring Nuclear Radioactive Materials (TENORM), and about the proper disposal of radioactive wastes into the environment. According to the available data on the mass flow and activity concentration of radioactive materials involved in various stages of the oil and gas industry, 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 of radiation and eventually increase the chance of developing cancerous diseases. This research attempts to thoroughly investigate the available literature and identify current knowledge and technical gaps associated with the presence of TENORM in the oil and gas industry. Three main gabs have been identified from the available studies that will be addressed in this study and 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; 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 public health and the environment.

The main goal of this thesis is to provide a road map for further research on key gaps it identifies in measures put in place to protect public health and the environment from radiological risk posed by TENORM in the oil and gas industry. To achieve that goal, this thesis presents a new approach of dynamic modelling 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 generic framework used to identify, evaluate, and model processes of potential TENORM occupational exposure accidents. Rational theory is used to model accident causation behaviour that usually contributes to its occurrence based on logical, inductive, and probabilistic analysis. The basic premise of rational theory is that an accident occurrence is a result of joint conditional behaviour among different parameters.

This thesis also presents an analysis of current TENORM waste disposal methods used in the oil and gas industry that are completely unsafe and unsupported by scientific evaluations or radiological risk assessments from either an engineering or a medical 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, a real scenario-based risk assessment of common TENORM waste disposal methods is evaluated and simulated based on a transport and fate model using RESRAD version 6.5. The results of the scenario-based risk assessment are compared with those obtained using a similar simulated scenario constructed from a literature review and medical opinion.

Finally, this study highlights the lack of consistency of safety standards related to radiological risks posed by TENORM in the oil and gas industry. It also investigates the main reasons that underlie political conflicts in the reservations about regulating technological risks such as nuclear issues, particularly in the oil and gas industry. There exists a real need for public participatory approach in the formulation of technological risk-management processes. The legislative decision-making is an important first step towards mitigating the technological risks of TENORM exposure in the oil and gas industry as well as maintaining a strong economy. Indeed TENORM exposure is a vital public issue as it concerns workers' safety and public health. Hence this thesis provides a framework for engaging public participation, which together with government legislation can promote public health and environmental safety, and aim to strike a balance between the interests of the authorities and the interests of the public.

Statement of original authorship

I wish to acknowledge that much of the inspiration and motivation for this study derives from my past fifteen years of extensive work experience in the oil and gas industry. Because the issue of TENORM exposure is seldom discussed within the industry, many workers are unaware of the risks of radiation they face on a daily basis, and the public is also at risk due to unsafe TENORM waste disposal methods. The results and techniques developed in this thesis are therefore presented with the intention of providing the framework for future expansion and development of research on this important subject. The work contained in this thesis is original and has not been previously submitted for a degree or diploma at any other institution of higher education. It contains no material previously published or written by another person except where due reference has been made in the text. To the best of my knowledge, no comprehensive or integrated studies have yet been carried out on the quantitative risk assessment and dynamic accident modelling of radiological exposure of TENORM in the oil and gas industry. Therefore, the originality of the proposed thesis consists in its methodology that constitutes a first comprehensive and integrated study to assess, quantify and evaluate radiological risks associated with TENORM in the industry using dynamic accident modelling and quantitative risk assessment management techniques.

Signature:

Date: May 2017

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List of Acronyms and Symbols

ACIR	Advisory Commission on Intergovernmental Relations
AEC	Atomic Energy Commission
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 Sulphate
BRF	Branching Factor
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CARBOLOG	Carbon Organic LOG
CEPN	Centre d'étude sur l'évaluation de la protection dans le domaine nucléaire

C_k	Consequences e.g((C2), mishap (C3), incident (C4) and accident (C5) catastrophe (C6))
CNSC	Canadian Nuclear Safety Commission
CO	Carbon Monoxide
CRCPD	Conference of Radiation Control Program Directors
DCF	Dose Conversion Factor
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
EMSPB	Emergency Management Safety Prevention Barrier
ENOR	Enhanced Naturally Occurring
EORT	Enhanced Oil Recovery Technologies
ESP	Electric Submersible Pump
ETF	Environmental Transport Factor

Fe	Iron
HDPE	High-Density Poly-Ethylene
HINAR	High Natural Radioactivity
IAEA	International Atomic Energy Agency
IAEA-TECDOC	IAEA Technical Documents
IAOGP	International Association of Oil and Gas Producers
ICRP	International Commission for Radiological Protection
IISPB	Isolation Integrity Safety Prevention Barrier
LNG	Liquid Natural Gas
LNT	Linear Non-Threshold
LPPE	Leaded Personal Protective Equipment
Mg	Magnesium
M&OSPB	Management & Organization Safety Prevention Barrier
NARM	Naturally Accelerator Produced Radioactive Materials
NAS	National Academy of Science
$N_{c,k}$	Number of abnormal events of consequence
NCRP	National Council on Radiation Protection and Measurements

NO_2	Nitrogen Dioxide
NOR	Naturally Occurring Radionuclides
NORM	Naturally Occurring Nuclear Radioactive Materials
NRC	Nuclear Regulatory Commission
NRPB	National Radiological Protection Board
ORP	Oxidation Reduction Potential
$P(C_k)$	Consequences occurrence probability
P(Xi)	Failure probability
Pb	Lead
pH	Activity of hydrogen ions
Po	Polonium
PNS	Post Normal Science
PP	Precautionary Principles
PPE&EDSPB	Personal Protection Equipment and Exposure Duration Safety Prevention Barrier
R	Resistivity
Ra	Radium
RC	Risk Coefficient

RESRAD	Residual Radioactivity (model)
RMN&EWS	Radiation Monitoring Network and Early Warning System
RPB	Release Prevention Barrier
SF	Source Factor
SHIPP	System Hazard Identification, Prediction and Prevention
Si	Silicon
$S_i(O)$	Initial contaminated zone concentration of radionuclide
SMART	SHIPP Methodology and Rational Theory
SO_2	Sulfur Dioxide
SOE	State-Owned Companies
Sr	Strontium
$SrSO_4$	Strontium Sulphate
t+1	Next time interval
TCP	Thermo-chemi-nuclear Conversion Plant
TCT	Thermo-chemi-nuclear Conversion Technology
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
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
WHO	The World Health Organization
X_i, SB	Safety barriers

Units of measure

Bq	Becquerel
Bq/cm^2	Becquerel per square centimeter (s)
Bq/g	Becquerel per gram
Bq/Kg	Becquerel per kilogram
Bq/l	Becquerel per litre
Bq/ml	Becquerel per Millilitre
μ Bq	Micro Becquerel
^{O}C	Degree(s) Celsius
cm	Centimeter(s)
g	Gram
g/yr	Gram per year
hrs	Hours
KW	Kilowatt
m	Meter
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	MilliRoentgens per hour
mrem/yr	Millirem(s) per year
mSv	MilliSievert
mSv/h	MilliSievert per hour
mSv/yr	MilliSievert per year
μSv/h	MicroSievert 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
μ R/h	Micro Roentgens per hour

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Chapter 1

Introduction

Preface

The production of oil and gas has increased dramatically since the 1980s due to the high global demand, and has resulted in increased technological risks due to the adoption of new production technologies such as Enhanced Oil Recovery Technologies (EORT). Some of the risks include TENORM (Technologically Enhanced Naturally Occurring Nuclear Radioactive Materials), and this raises a radiological concern for the workers, the public and the environment. It is difficult to identify TENORM exposure because signs of cancerous diseases resulting from radiological exposure may take many years to be discovered. Although it is incredibly difficult to eliminate accidents involving radiological exposure, the most viable solution should be a focus on occupational health and safety. Frequently, mitigation of accidents involving TENORM exposure can be achieved early on, and provided that appropriate safety measures and barriers are effectively 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 in order to achieve an inherently safer design to maximize safety. This thesis presents the first ever study to perform dynamic modelling and quantitative risk assessment analysis of TENORM occupational exposure in the oil and gas industry using the SMART approach. This new approach will integrate SHIPP Methodology and Rational Theory. The SHIPP methodology will be used to identify, evaluate, and model processes of

TENORM occupational exposure accidents, while rational theory will be used to model accident causation behaviour based on logical, inductive, and probabilistic analysis that increase level of confidence and certainty compared to many classical reasoning approaches widely used by classical risk assessment approaches. This model relies on five factors: 1) the accuracy of TENORM precursor data gleaned from the literature and industry experts; 2) rational analysis of safety barriers performance; 3) TENORM occupational exposure causation behaviour modelling and simulation; 4) prediction; 5) updating.

Moreover, this research aims to address the lack of statistically representative data of quantitative risk assessment and dynamic accident modelling for the workforce exposed to radiological risks associated with TENORM waste disposal methods currently used in the industry. This thesis will present a scenario-based risk assessment approach based on fate and transport model for TENORM waste that has been disposed of in evaporation ponds. Unfortunately, TENORM waste disposal in evaporation ponds is considered an economical alternative for many onshore oil and gas companies for the disposal of huge quantities of contaminated water co-produced during oil and gas production. Thus, this approach is designed to measure and dynamically update doses and excess carcinogenic risks through different pathways of exposure using real input data. Scenario-based risk assessment approach based on fate and transport model contributes to the development of inherently safer designs to evaluate the performance of current TENORM waste disposal methods and improve operational strategies, thus minimizing the danger of radiological risk on the workers, the public, and the environment.

Finally, this research also highlights the impact of absence of legislation and the lack of consistency of safety standards related to radiological risks posed by TENORM in the oil and gas industry, on health and safety of the workers, and the efficiency of current TENORM waste disposal methods.

1.1 An overview of TENORM in the oil and gas industry

In onshore and offshore oil and gas production activities, a mixture of TENORM, oil, gas, water, sludge, and sand is brought to the surface via drilled wells through down-hole completion and production equipment. 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. 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. After separation, the formation water (also called production water) is either discharged to the ocean or sea, or used for re-injection purposes, which enhance recovery in the depleted formations. Contaminated oily sludge and sand obtained from the reservoir are also removed and disposed of in land farms 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 equipment (Kvasnicka, 1996). Pipelines then carry crude oil to downstream facilities for further refining. Accordingly, the refined products of both oil and gas may still contain TENORM will be either distributed locally for domestic and industrial purposes such as filling stations, factories and power plants or shipped to other countries. Process flowchart shown in Fig. 1.1 illustrates the presence of TENORM during different stages of oil and gas extraction and production activities.

Alongside oil and gas production, TENORM is also found in the waste generated by the oil and gas industry (ALNabhani et al., 2016a; ALNabhani et al., 2016b). Annually, the global petroleum industry generates millions of tonnes of TENORM wastes including produced water, scales, sludge, and contaminated equipment; which are disposed of either above ground or underground (Strand, 1999; ALNabhani et al., 2016b). Accordingly, there is a growing concern as to how these massive volumes of daily produced TENORM can be managed and disposed off in a safe manner. Researches involving last three decades of oil and gas production history have confirmed the fact that Technologically Enhanced Naturally Occurring Nuclear Radioactive Materials (TENORM) are coproduced with oil and gas production. Therefore, TENORM pose significant risks to a large number of people involved in the oil and gas industry (Gesell, 1975; Steinhäusler, 2005; ALNabhani et al., 2015; ALNabhani et al., 2016a; ALNabhani et al., 2016b). However, for economic and political reasons, some industries have been reluctant to admit presence of TENORM in their operation (ALNabhani et al., 2016a). 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 as well as at waste disposal facilities (ALNabhani et al., 2015; ALNabhani et al., 2016a; ALNabhani et al., 2016b). Those who may be affected include workers in drilling and associated services. Worker exposure to radiation can occur during normal operations and during inspection or maintenance facility work. For instance, maintenance workers working with various contaminated tools and equipment with TENORM such as bottom hole assemblies, down hole and completion equipment, wellheads, flow lines, separators, pumps, and manifolds are at high risk of radiological exposure.

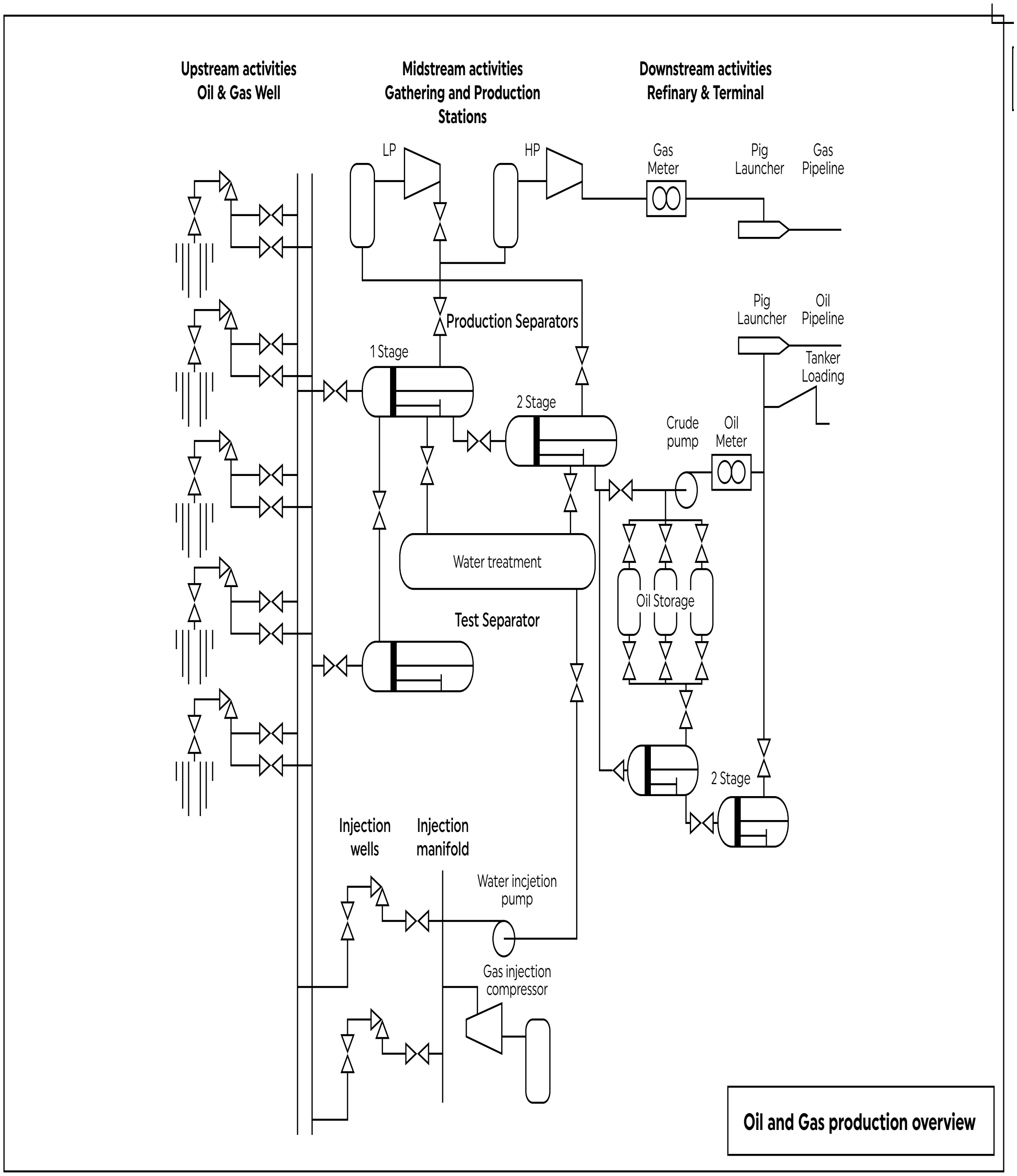


Figure 1.1 Distribution flowchart of TENORM in the petroleum exploration and production processes.

1.2 Research background and problem statement

This research identified three main problems associated with TENORM in the oil and gas extraction and production activities that have not yet been explored or fully addressed in the available systematic reviews, which are:

(1) Occupational exposure to radiological risk associated with TENORM in the oil and gas industry.

It is critical to realize that TENORM exposure is truly a global issue due to the global distribution of reserves. Thirty years worth of research has shown that some workers in the oil and gas industry are exposed to elevated levels of radioactivity (Gesell, 1975; Steinhäusler, 2005). However, for economic and political reasons, this industry has been reluctant to admit that its employees could be exposed to technologically enhanced nuclear radiation. 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 as well as at waste disposal facilities. Those who may be affected include workers performing drilling and associated services, including but not limited to crew members involved in workover, fluid filtration, coring, hydraulic fracturing, fishing and milling, waste management, perforation, logging, wire line, and directional drilling services.

(2) Radiological risks from TENORM waste disposal methods commonly used in the oil and gas industry.

The production of oil and gas has increased greatly to satisfy growing demands worldwide, and has led to increasing the volume of generated TENORM wastes in the light of daily global production of oil and gas, which poses a radiological risk to workers, the general public and the environment. Indeed a serious concern arises as to how to dispose of these wastes in a safer way as compared to the practices currently used by the oil and gas industry that are 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 potential sources affecting workers, the public, food, water resources, soil and the environment. A scenario-based approach is proposed to support the risk assessment of TENORM wastes considering various fate and transport exposure pathways, and the potential risk of radiation exposure to workers, the general public and the environment resulting from the most common TENORM waste disposal methods using RESRAD 6.5. RESRAD 6.5 is software been developed by Argonne National Laboratory operated by the University of Chicago for U.S. Department of Energy to perform uncertainty/probabilistic time-integrated dose and risk analyses with an improved probabilistic interface. RESRAD 6.5 is one of the most advanced, powerful, and reliable modelling software widely used by many organizations and academic institutions such as the U.S. Nuclear Regulatory Commission, U.S. Environmental Protection Agency (EPA).

(3) Absence of legislation and the lack of consistency of safety standards related to radiological risks posed by TENORM in oil and gas.

Some of the related legislation as well as the industries producing TENORM tend to avoid such engagement or even the association with anything related to the word “nuclear” particularly in oil and gas industry. By contrast, it has been scientifically proven that TENORM exist in the rock formations containing oil and gas are nuclear materials in nature with same physical and chemical properties. In fact, oil and gas industries are always reluctant to inform the workers involved in their activities of the great possibility of being exposed to radiological risks, or to make them aware of their policies regarding radioactive material waste disposal methods that pose serious health and safety risks. Such risks also include direct radiation to the public and industrial workers, the contamination of water resources, soil, plantations, the food chain, and the atmosphere. This reluctance could be attributed to many reasons, but most notably economic and political reasons as well as the lack of knowledge of the workers and the public. Since TENORM issue is serious concern that is threating the health and safety of the workers, the public and the environment, it is therefore a public and social issue where public participation should be granted by the legislator in the formulation of safety laws, regulations and policies in the oil and gas industry. On the other hand, many of the available regulatory radiological safety standards are found inconsistent with each other about a precise characterization of a safe exposure to low radiological doses, and there is no commonly agreed standard.

1.3 Thesis contributions and objectives

This thesis contributes to the development of new scientific knowledge in the area of safety and risk assessment science. It offers innovative theoretical, analytical, methodological, and technological approaches in the arena of dynamic risk assessment and management of technologically enhanced naturally occurring nuclear radioactive material (TENORM) in the oil and gas industry. To the best of my knowledge, no comprehensive studies have so far been carried out on the quantitative risk assessment and dynamic accident modelling of radiological exposure of TENORM in the oil and gas industry. Most available datasets are static and focus primarily on identifying and quantifying the presence of NORM in the oil and gas industry rather than dynamically assessing and quantifying radiological risk associated with TENORM coproduced during oil and gas production. Accordingly, this study aims at contributing to the literature by providing a comprehensive and systematic study related to the radiological risk in the oil and gas industry to serve as a roadmap for extensive research in the future by introducing for the first time: 1) novel thinking to the fields of dynamic quantitative risk assessment and accident modelling of TENORM occupational exposure in the oil and gas industry using a new methodology, the SMART approach, which integrates the SHIPP methodology and rational theory in order to gain a better and more accurate understanding of accident causation behaviour and safety barrier performance; 2) a new approach which emphasizes the importance of stimulating the role of public participation in the formulation and legislation of TENORM risk management policy in the oil and gas industry; 3) the scientific theories and facts regarding TENORM in the oil and gas industry, e.g. TENORM used as an indication for the presence of hydrocarbons, TENORM enhancement, nuclearity of TENORM; 4) a scenario-based risk assessment based on both engineering and medical recommendations to evaluate the effectiveness and performance of current TENORM waste disposal options currently used in the oil and gas industry; 5) provide empirical evidence that exposure to even low-doses of radiation is still unsafe and has a significant potential to increase carcinogenic risk from medical perspective.

Furthermore, the originality of the proposed thesis also contributes to the invention of two important new technologies that are intended for patent application. These technologies considered as an important contribution to the scientific community and the industry, which are: I) Thermo-chemi-nuclear Conversion Technology (TCT). This technology optimally manages and safely disposes of TENORM wastes, and utilizes them to generate renewable energy and synthesis fuel with no impact on the public or the environment; II) special personal protective equipment shielded with an effective and lightweight layer of leaded material (LPPE) that is able to provide enough protection for workers to guard against radiological risks.

1.4 Proposed methodology and scope of work

Four methodologies and their associated scopes of work are presented in this section to address the identified problems associated with TENORM in the oil and gas extraction and production activities, which are:

(1) A comprehensive review of the available literature in order to identify key knowledge and technical gaps associated with the current understanding of TENORM issues in the oil and gas industry. The scope of work of this methodology is to clarify the distinction between NORM and TENORM concepts. Indeed the lack of a clear understanding of the difference between NORM and TENORM in the industry, and of whether these are classified as nuclear hazardous material or not, has contributed to the absence of legislations and to inconsistencies in the available regulations governing radiological risk management. This dilemma will be overcome by scientifically proving that radioactive material associated with oil and gas are originally natural nuclear materials, which are technologically enhanced as a result of human intervention and the adoption of enhanced oil recovery technologies designed

to enhance oil and gas recoveries. The review will also investigate the geochemistry of the TENORM and reveal how radioactivity measurements are used to identify whether a given formation contains oil or gas. Thus this study attempts to prove that TENORM and their risks are associated with oil and gas extraction and production, including upstream to downstream processes, and are present even in the final products. Finally, it will explain in more detail how TENORM can be found in various forms during the entire process of oil and gas extraction and production. All the issues above will be discussed in detail in chapter two.

(2) The development of a new approach of dynamic accident modelling and quantitative risk assessment management of TENORM occupational exposure in the oil and gas industry using the SMART approach. This new approach will integrate SHIPP Methodology and Rational Theory. The SHIPP methodology will be used to identify, evaluate, and model processes of TENORM occupational exposure accidents, while rational theory will be used to model accident causation behaviour based on logical, inductive, and probabilistic analysis that increase level of confidence and certainty compared to many classical reasoning approaches widely used by classical risk assessment approaches. It will rationally model and simulate accident causation behaviour using rational theory and Monte Carlo Simulation so that uncertainty associated with precursor data is minimized. The new approach will also perform a qualitative and quantitative risk analysis based on safety barriers performance evaluation, and use the event tree technique to enhance and reinforce the accident model, characterizing its cause-and-effect relationships. The event tree analysis results will be based on the failure of available safety barriers, also known as prior

failure probability analyses, and perform consequence assessment in order to estimate the risk value. For each severity level, radiological consequences will be assessed as they impact people, the environment, and company reputation. Since the main objective of this assessment is to evaluate occupational exposure risk, this study will focus only on the impacts to the health of workers, and estimate the prior risk value for each consequence level via the prior probabilities and severity of consequences. Indeed traditional static risk analyses are not adequate to judge a complex and dynamic system exhibiting high variability and uncertainty.

Prior failure probabilities of the safety barriers will be updated using Bayesian updating theorem to formulate the likelihood of failure probabilities in the next time interval, then simulate and model possible exposure scenarios and possible safety barriers failure for 1000 turns. The prior estimation for preliminary decision-making that will be used to calculate the posterior failure probabilities of safety barriers during the ensuing time interval using Bayesian updating theorem will the be incorporated into the event tree analysis to obtain the consequence occurrence probabilities. Finally, a decision can be taken whether the estimated risk value and the certainty level are acceptable or not. Therefore, further action or decision-making will be made based on either Risk Reduction Measures Methodology, Adaptive Risk Management Methodology, or Precautions Principals Methodology. This approach will be discussed in detail in chapter three.

(3) The introduction of a scenario-based risk assessment approach to the evaluation of TENORM waste disposal options in the oil and gas industry. This approach aims to investigate and analyze the effectiveness of current TENORM waste disposal options

and available risk assessment methods commonly used in the oil and gas industry. It will do so by using fate and transport model and exposure pathways methodology to study plausible scenarios in which the contaminants can migrate through the geosphere and biosphere, before reaching the environment, food, water recourses and eventually humans. All of these issues will be addressed through introducing, modelling and simulating a real case scenario-based risk assessment of TENORM waste disposed in an evaporation pond using RESRAD (Version 6.5) where real data that are dynamically updated will be used as input parameters to evaluate with more accuracy the potential radiological doses and increased carcinogenic risks. Finally, will validate the simulated results and benchmark the findings from the real case scenario with results obtained using a similar simulated scenario constructed from a literature review, so as to confirm how real input data that are dynamically updated affects the results' accuracy and, therefore, the final decision. This approach will be discussed in detail in chapter four.

(4) The introduction of a new approach highlighting the importance of public participation in the development and legislation of TENORM risk management policy in the oil and gas industry. To formulate this approach, a through investigation will be required to inquire about the reasons behind the lack of legislation, inconsistencies in the current safety regulations, and standards to regulate TENORM issues in the oil and gas industry, highlighting the importance of stimulating the role of public participation in the formulation of legislation that strives to strike a balance between the interests of the authorities and the interests of the public, discussing the challenges faced by the law in regulating radiological risks, investigating public participation in

the TENORM risk management policy development process based on an epistemological perspective involving an independent academic and technical voluntary community panel, which could support government efforts to address the perceived risks and benefits of technologies on behalf of the public, establishing a public engagement strategy with different levels of participation that includes diverse mechanisms and scope of work of issues that people perceive as relevant in their daily life, such as the carcinogenic diseases, radiological contaminate of water, air, soil and food resources, finally tackling all issues thoroughly and investigating the extent whether and to what extent government emergency plans are capable to protect public health and the environment in case any major radiological accident occurs. This approach will be discussed in detail in chapter five.

1.5 Organization of the thesis

This thesis is divided into four phases and seven chapters, as explained in Figure 1.2 below. Phase one is mainly comprised of chapter one, which provides an introduction to the thesis and outlines the problem statement, contributions, objectives, and methodology of the proposed research. Phase two mainly consists of chapter two, which is a literature review that outlines the history of TENORM in the oil and gas industry and explains the theoretical background and basic geochemical principles that will be used to addressed some of the central issues in this thesis. The final part of chapter two outlines key knowledge and technical gaps associated with the current understanding of TENORM issues in the oil and gas industry.

Phase three of the thesis comprises chapters three to five and presents a thorough investigation of the TENORM radiological risks associated with oil and gas extraction and production activities. Chapter three discusses a new approach for TENORM occupational exposure dynamic accident modelling and quantitative risk assessment in typical oil and gas extraction and production operations. This model uses the SMART approach coupled with SHIPP methodology and rational theory. Chapter four illustrates how real, dynamic data and final medical opinions are important to arrive at accurate conclusions in evaluating the performance of TENORM waste disposal methods currently used by the oil and gas industry, which are not based on scientific evaluation or accurate engineering risk assessment. This finding is validated using a real scenario-based risk assessment for TENORM waste disposal in evaporation ponds. The finding from this real scenario will be compared with similar risk assessments from other literatures. Chapter five presents a historical investigation of the gaps and inconsistencies in the current safety standards, regulations and legislation governing radiological risks generally and most particularly in the oil and gas industry. It also describes how policy-making for TENORM risk management in oil and gas development can only be well integrated if it includes participatory processes that involve all concerned parties. Those three chapters and the literature review in chapter two were first written as separate journal articles; three of them are already published, and one is currently under review for possible publication. Finally, phase four of the thesis comprises chapters six and seven. Chapter six provides the major conclusions of this research, and chapter seven offers set of recommendations and conceptual understanding of proposed technologies to manage TENORM produced during oil and gas operation. The recommendations presented in this chapter are part of system development program of TENORM risk management in the oil and gas industry that are intended for patent application. These recommendations were first written as a separate journal article, which is currently under journal review for possible publication. These recommendations present a new technology of special personal protective equipment shielded with an effective and lightweight layer of leaded material (LPPE) and a novel technology able to manage and treat TENORM waste using Thermo-chemi-nuclear Conversion Technology (TCT).

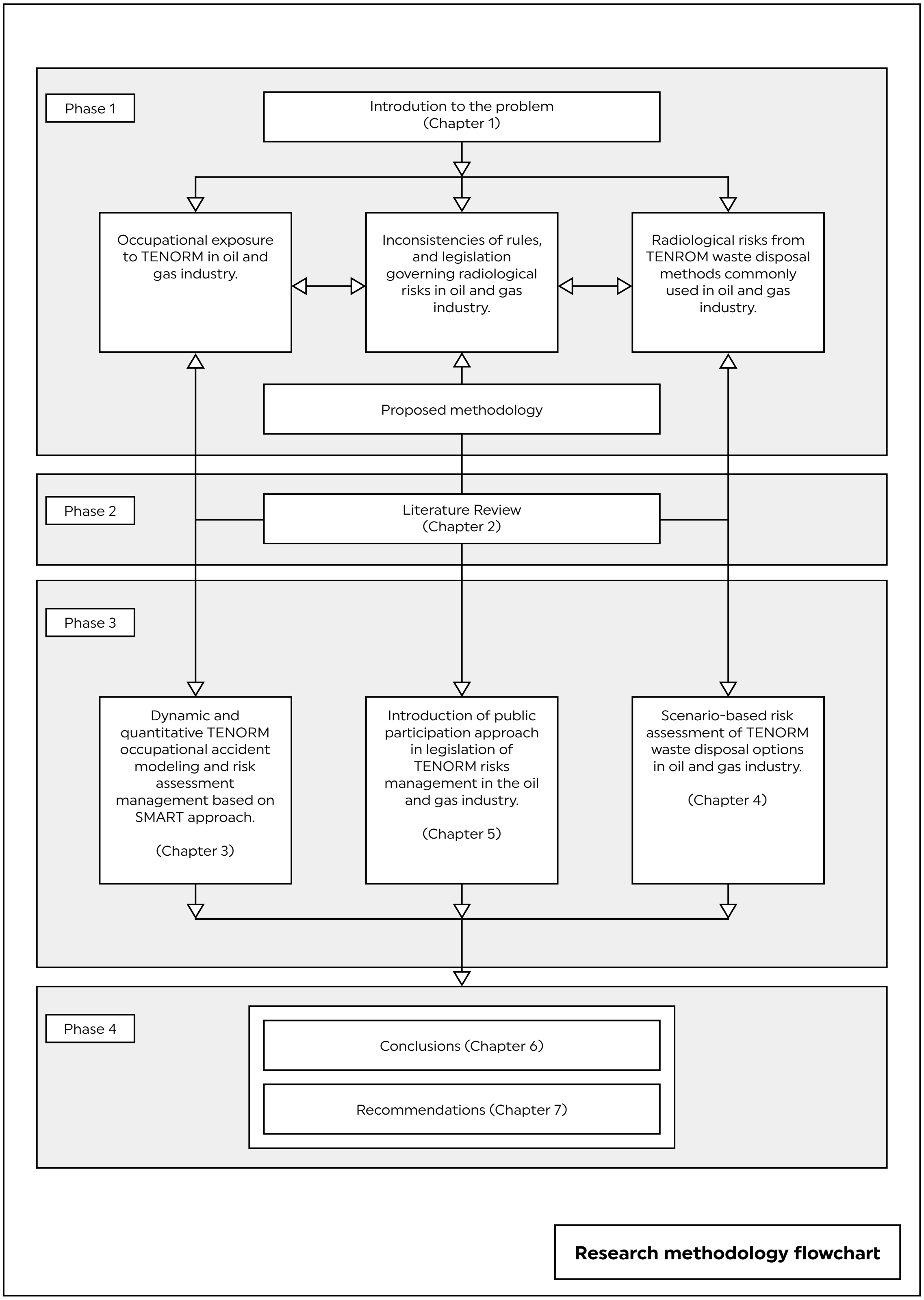


Figure 1.2 Research methodology flowchart.

Chapter 2

Literature Review

Authorship and contributorship

This work has been published in 2015 by Khalid AL Nabhani, Faisal Khan, Ming Yang in the journal *Process Safety and Environmental Protection* (volume 99, pages 237–247) under the title "Review technologically enhanced naturally occurring radioactive materials in oil and gas production". This article can be accessed by following this link:

https://www.researchgate.net/publication/282980810_Technologically_Enhanced_Naturally_Occurring_Radioactive_Materials_in_Oil_and_Gas_Production_A_Silent_Killer

The first author (Khalid ALNabhani) formulated the research review, identified current technical and knowledge gaps, developed the approach, executed the study, and wrote the first draft of the manuscript. The co-authors (Drs. Faisal Khan and Ming Yang) supervised the work, critically reviewed the approach and suggested revisions to the manuscript.

Preface

This chapter reviews the literature that identifies Naturally Occurring Radioactive Materials (NORM) in oil and gas production. It further explains how processes associated with the recovery of oil and gas enhances NORM'S concentration and develops Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). It redefines TENORM from technical and scientific perspectives, and explains how spectral gamma ray logging technology helps to prove that NORM is used as an indication of oil and gas presence. This chapter 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 through process safety approaches. Finally, it identifies the knowledge and technical gaps related to TENORM in oil and gas production, most of which are addressed in this chapter.

2.1. Introduction

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 and Burton (1904) also reported the presence of higher than background concentrations of Naturally Occurring Radioactive Materials (NORM) in crude petroleum. The presence of NORM was also reported in numerous Russian and German research studies between 1920 and the 1930s (ALFarsi, 2008). However, from a radiation protection point of view, an official survey had not been conducted until the early 1970s (AEC, 1972). Subsequent to 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 & 1993; IAEA, 2003a; IAEA, 2003b). 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 prologue for further investigation of some important knowledge gaps related to TENORM that have not yet been addressed in details. This includes but is not limited to an understanding of the nuclear facts of naturally occurring radioactive material 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 human 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 production of oil and gas can enhance NORM to produce Technically Enhanced Naturally Occurring Nuclear Radioactive Material (TENOM). Particular focus is placed on the presence of TENORM in produced water and wastes. All of the issues mentioned above call 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.

2.2. Definitions of NORM/TENORM

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, NOR (Naturally Occurring Radionuclides) 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 Technologically Enhanced Naturally Occurring Radioactive Materials (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 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 (Cullenand 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 as a result 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 below summarizes different definitions of naturally occurring radioactive material from different literature reviews.

Table 2.1 Development of NORM definitions

S.N	**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	Focus 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 (Commonly used in industries)

This study considers TENORM as geo-phys-thermo-chemical processes in which the concentration levels of radionuclides of naturally occurring radioactive materials are 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 naturally occurring radioactive material 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 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) such as reinjection of produced formation water contaminated with radioactive materials into geological formations contain NORM and hydrocarbons and other industrial practices used during oil and gas exploration, extraction and production activities (Ajay et al., 2012; Bou-Rabee et al., 2009; Bourdon et al., 2015; Dresel et al., 2010; Farooqui et al., 2009; IAEA, 2013; Jefpreyg et al., 1987; Krane, 1978; Leopold, 2007; Organo and Fenton, 2008). For instance, during oil exploration, remote-sensing methods of mapping and explosive seismic associated with seismic exploration processes enhance the activity concentration of NORM. In addition, NORM enhancement can be affected by drilling operations and well logging activities such as radioactive tracers that are used in evaluating the formation and the effectiveness of well cementing and underground water and crude oil flow direction, and induced neutrons well logging; well stimulation processes such as well acidizing, well perforation, and formation fracking activities that use produced water, which already contains high activity concentrations levels of NORM as a medium to fracture producing zone and consequently enhancing activity concentration of NORM already exist in those fractured rock formations; the disposal of TENORM waste (re-injecting of produced TENORM wastes into under-ground formations where they originally came from- 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 flow. All of these new technologies and human interventions are seen as 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) were higher than that of the control samples from a non-oil bearing community.
- The contour maps of the studied area showed a non-linearity 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.

Furthermore, from the perspectives of nuclear physics and chemistry, NORM 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 sub-atomic 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 or particles or nuclear radiation in the form of alpha particles (emitting nucleons), beta particles (emitting an electron or positron or neutrino) or gamma rays (photon or energy emission) (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 as a consequence 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. The existence of this phenomenon was discovered in 1972 at Okloin Gabon, Africa by French physicist Francis Perrin (Smellie, 1995).

2.3. NORM in oil and gas formations

The scientific literature has addressed the presence of NORM in oil and gas formations in a number of countries. In particular, there have been findings in the USA, Poland and the Netherlands. Fisher (1995a) and (1995b) reported that in the USA 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, phosphate rock and chert. The 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 instance, 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 (Bareja, 1984). 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. Geochemically, 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, sulphates and silicates (Kumar et al., 2012). These are very similar to 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 lithophiles (rich of Microorganism), and both occur in the 4^+ oxidation states. However, Uranium can also be oxidized to the oxidation state 6^+ as UO_2^{2+} and found more soluble with hydrocarbons.

This is well within the redox potential range in geological environments (Krauskopt, 1969). Uranium enrichment precipitation occurs more in reducing environments (contain hydrogen, carbon monoxide and hydrogen sulphide), often of an acidic nature and typically in organic-rich sediment like darker marine shale and carbonate that contains more hydrocarbons, where high levels of radioactivity concentration were found with 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 much more soluble than the U^{4+}ion, which also explains why radioactive materials are found more soluble with formation water co-produced 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 uranylion (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 uraneousions is highly dependent upon Eh and pH conditions (hydrogen ions (pH), and the activity of electrons (Eh)). As a consequence, the following inorganic uranium forms are typical for sedimentary rocks (Jonkers et al., 1997):

- Sandstone UO_2 (Uranite) and $USiO_4$ (Coffinite): U contents average of 1.5 ppm (around 20 μ Bq (U238/g)).

- Limestone (UO_2) (CO_3): U contents average of 2.5 ppm (around 30 μ Bq (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 μ Bq) (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 μ Bq (Th232/g)).

- Limestone: Th content average of 1.1 ppm (around 25 μ Bq(Th232/g)).

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

Generally, the mobilization of uranium, thorium and the irradionuclide 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 naturally occurring radioactive materials and their geological formation is important in order 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 naturally occurring radioactive materials are radionuclides decay from uranium or thorium series, which are found mainly in sedimentary formations of common shales, blackshale, sandstones, orthoquartzites, siltstones, claystone, carbonates, bentonites, carbonate rocks, halite, anhydrite and phosphate rock where 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 radiation 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 log that are capable of calculating the Total Organic Carbon content (TOC). Practically, there are different techniques adopted by the industry to calculate TOC.

These include the Δ log R technique, the optimal superposition coefficient Δ log R technique, the CARBOLOG (Carbon Organic LOG) technique. These are mathematically interpreted as:

$TOC = \Delta \log R * 10^{(2.297-0.168LOM)} + \Delta TOC$,   (2-1)

Where,

LOM is the amount of level organic metamorphism (Hood et al., 1975); Δ TOC is regional background level.

$\Delta \log R = \log R/R_{baseline} + 0.0061(\Delta T - \Delta T_{baseline})$ (2-2)

Where Δ log R is the curve separation between porosity log and resistivity log; R is the resistivity measured in Ω m; Δ t is the transit time measure in us/m; $R_{baseline}$ is the resistivity corresponding to the $\Delta t_{baseline}$ when the curves are baseline in non-source rocks.

However, selecting 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 Δ 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:

$TOC = a \log R + b \Delta t + c$ (2-3)

Where a, b, c is constant coefficient.

The CARBOLOG (Carbon Organic LOG) technique

$TOC = a \Delta t + b \Delta t^{-1/2} + c$, (2-4)

Where a, b, c is constant coefficient.

Accordingly, it can be concluded that there is a strong correlation 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 shale are ordinarily a good source of hydrocarbon, and 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 found in many equipment associated with the various stages of production including but not limited to the following :

- Down-hole equipment and materials such as 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 number three of this thesis.

2.4. TENORM in produced water and wastes generated by the oil and gas industry

TENORM are brought to the surface as suspended or dissolved particles with formation water that is produced as the reservoir pressure falls over time 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 American Petroleum Institute (API, 1989), more than 18 billion barrels of waste fluids from oil and gas production were being generated annually in the United States versus 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 in order to comply with reuse and discharge limits, the common practice in oil and gas industries is reinjection of produced water into the formation to enhance recovery from it or to dispose of it in an economical manner (Veil, 1998). However, this re-injection in fact increases formation water salinity and therefore enhances NORM activity concentration. Unfortunately, this practice is widely used in the oil and gas industry around the world. For instance, the Radium-226 activity concentration found is almost similar to the range of values reported in the waste generated in Australia (Holland, 1998) and USA (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 re-injection 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, 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 naturally occurring radioactive materials. Consequently, this gives rise to a serious health hazard for workers in this industry.

2.5. Common forms of TENORM wastes

TENORM wastes result from Uranium-238 and Thorium-232 series and their decay products are brought to the slurry surfaces in different forms through the produced water (Cooper and Malcolm, 2005) or drilling fluids and may contain levels of radioactivity above the surface background (API, 1992; Rood et al., 1998 and 2001; Shawky et al., 2001; Matta et al., 2002; Al-Masri and Suman, 2003; Godoy and Crux, 2003; Hamlat et al., 2003; Mohammad 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 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 radionuclides, sediments, bacterial growth, corrosion particles and scale debris precipitate from produced water due to temperature and pressure change (APPEA, 2002; Omar et al., 2004). The main radionuclides of interest in sludge are Radium-226, Polonium-210, lead-210 and Radium-228 according to IAEA-TECDOC-1712 (IAEA, 2013). Radioisotopes of Radium-226 and Radium-228 are not only incorporated into sludge, but can also 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 in the vicinity of separation tanks, for instance, 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, slops tanks of oil production facilities (IAOGP, 2008).

Furthermore, 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 down whole tools such as completion tools, packers, casings, liners, electric submersible pumps, bottom hole assemblies as well as in completion tubing and piping (API, 1989). Moreover, down hole equipment used in oil wells such as casing and tubing also found to be highly contaminated with TENORM scale from outside and according to Michigan survey (Minnaar, 1994), it has been reported high contamination of (5300 R/h) on outside down hole 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 sulphates, 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 sulphate, 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 Petinatti da Cruz, 2003; Al-Masri and Aba, 2005). Moreover, TENORM scales encountered in oil and gas facilities can also be incorporated into sulphate scale such as $BaSO_4$, $SrSO_4$, and carbonate scale such as $CaCO_3$.

According to 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 U.S petroleum industry. The available data indicates that total radium in scale and sludge varies greatly from undetectable levels to 15170 Bq/g in scale and 25900 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 drilling cuttings that are generated as the rock is 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 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, where γ radiation can travel up to hundreds of meters in the air (IAEA, 2008) and 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 gas film. Radon presents in varying degrees in natural gas and dissolves in the (light) hydrocarbon and 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 5 times background (Abdel-Sabour, 2014).

2.6 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 TENORM risks and 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 literatures with respect to TENORM issues in oil and gas.

2.6.1 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 that 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 insure the quality and integrity of research.

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

The current regulatory and legislation status of TENORM has not been well established, particularly in relation to the issues that affect and threaten human health and the environment as a result of occupational radiological exposure or radiological pollutions from huge volumes of TENORM waste daily generated from oil and gas production and their disposal processes. Therefore, risks posed by TENORM produced from oil and gas production are significant enough to warrant immediate actions to develop state regulatory controls and to standardize international guidelines for TENORM safety management in the oil and gas industries. This issue is an important concern in the USA because in the absence of federal regulations, many states have begun to develop regulatory programs to control TENORM in oil and gas. However there remains the challenge of obtaining adequate information and understanding to devise appropriate regulations that are able to mitigate or eliminate TENORM risks associated with oil and gas production.

There is a significant knowledge gap also in many TENORM guidelines that are appropriate for the handling, storage of TENORM wastes, but that fail to adequately outline considerations regarding the long-term assessment, monitoring and management of disposed TENORM wastes in a safe and environmental friendly manner, and the implications of such disposal options on environmental 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. 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 instance, neither the US Environmental Protection Agency 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 instance, 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. Taking into account that some of these TENORM radionuclides in such waste have very long half life of radiation that can exceed thousands of year, it becomes very important to have accurate inventory records so that grandchildren and their descendants know exactly where these wastes were dumped, and are thus able to avoid living with such waste for thousands of years.

2.6.2 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 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 oil and gas 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 modelling and quantitative risk assessment and management

Understanding the conceptual models for TENORM system behaviour will bridge the primary technical gaps in developing new approaches of dynamic accident modelling 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 logs and field correlation logs. This data is a valuable source of information that can be used to characterize the geological distribution of 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 scientific evaluations or radiological risk assessments from both engineering and medical perspectives. These practices include disposal in land farms or injection into underground or seabed formations, and are designed only to temporarily prevent the direct exposure of workers and the general public to radiation. Moreover, they have created additional problems and unforeseen hazards.

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 in order 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 similar to the Thermo-chemi-nuclear Conversion Plant (TCP) invented and proposed at the end of this thesis in the chapter that outlines recommendations for future projects.

Utilization of and recycling of TENORM wastes

Results from TENORM surveys indicate that radionuclide concentration can vary in range from undetectable to extremely high levels. For instance, according US EPA (1993) and Smith et al. (1996), it has reported that activity concentrations in waste sludge can reach as high as 25900 Bq/g. Moreover, extremely high radium concentration was measured in produced water as high as 159,000 pCi/L in sludge according to Michigan Survey (Michigan Department of Public Health, 1992); therefore, the potential of energy optimization produced from enhanced radioactive nuclides contained in TENORM waste may provide an area for future research consideration, provided that it is found scientifically, technically and economically feasible to use that energy for other applications. Energy generated by TENORM waste could be assessed directly, or by investigating data collected from well logging 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 TENORM waste in a safe and efficient manner as compared to current practices.

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 the general public also can be at the risk of being exposed to radiation through different exposure pathways. The pathways of concern are internal inhalation (for instance TENORM suspended particle in 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 cancerous 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.

Chapter 3

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

Authorship and contributorship

This work has been submitted to the *Journal of Petroleum Exploration and Production Technology* by authors Khalid ALNabhani, Faisal Khan and Ming Yang on May 2016 under title "Dynamic modelling of TENORM exposure risk during drilling and production". On January 2017, this work has been accepted and published. Full details of this article can be accessed through the following link:

https://www.researchgate.net/publication/314051967_Dynamic_modeling_of_TENORM_exposure_risk_during_drilling_and_production

The first author (Khalid ALNabhani) identified the research problem, developed the approach, executed the case study, and drafted the manuscript. The co-authors (Drs. Faisal Khan and Ming Yang) supervised the work, critically reviewed the developed approach, and provided valuable comments to improve the manuscript.

Preface

There is a dearth of available information regarding dynamic modelling and risk assessment of TENORM occupational exposure in the oil and gas industry. Experts nevertheless fear that 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 in various stages of the oil and gas industry. Unfortunately, these doses often exceed the currently acceptable occupational exposure dose limits for occupationally exposed persons. Therefore, this chapter presents a methodology to bridge this knowledge gap by modelling the workforce TENORM radiation exposure at different oil and gas operation stages. This is achieved by integrating SHIPP (System Hazard Identification, Prediction and Prevention) Methodology And Rational Theory (SMART approach). The SMART approach is applied to attempt an integrated framework for TENORM occupational exposure risk assessment. The application of the proposed approach is illustrated with a case study.

3.1 Introduction

Thirty years worth of research has explored the fact that Technologically Enhanced Naturally Occurring Nuclear Radioactive Materials (TENORM) pose significant risks to a number of people involved in the oil and gas industry (Gesell, 1975; Steinhäusler, 2005). Regardless of the exposure level, chronic cancer is the ultimate and eventual consequences of radiation exposure (ALNabhani et al., 2016b). However, it is possible to mitigate accidents involving radiological exposure at an early stage through preventative methodologies, including effective 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 is be difficult to identify, especially in early stages. Indeed it can take many years for negative health affects 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. In order to protect health and increase safety by preventing instances of major exposure, it is critical to ascertain the presence and adequacy of safety barriers. Thus this chapter focuses on TENORM exposure modelling and quantitative risk assessment in typical oil and gas extraction and production operations using the SHIPP (System Hazard Identification, Prediction and Prevention) Methodology And Rational Theory (SMART approach). The proposed approach has the following unique features: i) dynamic modelling of TENORM occupational exposure considering safety barrier performance, ii) uncertainty reduction throughout prediction of the failure probabilities of safety barriers, and iii) dynamic updating of any abnormal event probability occurrence as new information becomes available. The proposed approach provides an integrated framework for dynamic prediction and TENORM exposure risk information updating. The outcome of this approach would help to monitor radiation exposure risk dynamically, to support the development of effective safety and protective measures, and to minimize the overall oil and gas operation risk.

3.2 TENORM exposure modelling and risk assessment using the 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; Rathnayakaa et al., 2013). Rational theory is used to systematically model the behavior of all possible root and passive causes that usually contribute to accident occurrence based on logical, inductive, and probabilistic analysis. The basic premise of rational theory is that an accident occurrence is a result of joint conditional behavior among different parameters. By integrating the SHIPP methodology and rational theory, the SMART approach is able to: i) identify the interaction between systems and their subsystems, as well as the source of TENORM and its distribution in oil and gas extraction and production processes; ii) identify and analyse TENORM exposure scenarios; iii) model different 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 or precautionary principle methodologies. Figure 3.1 presents the SMART approach flowchart developed for TENORM occupational exposure risk modelling. The proposed approach was demonstrated and validated using a case study of TENORM occupational exposure scenarios for a sample of 2,271 workers involved in different kinds of typical oil and gas activities.

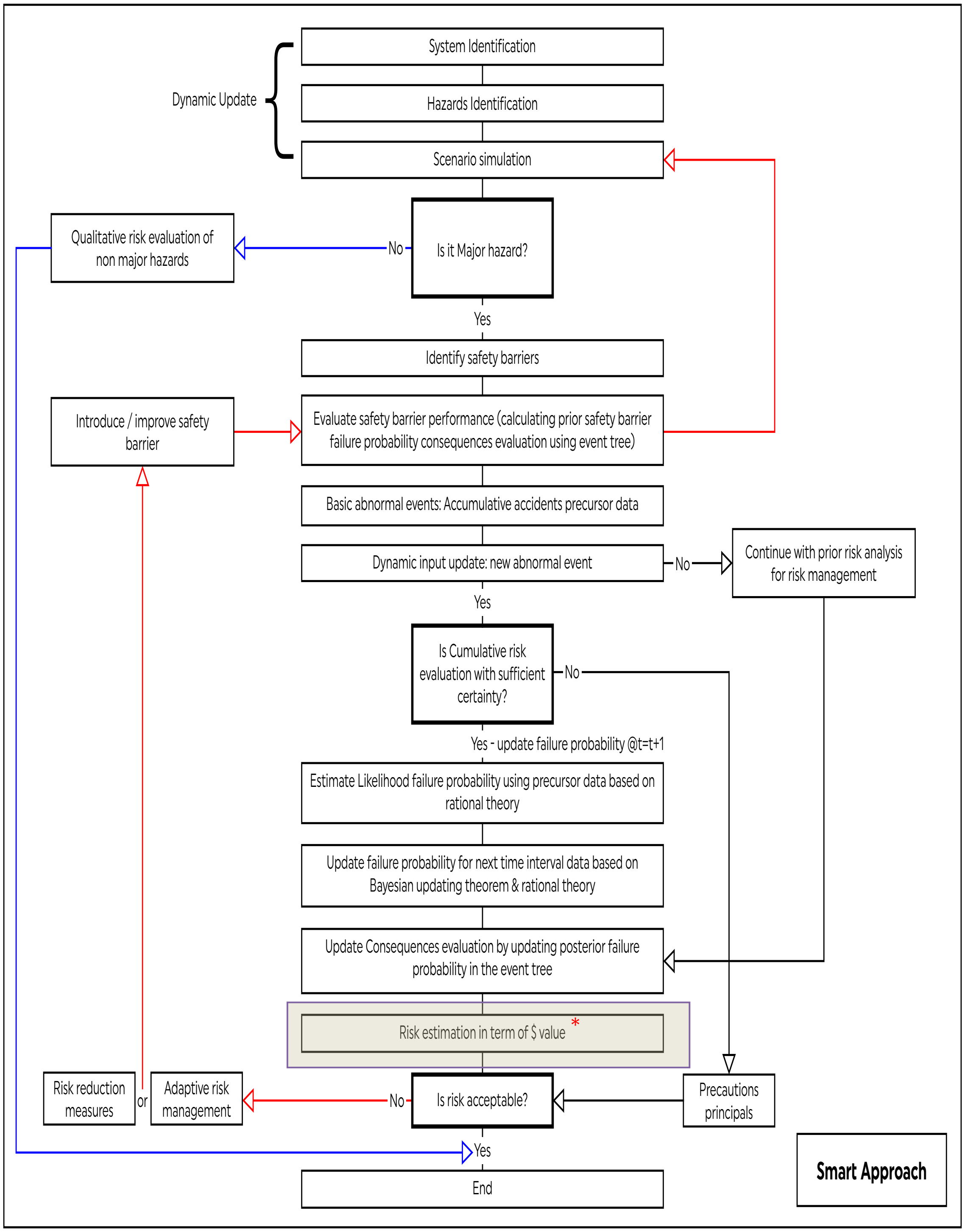


Figure 3.1 Flowchart of SMART approach.

(* TENORM risks estimation in term of $value is not covered by this study at this stage.)

3.3 TENORM occupational exposure scenario modelling and prediction

In the present study, scenarios of TENORM occupational exposure were modelled and simulated using the SMART approach. A sample was taken of 2,271 workers involved in different oilfield activities where TENORM occupational exposure and materials are expected as shown in Figure 3.2 in order to simulate different possible radiological occupational exposure in the oil and gas industry as a result of possible failure of identified safety barriers. A period of ten years was considered for serious carcinogenic risk. 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. As new evidence or new information became available at any time during evaluation process, the safety barrier failure probabilities were dynamically updated. Subsequently, 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 was to develop effective risk management strategies to aid in identifying critical safety barriers that need to be maintained in the oil and gas industry and achieve the lowest risk.

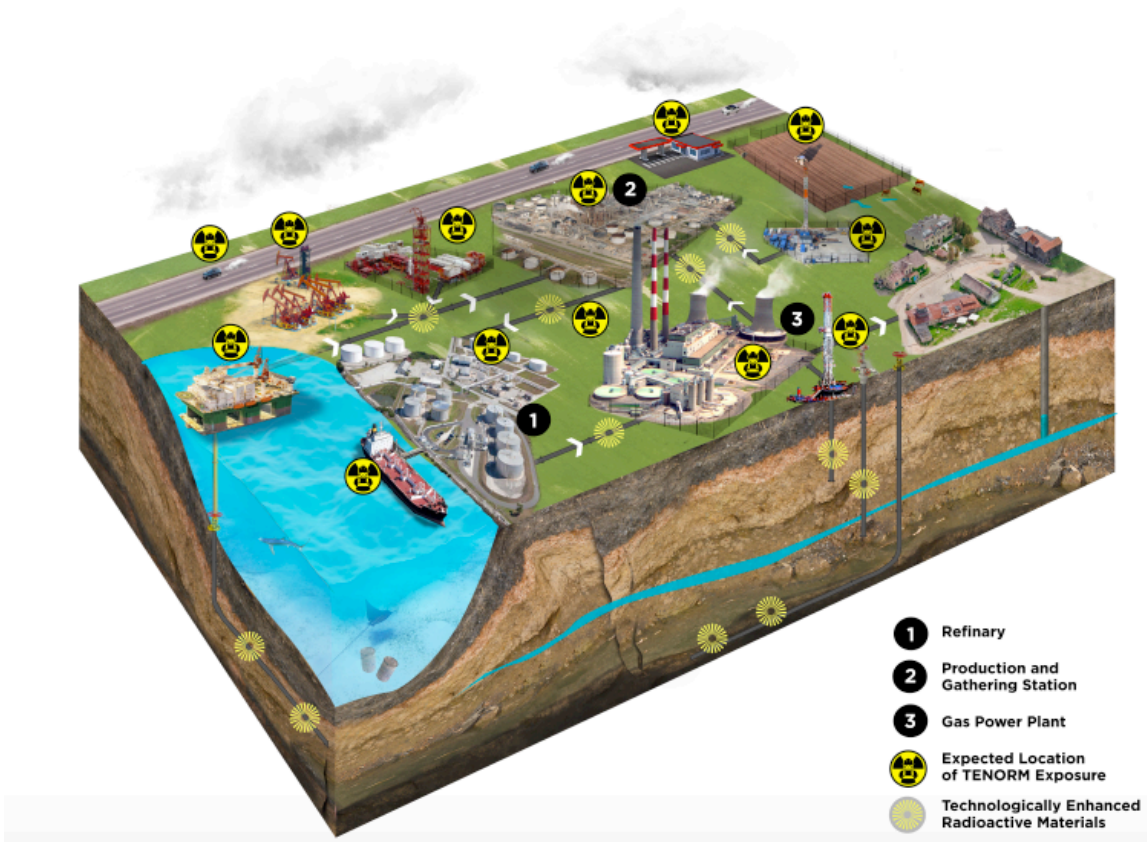


Figure 3.2 An overview of TENORM presence during oil and gas extraction and production activates.

3.3.1 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 down-hole completion and production equipment. This mixture then travels to midstream equipment via a separator, which removes the gas and relays it to a downstream gas purification plant. The degassed oil stream is further pumped to midstream production from the upstream facilities via flow lines. Gathering and production stations then remove the oily sludge, sand, and geological formation water that are contaminated with TENORM. 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 downstream facilities for further refining, where the refined products may still harbor TENORM. Smith (1992) reported that TENORM can be transported in different forms in the produced hydrocarbons, which confirms their existence wherever there is oil and gas or even 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, 2010). This could be attributed to the presence TENORM that also contain the hazardous and poisonous chemical.

3.3.2 Safety barriers identification and evaluation

During oil and gas extraction and production processes, five sequential and interconnected safety barriers for radiation prevention could be identified, which remain largely unimplemented in the oil and gas industry. These are as follows:

(1) Early Detection Safety Prevention Barrier (EDSPB). This is considered to be 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 provide information on early TENORM presence associated with hydrocarbon evaluation, and its level of radioactivity prediction.
- Down-hole real time detectors that are capable of detecting the radioactively level from rock formation during drilling activities. Surface sensors should also be fixed at different locations in drilling rigs such as at the cellar, the wellhead, the flowline connected to bell nipple, the mud system, the waste pits and the rig floor.
- Sensors that can be placed in flowlines 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 considered to be 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 flowlines, 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 programs, safety policies, operating procedures, decision-making, management practices and knowledge, leadership and communication.

The associated event tree model was utilized to demonstrate the consequences of TENORM exposure based on the failure of each of these 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 failure of different safety barriers, as is shown in Figure 3.3.

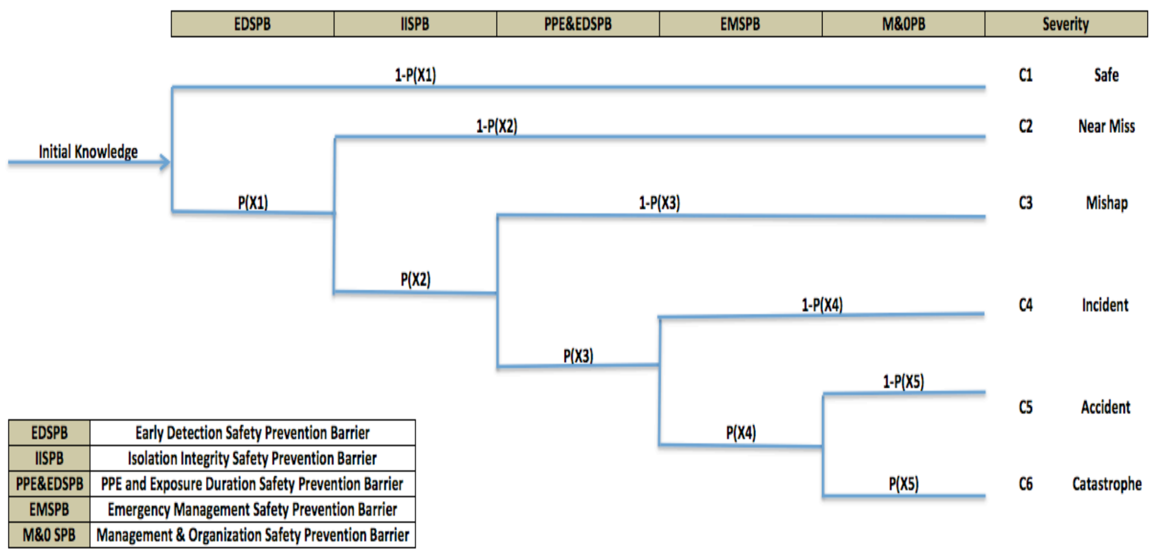


Figure 3.3 Event tree of TENORM occupational exposure in the oil and gas industry.

In this risk assessment, the radiation exposure scenario was described in terms of safety barrier failures. Due to a dearth of relevant literature on this subject, the failure probabilities of the identified safety barriers were assigned by expert judgment with the support of professional academic experts from Centre for Risk, Integrity and Safety Engineering (C-RISE-Memorial University) (Table 3.1). These values are utilized here for illustration and validation purposes

Table 3.1 Failure probabilities of safety barriers (based on expert judgment, 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 & Organization Safety Prevention Barrier-M&O SPB	0.10

The failure and success of a safety barrier is represented as a node with two outcomes. For example, if the first safety barrier EDSPB is successful, then the desirable outcome is “safe”. If it is unsuccessful, the penultimate safety barrier, IISPB, is activated. If this node is successful, the outcome is labelled “near miss”. If unsuccessful, the safety function PPE&EDSPB is activated. The successful outcome of this node is “mishap”. In the case of a failure, the next safety barrier, EMSPB, is activated and this leads to the consequence being labelled “Incident ”. If this barrier fails, the last safety barrier M&OSPB is activated. When M&OSPB is successful, the end state is labelled “accident”. If M&OSPB is unsuccessful, the end state consequence is labelled “catastrophe”.

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:

$$P(C_k)=\prod_{j \in SB_k} X_i^{\theta,I,k} (1-x_i)^{1-\theta_{i,k}} \quad (3\text{-}1)$$

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 3.2 illustrates prior probabilities of consequences occurrence.

Table 3.2 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 Catastrophe	5.0×10^{-6}

3.3.3 Modelling prediction and updating

Conditional or marginal probability approaches are widely utilized in classical accident modelling and risk assessment. These approaches are inaccurate predictors for a wide range of operating conditions (Tesfatsion, 2015). However, the proposed SMART approach in this study is predicated on a rational prediction model that attempts to ensure a more accurate predictive model for TENORM occupational exposure and associated risk by considering the two adjoined events (safety barriers failures and abnormal events) rather than a single event (abnormal events). Therefore, having a more accurate predictive model will enhance the accuracy of the decisions for the improvement of the safety system. Mathematically, the rational prediction model is presented as follows:

$$P(data) = P\,(data \mid X_i)$$

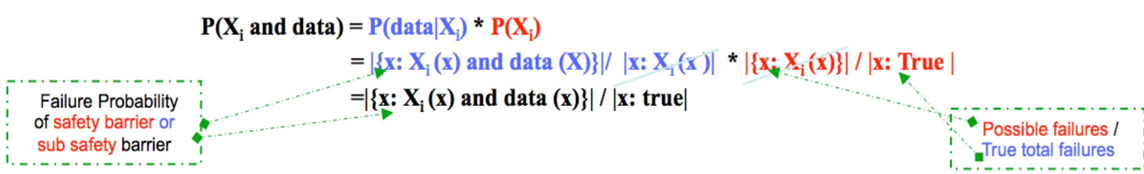
$$P(data) = P\,(data \mid X_i{:}True)$$

$$P(X_i) = |\{x{:}\ X_i\,(x)\}| \,/\, |x{:}\ True|$$

Then conditional probability expressed as:

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

Finally, the joint probability of this model expressed as:



Using symmetry, this equation can be written as Bayesian updating theorem as expressed in equation (3-2) below (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)

$$P(X_i \text{ and data}) = P(data|X_i) * P(X_i) \qquad (3\text{-}2)$$

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).

- $P(data|X_i)$ 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 interval in order to prevent TENORM occupational exposure in the oil and gas industry. Therefore, cumulative abnormal event data are a necessity to estimate failure probability. These data were assumed with the consensus of technical experts based on the performance of the available safety barriers. Cumulative abnormal event data are shown in Table 3.3. The probabilities (Table 3.4) of precursors to abnormal events were computed based on the data provided in Table 3.3.

Table 3.3 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 3.4 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

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 3.5 below.

Table 3.5 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

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 one thousand cycles in order to determine how random variation and associated errors affect the uncertainty and performance of the modelled parametric system. The cumulative precursor data P(X_i and data) were 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 one thousand runs so that this data best matched with the other data, or best represents the current knowledge state, and is denoted by \{(X_i and data)$_1$, (X_i and data)$_2$, ..., (X_i and data)$_q$\}. Table 3.6 below illustrates the improved quality of the cumulative precursor data of abnormal events extracted randomly from the simulated data.

Table 3.6 Cumulative precursor data of abnormal events simulated over ten 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

The generated data then was used to calculate the likelihood failure probability of safety barrier in the next time interval of ten years using equation (3-3):

$p(data|xi) = [N_{F,I} \mid (N_{F,i} + N_{S,i})]$ (3-3)

$N_{S,I} = N_{C,k}$, for k = i

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

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

The failure probabilities for all safety barriers are listed in Table 3.7.

Table 3.7 Likelihood failure probabilities for all safety barriers.

Likelihood failure probability for each safety barrier P(Xi and data)					
Years	**EDSPB**	**IISPB**	**PPE&EDSPB**	**EMSPB**	**M&0PB**
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

Safety barriers failure probability update

The Bayesian updating mechanism was then utilized to update the likelihood failure probability of the safety barriers over the following ten years when new types of evidence arose or changes occurred in oil and gas processing. Thus, updated failure probabilities uncover the consequence occurrence probabilities, which were updated using event tree analysis. According to rational theory, the likelihood failure probabilities of a given safety barrier X_i are affected by a combination of latent or physical and dependent or independent random variables. 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 per equation (3-4) as follows.

$$P(X_i|data) = [P(data|X_i)\ p(X_i)]/ \sum[P(data|X_i)\ P(X_i)] \qquad (3\text{-}4)$$

Where $P(X_i|data)$ is the posterior failure probability of the safety barrier, $P(data|\ X_i)$ is the likelihood failure probability of the safety barrier, p(xi) is the prior failure probability of the safety barrier, data are the new information or evidences arrived and $\sum[P(data|X_i)\ P(X_i)]$ is the normalizing factor .

Table 3.8 and Figure 3.4 illustrate the updated failure probability for safety barriers over ten years and updated based on the arrival of new evidences that contributed into the failure probability of safety barriers.

Table 3.8 Posterior failure probability data for safety barriers failures over 10 years.

Posterior failure probability for each safety barrier over 10 years $P(X_i|data)$					
Years	**EDSPB**	**IISPB**	**PPE&EDSPB**	**EMSPB**	**M&OPB**
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

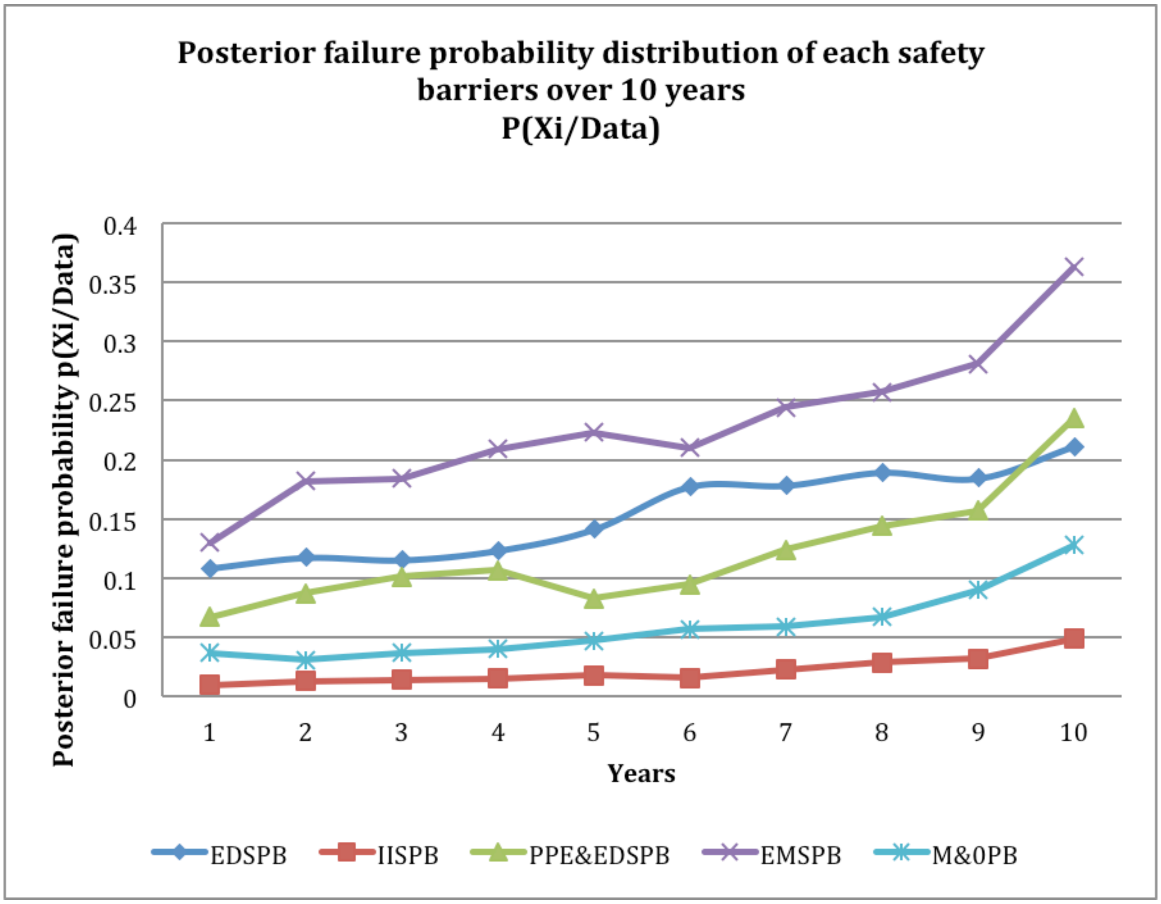


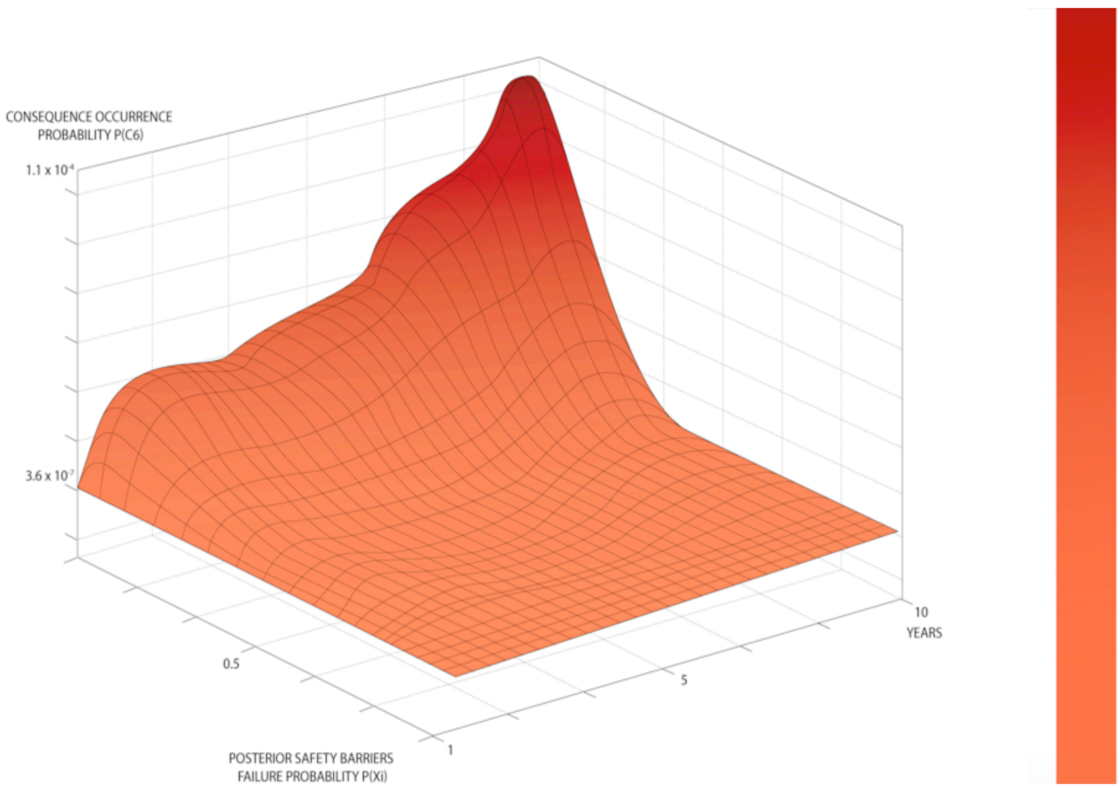
Figure 3.4 Posterior failure probability distribution of each safety barriers failure over 10 years.

Consequence occurrence probability update

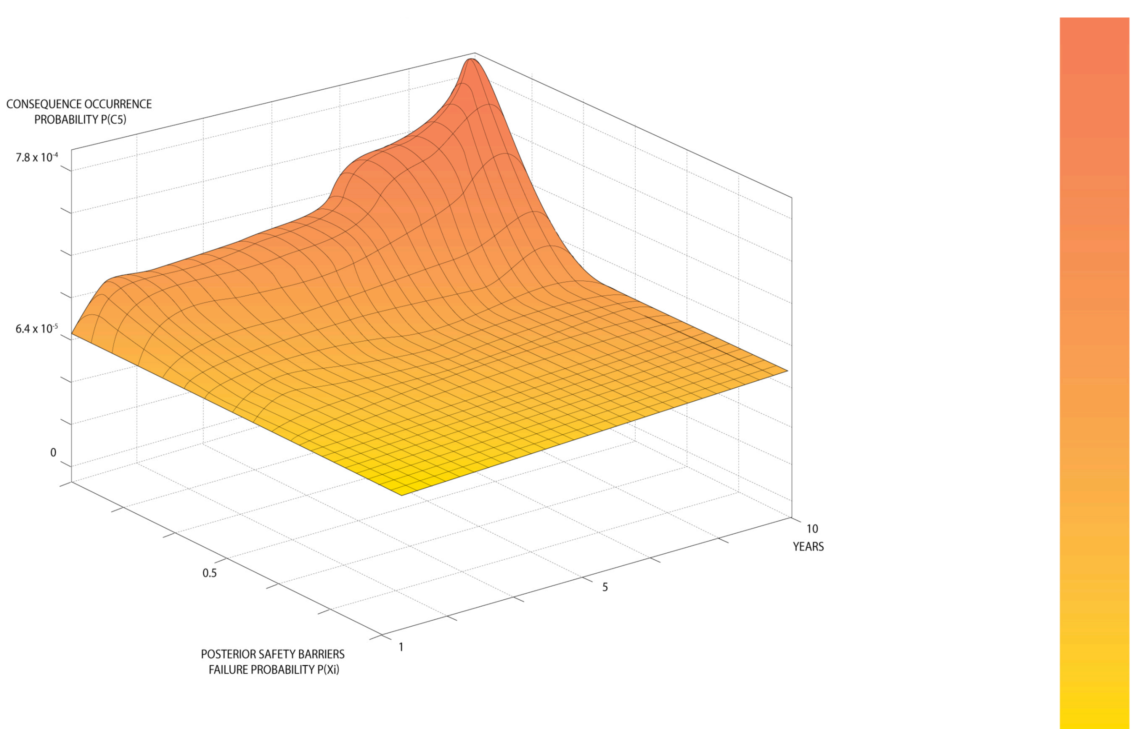
The updated failure probabilities of the safety barriers in this model were utilized to estimate occurrence probabilities for each severity level. These probabilities were then fed into relevant branches of the event tree shown in Figure 3.1, and equation (3-1) was utilized to estimate the posterior occurrence probabilities of each severity level over the ten years as shown in Figures 3.5. Table 3.9 below illustrates posterior probabilities of consequences occurrence in year ten.

Table 3.9 Posterior estimate of occurrence probability of each consequence in year ten.

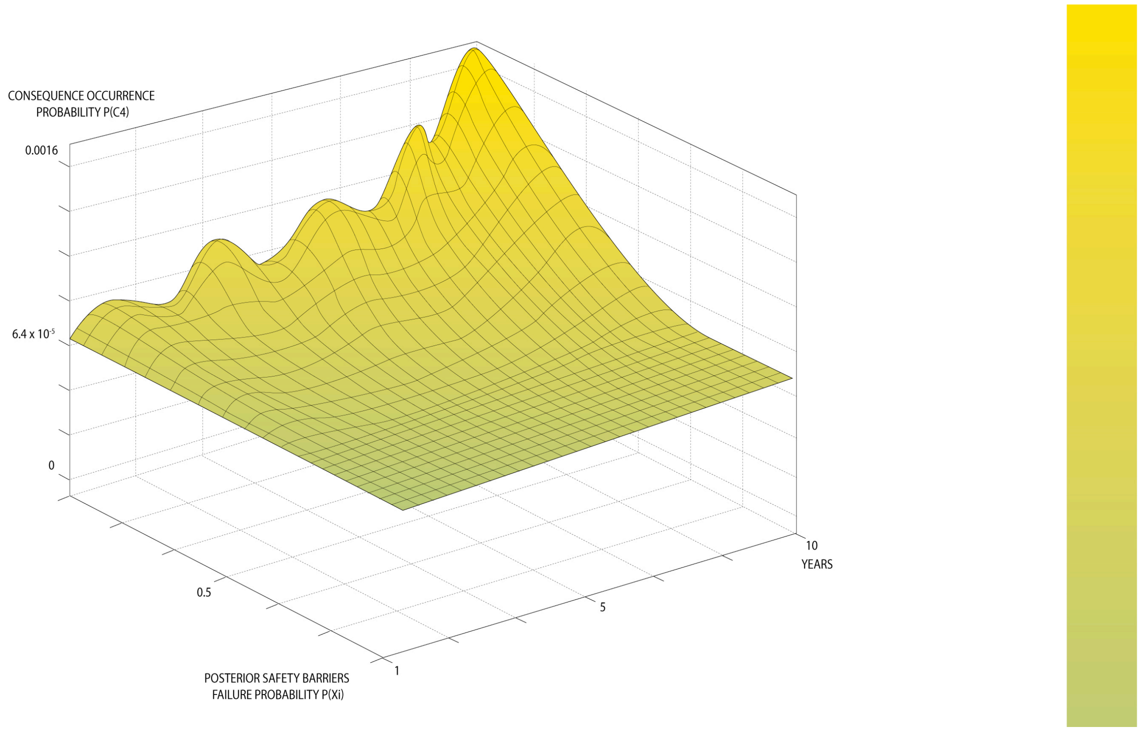
Posterior estimate of occurrence probability of each consequence in year 10	
Consequences (C_k)	**Occurrence probability $P(C_k)$**
C_1 (Safe)	0.788
C_2 (Near Miss)	0.201
C_3 (Mishap)	8×10^{-3}
C_4 (Incident)	1.6×10^{-3}
C_5 (Accident)	7.8×10^{-4}
C_6 Catastrophe	1.1×10^{-4}



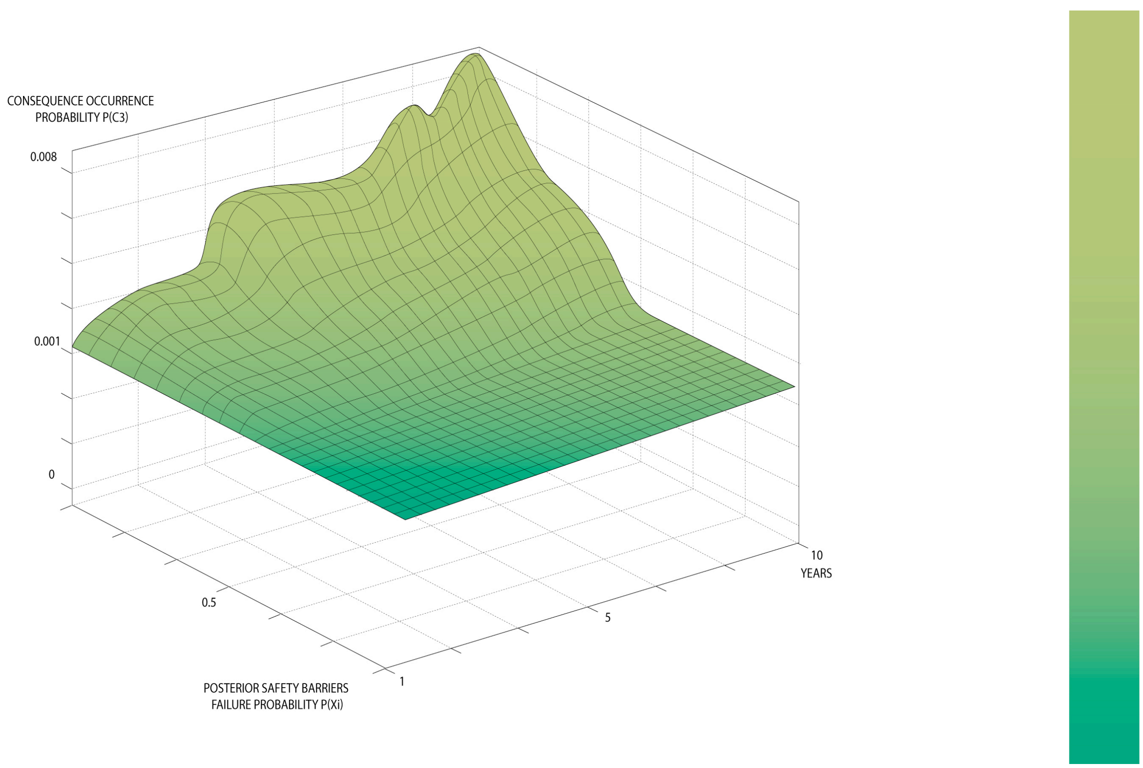
(C_6) Catastrophe



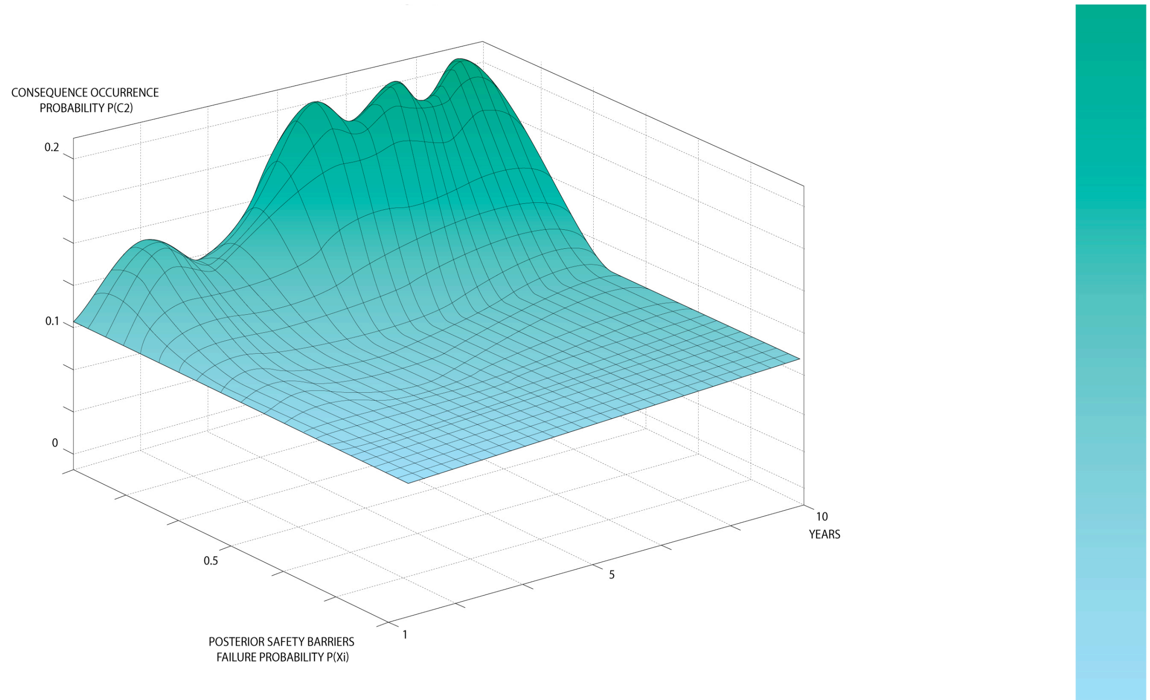
(C_5) Accident



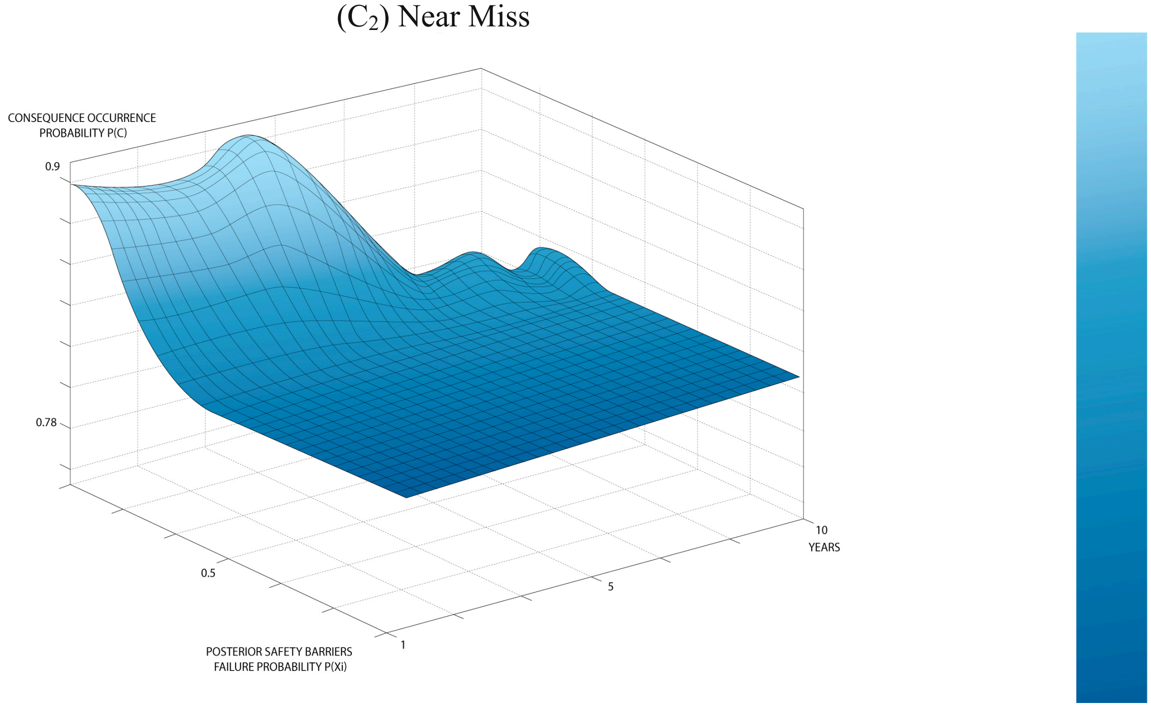
(C_4) Incident



(C_3) Mishap



(C_2) Near Miss



(C_1) Safe

Figure 3.5 Overall variations of updated consequences occurrence probability distributions over a period of ten years.

3.4 Analysis and discussions

The dynamic TENORM occupational exposure risk modelling was based on the performance of five identified sequential safety prevention barriers and their sub-elements that are mostly absent in many oilfields. These safety barriers are the Early Detection Safety Prevention Barrier (EDSPB); the Isolation Integrity Safety Prevention Barrier (IISPB); the Personal Protection Equipment and Exposure Duration Safety Prevention Barrier (PPE&EDSPB); the Emergency Management Safety Prevention Barrier (EMSPB); and the Management and Organization Safety Prevention Barrier (M&OSPB). To test the validity of the model, a quantitative risk assessment was performed using the SMART methodology coupled with a probabilistic approach. Model validation was based on three main 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 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 not yet started to degrade. 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 adopted in the second phase of the SMART approach were utilized to predict the failure likelihood and update the prior failure probabilities of the identified safety barriers over the ten year period. The prediction attempted to present a better visualization of the safety performance in a ten-year period so that appropriate decisions can be made to bolster current safety strategies. As shown in Figure 3.4, Bayesian posterior probability values for the safety barrier failures have drastically increased as a result of system degradation within the ten-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 some of the legislation that is in place, 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 an clear admission that the workers are exposed to radiation (ALNabhani et al., 2016a). 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 ten-year period. Despite 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 Figure 3.5. 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 in place for early stage activities. For instance, if an early detection prevention barrier were in place, it would allow the industry to predict the presence of TONERM in their oilfields and well holdings at early stages by using well logging data that contains radioactivity data that 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 very early stage.

As a consequence 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 Figure 3.5. 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 equipment are unfortunately not radiologically insulated or designed to prevent gamma radiation emitted by TENORM passing through or in their scale depositions. As a result of the failure of the second safety 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 particular, 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 ten years of continuous exposure; however, it has a sharp increasing tendency in probability from 3.6 x 10^{-07} to 1.1 x 10^{-4} as shown in Figure 3.5, which is almost a 3000-fold increase, and this raises serious concerns. Most importantly, some safety barriers such as the Emergency Management Safety Prevention Barrier (EMSPB) and the Management and Organization Safety Prevention Barrier (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 behaviour 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. Figure 3.5 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.

3.5 Conclusions

TENORM is a potentially serious environmental and occupational risk in oil and gas operations. To assess radiation exposure risk to workers, a new methodology of dynamic modelling scenario based risk assessment was proposed. 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 were identified and are considered to provide workers sufficient protection from radiation exposure during oil and gas extraction and production activities. The SMART approach provides a systematic framework for modelling, predicting, updating, and managing the TENORM exposure risk during oil and gas production. 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 assess it with safety barrier performance. Based on the results, it is apparent that there is a need to develop appropriate safety measures for protecting 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 radiological waste volume created during production that also contributes to serious radiological issues for workers, the public and the environment. The next chapter presents a new approach as well as a scenario-based risk assessment of TENORM Waste disposal options in the oil and gas industry.

Future studies to be done according to the SMART approach process flowchart include the estimation of the TENORM economic risk, and how to establish a successful and thorough TENORM management system.

Chapter 4

Scenario-based Risk Assessment of TENORM Waste Disposal Options in the Oil and Gas Industry

Authorship and contributorship

This work has been published by Khalid ALNabhani, Prof. Faisal Khan, and Dr. Ming Yang in 2016 under title "Scenario-based Risk Assessment of TENORM Waste Disposal Options in the Oil and Gas Industry. It appears in volume 40 of *Journal of Loss Prevention in the Process Industries*, at pages 55-66. This article can be accessed through following link:

https://www.researchgate.net/publication/287150884_Scenario
based_Risk_Assessment_of_TENORM_Waste_Disposal_Options_in_Oil_and_Gas_Industry

The first author (Khalid ALNabhani) and co-authors (Drs. Faisal Khan & Ming Yang) formulated the research problem. The first author structured the approach, designed and conducted the scenario and the risk assessment. The co-authors (Drs. Faisal Khan & Ming Yang) critically reviewed the developed approach and provided further suggestions to improve both the approach and the manuscript.

Preface

Technologically Enhanced Naturally Occurring Nuclear Radioactive Materials (TENORM) waste in the petroleum industry has become a serious concern as a potential source of radiation. The risk of being exposed to TENORM waste must therefore be identified and controlled to protect workers, the general public and the environment. This chapter presents an analysis of TENORM waste disposal options and risk assessment methods commonly used in the oil and gas industry. To assess their effectiveness, the study presented in this chapter utilizes an integrated fate and transport model and exposure pathways. The study also studies plausible scenarios in which the contaminants can migrate through the geosphere and biosphere, reaching the environment, animals and humans. A real case scenario of TENORM waste disposed in an evaporation pond is simulated using RESRAD (Version 6.5) where real data that are dynamically updated are used as input parameters to evaluate the potential radiological doses and increased carcinogenic risk. To both understand and validate the simulated results, the findings of the real case scenario are compared with results obtained using a similar simulated scenario constructed from a literature review discussed later in the same chapter.

4.1 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 cuttings and contaminated produced water which contains different levels of soluble radioactive materials ranging from low to high level radioactive isotopes. As mentioned earlier, the wastes from radioactive isotopes decay normally from Thorium- 232 and Uranium-238 series that are likely to be enhanced technologically as a consequence of physical and chemical processes associated with oil and gas production (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 and plants. 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, 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, 1993; 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; Gazineu et al., 2005). The ratio of produced water to oil is approximately 10 to 1, and according to the American Petroleum Institute, API (1989) and ALFarsi (2008), 18 to 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 re-injected for enhanced recovery or disposal, and about 234,000 m^3/day was treated and discharged to the ocean (Clark and Veil, 2009). These figures have increased rapidly as a result of the increase in oil production to satisfy growing demands, thereby increasing the volume of generated TENORM wastes and raising the concern of how to depose of them safely.

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

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

With the increased concentration of TENORM wastes produced during 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 & Production Forum and the American Petroleum Institute. Figure 4.1 below summarizes different disposal alternatives proposed according to concentration limits, the degrees of isolation from the public and cost.

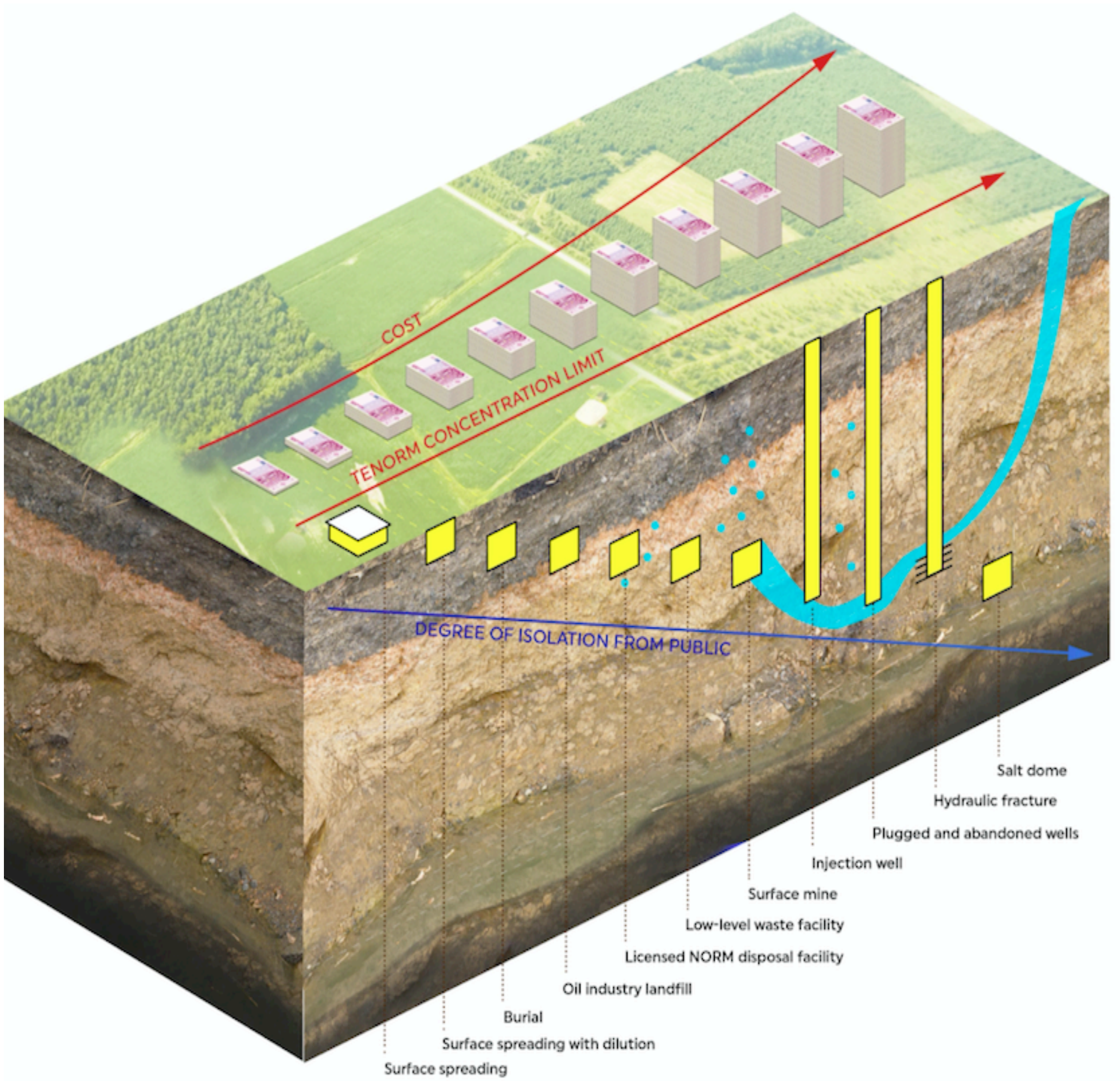


Figure 4.1 Suggested disposal alternatives for NORM/TENORM wastes.

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

- Injection/re-injection of waste together with cuttings and other types of non-radioactive production wastes:

  (1) Well injection/re-injection into the reservoir;

  (2) Well injection by hydraulic fracturing; 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.

(16) Salt Dome disposal where TENORM wastes are injected and placed into old abandoned underground salt domes formations.

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

Many of the suggested 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. This study demonstrates the potential risk of radiation exposure for workers, the general public and the environment resulting from the most common TENORM waste disposal methods. A scenario-based approach has been applied to support the risk assessment of TENORM wastes considering various fate and transport exposure pathways.

The infographic sketch (Figure 4.2) demonstrates the most common TENORM waste disposal methods used in the oil and gas industry. It also illustrates the adverse effects of radiological pollution from TENORM wastes disposal methods and potential sources of exposure for workers, the public, food, water resources, and the environment. This study simulates a real scenario of TENORM waste disposal in evaporation pond using the RESRAD 6.5 modelling 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 the 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 perspective. Indeed from the standpoint of public health and safety, medical opinion is the most accurate way to determine safe exposure to radiological risk.

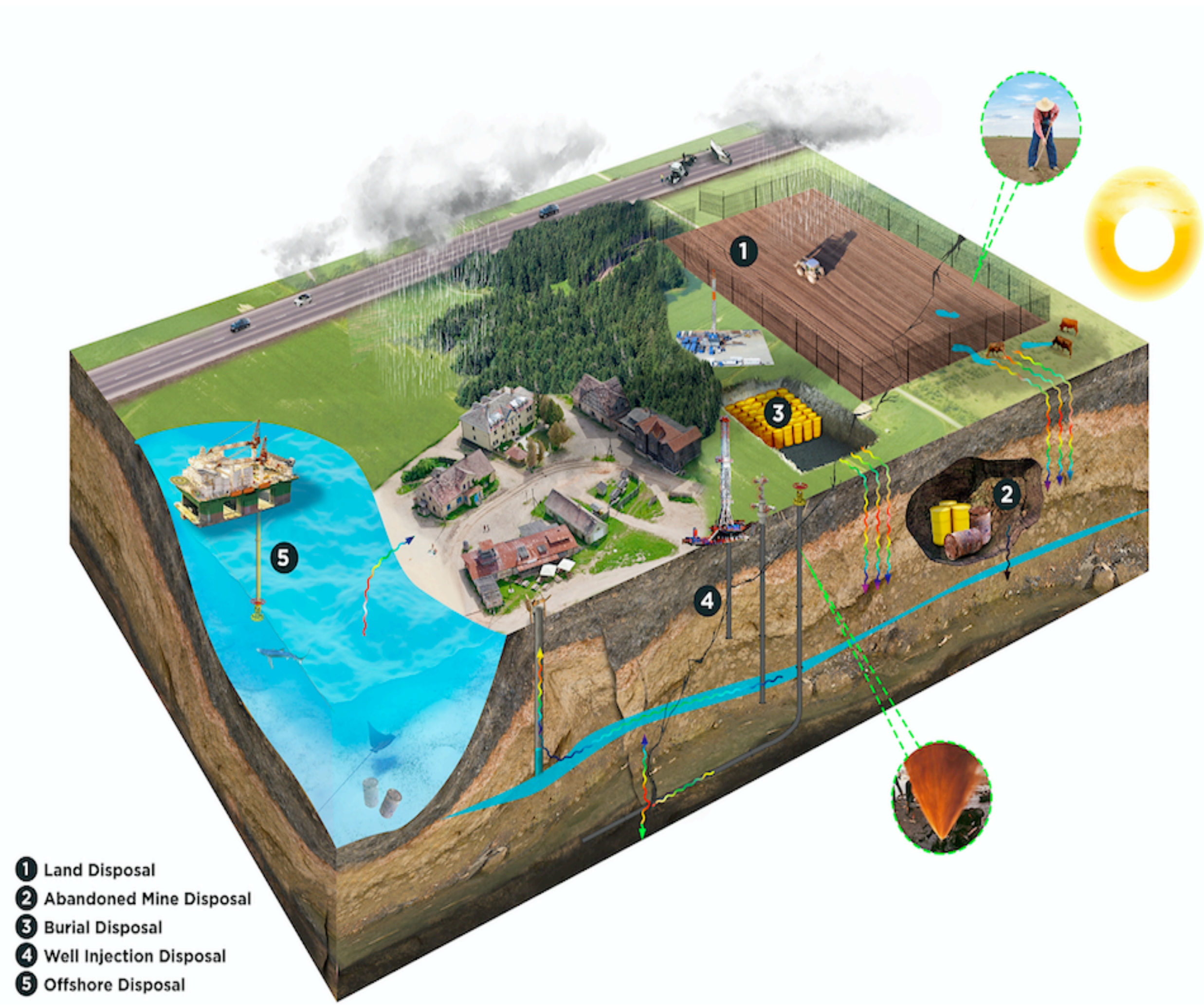


Figure 4.2 Common TENORM waste disposal options used in the oil and gas industry.

4.3 Risk assessment of TENORM waste disposal options

Figure 4.3 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.

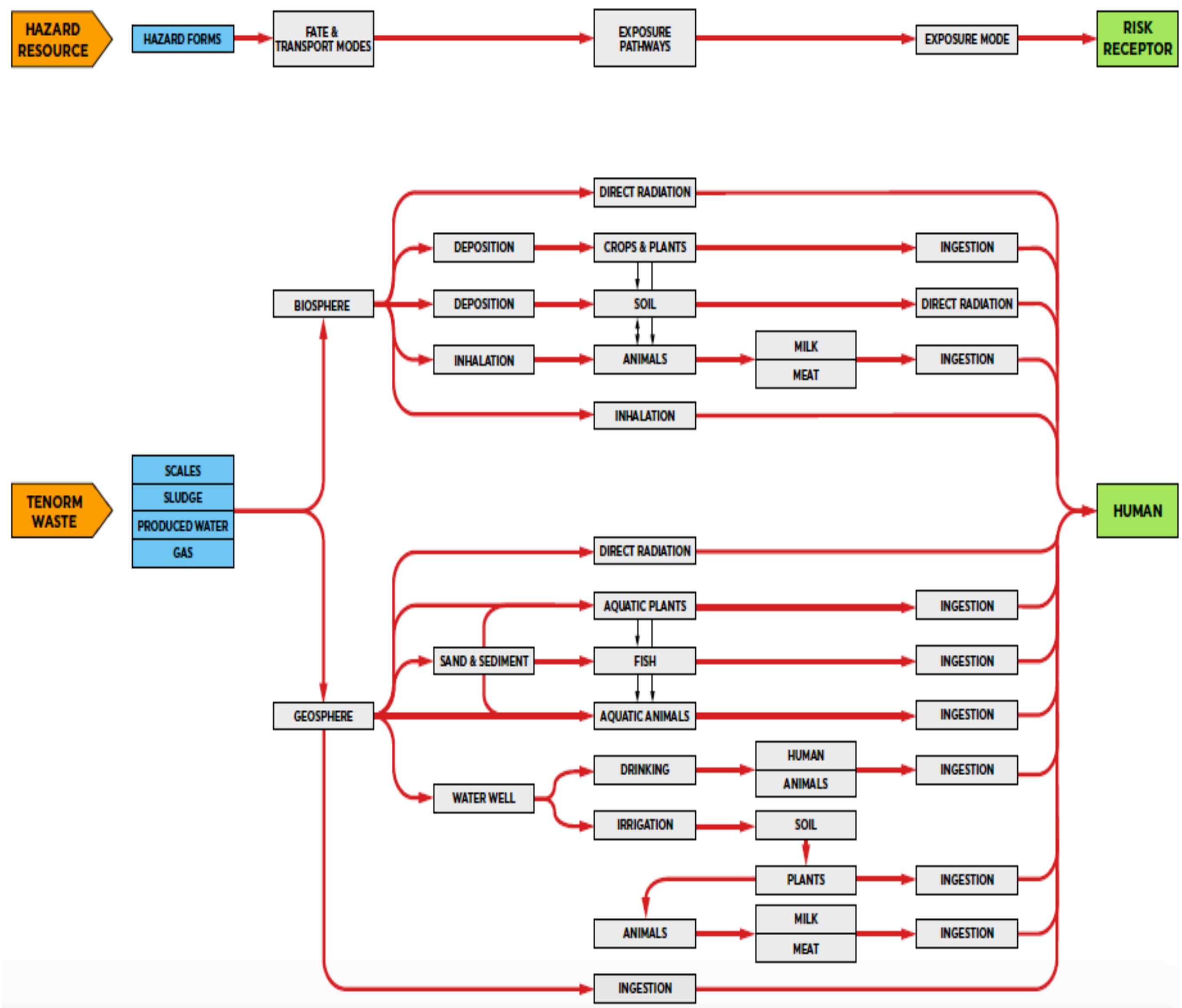


Figure 4.3 Fate and transport model.

The general fate and transport model investigates all possible fate and transport pathways of the disposed radionuclides. 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. While, the geosphere may consist of the aquatic system such as sea, lakes, rivers, or a well that 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 meters 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; skin contact; inhalation of radon and other radionuclides during soil mixing or evaporation (Vandenhove et al., 1999). Radiological surveys conducted by US EPA (1993) have also indicated that TENORM contamination in some scrap pipes stored in disposal sites may have contaminated the surrounding environment. These surveys found that some equipment and disposal locations exhibited external radiation levels above 2 mR/hr 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.

4.3.1 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 considered an economical alternative for many onshore oil and gas companies for the disposal of huge quantities of contaminated 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). Coproduced water contaminated with TENORM is then dumped into the pond. RESRAD 6.5 for doses assessment has been used to assess the health risk of TENORM exposure from these ponds for operators and others, including workers located in production stations that may be as far away as 1000 meters. The assessment considers different exposure pathways based on fate and transport model tailored for the assigned scenario as shown in Figure 4.4.

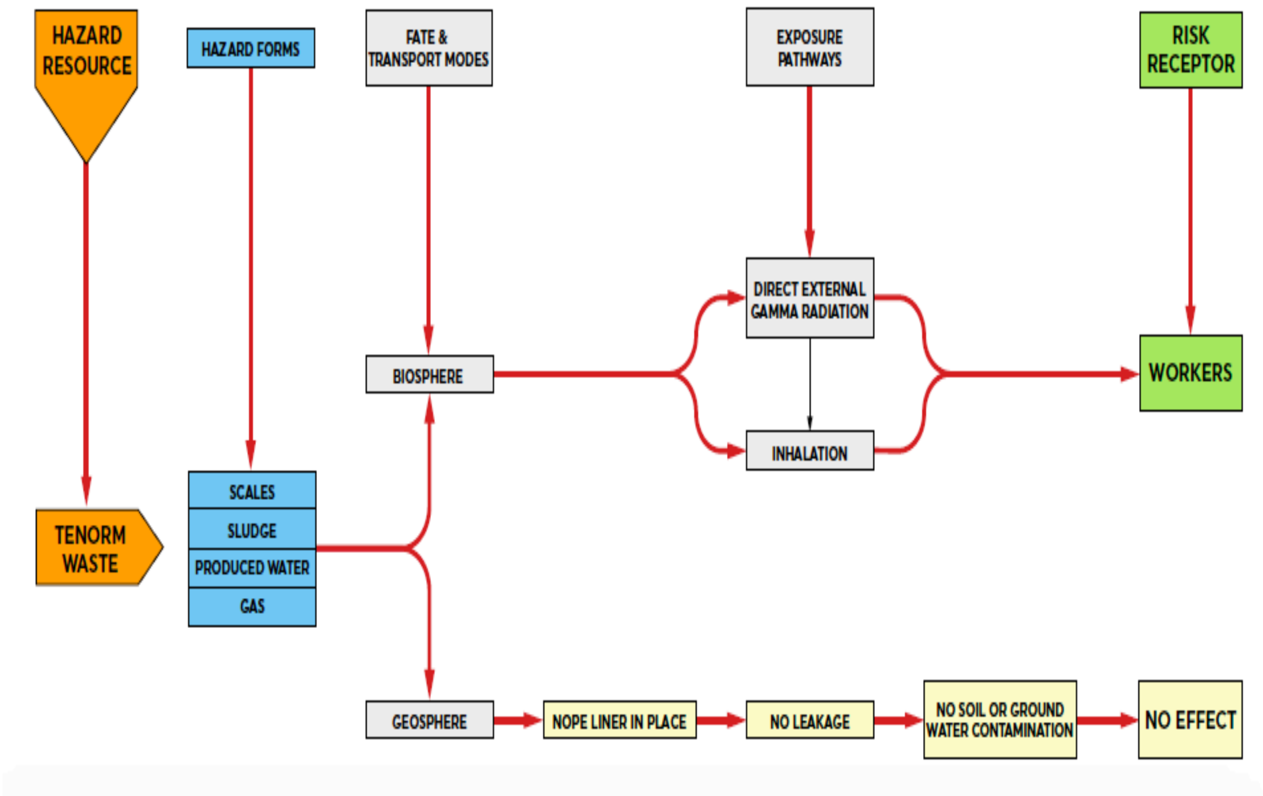


Figure 4.4 Different exposure pathways of TENORM waste disposed in an evaporation pond based on fate and transport model.

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 next 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.

Scenario Description

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

- Hazard Source: TENORM waste.
- Hazard Forms**:** Co-produced water contaminated with TENORM waste from oil and gas production with a potential mixture of sludge, scales and gases. This rate is modeled as a function of the geometry of the contaminated zone and the decay of the radionuclides.
- 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.
- 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.
- 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 housing or farming.

- Mode of Exposure Pathways*:* The scenario modelling was conducted for evaporation ponds located in a desert, therefore the only external radiation sources considered were radiation from the pond and contaminated soil collected from the pond after evaporation, inhalation and ingestion of the dust and vapours 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 modelling 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 of (0.603 Bq/g, 1.12 Bq/g and 1.65 Bq/g**).**
- Activity concentrations of above three samples were assumed homogenously distributed in the pond.

- Secular equilibrium between radioactive parent and daughters (constant rate of energy decay per unit time).
- The pond is lined with HDPE liner.
- TENORM waste thickness is 100 cm.
- Total area of the pond is 40000 m^2.
- Exposure duration: 4 hours per day × 365days 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 hours 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 ^oC; 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 internal exposure to radiation or intake of radionuclides via inhalation based on age- and gender-specific coefficients for individual organs, along with organ-specific dose rate conversion factors (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 1997a). 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. The intake contributing doses (Bq/yr or pCi/yr) and excess cancer risk probability can be computed by using the following equation:

$$(\text{Intake contributing doses })_{j,p}(t) = \sum_{i=1}^{M} ETF_{j,p}(t) \times SFij(t) \times S_i(0) \times BRF_{i,j} \qquad (4\text{-}1)$$

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

M = the number of initially existent radionuclides,

$ETF_{j,p}(t)$ = environmental transport factor for radionuclide j at time t (g/yr),

p = primary index of pathway,

$SF_{ij}(t)$ = 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 equation (4-2) below:

$$(\text{Excess Cancer risk})_{j,p}(t) = \sum_{i=1}^{M} \underbrace{ETF_{j,p}(t) \times SF_{ij}(t) \times S_i(0) \times BRF_{i,j}}_{\text{Intake contributing doses}} \times RC_{j,p} \times ED \qquad (4\text{-}2)$$

Where,

$RC_{j,p}$ = risk coefficient for environmental pathways exposure (risk/yr)/(pCi/g) (Risk Coefficients for external and internal (inhalation and ingestion) exposure are listed in Appendix A & B), ED = exposure duration (Year).

Calculation of: $ETF_{j,p}$, SF_{ij} , $S_i(0)$ $BRF_{i,j}$

- The environmental transport factor $\{ETF_{ij,\,pq}(t)\}$, which is the time-dependent ratio is calculated as per equation (4-3) below:

$$ETF_{ij,\,pq}(t) = E_{ij,\,pq}(t)/[S_i(0) \times SF'_{ij,\,pq}(t)]\ , \qquad (4\text{-}3)$$

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/yr [pCi/yr] 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].

$SF'_{ij\ pq}(t)$ = 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 equation (4-4) below

$$SF_{ij}(t) = S_{ij}(t)/S_i(0) , \qquad (4\text{-}4)$$

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 ith 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 1,000 years for three different levels of TENORM waste activity concentrations (^{226}Ra/ ^{228}Ra activity: 0.603, 1.12 and 1.63 Bq/g).

Figures 4.5 and 4.7 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 Figures 4.6 and 4.8.

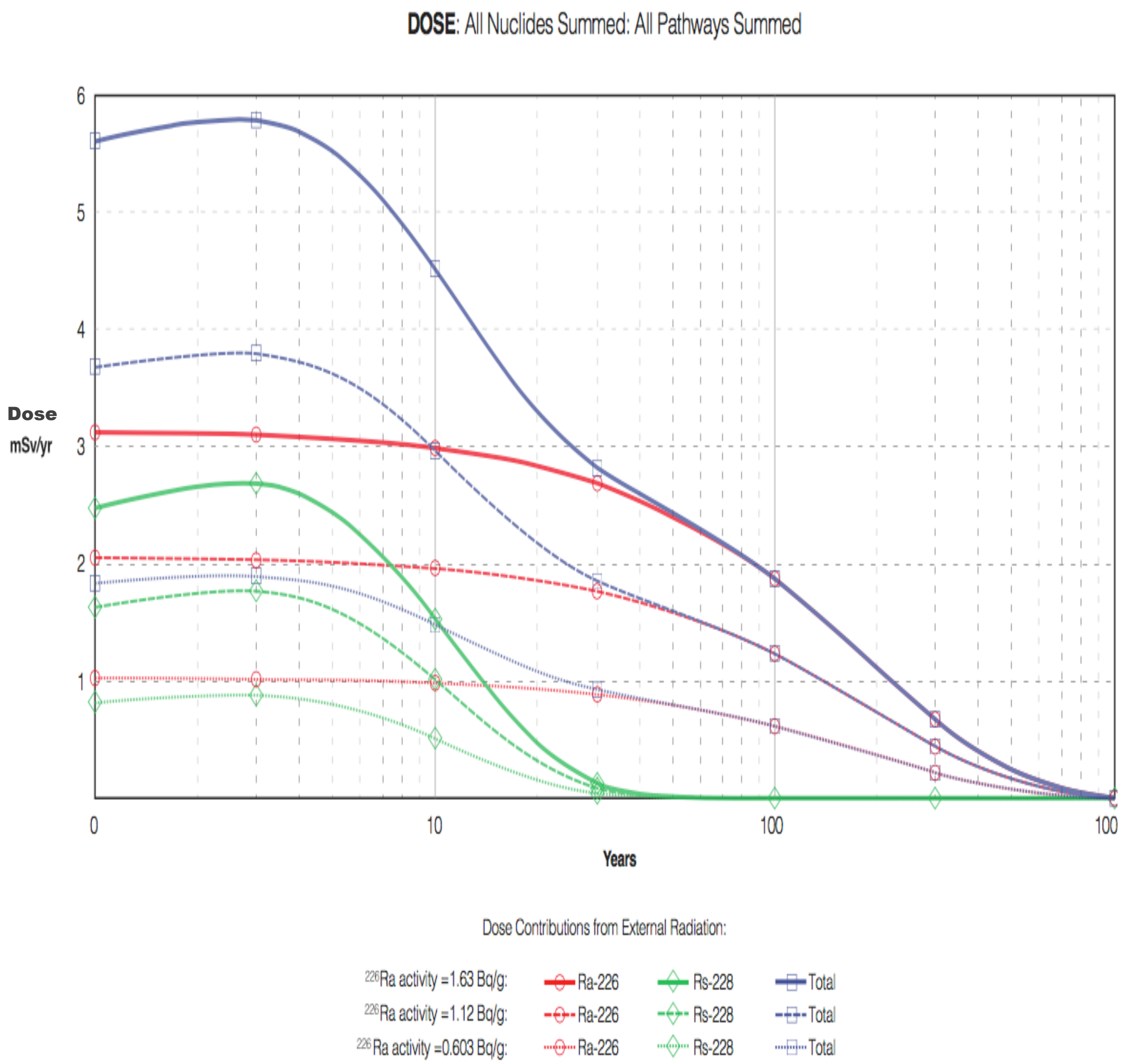


Figure 4.5 Doses contribution from external radiation exposure pathway ($^{226}Ra/^{228}Ra$ activity concentration 0.603, 1.12 and 1.63 Bq/g).

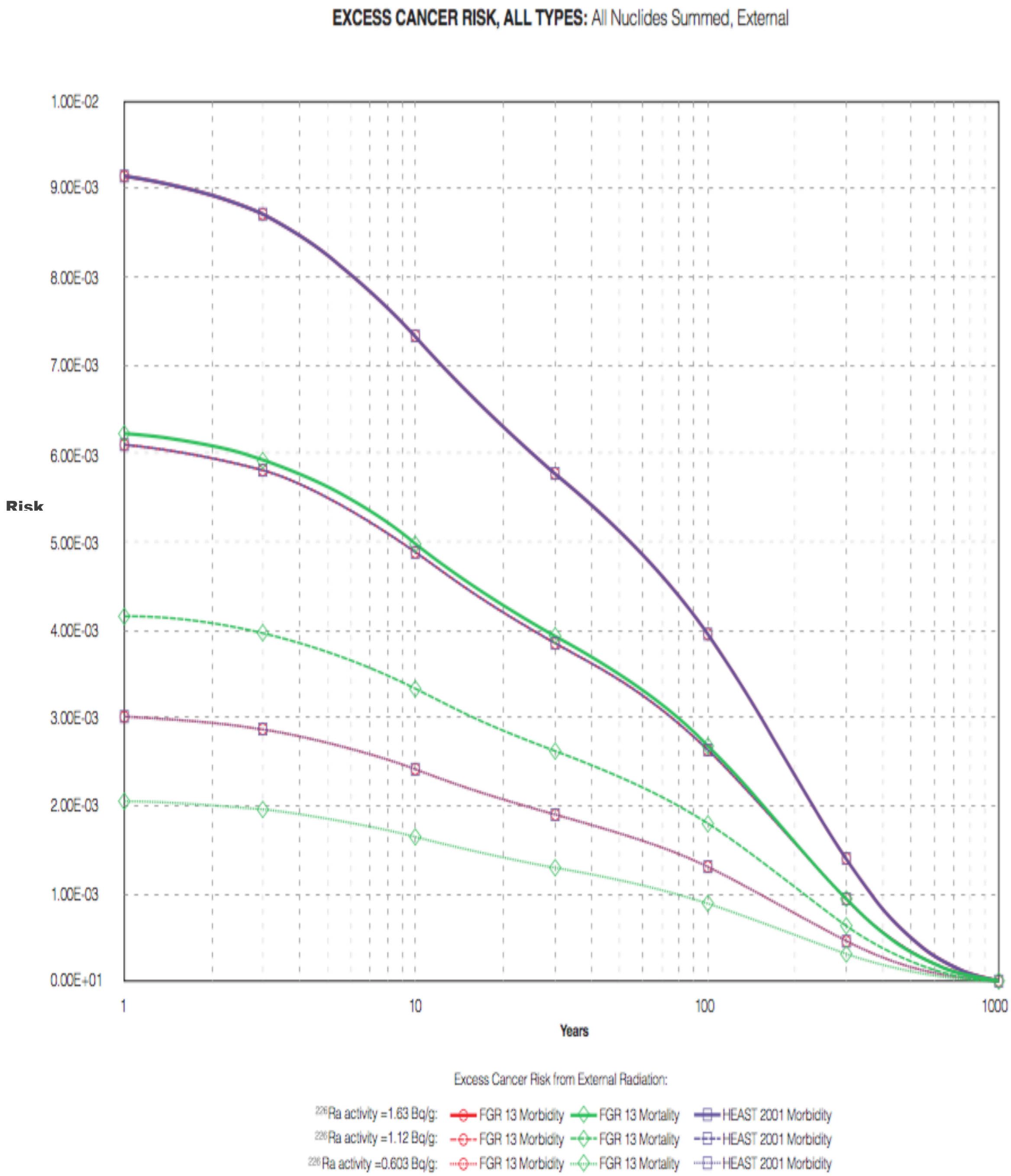


Figure 4.6 Excess carcinogenic risks from external radiation exposure pathway ($^{226}Ra/^{228}Ra$ activity concentration 0.603, 1.12 and 1.63 Bq/g).

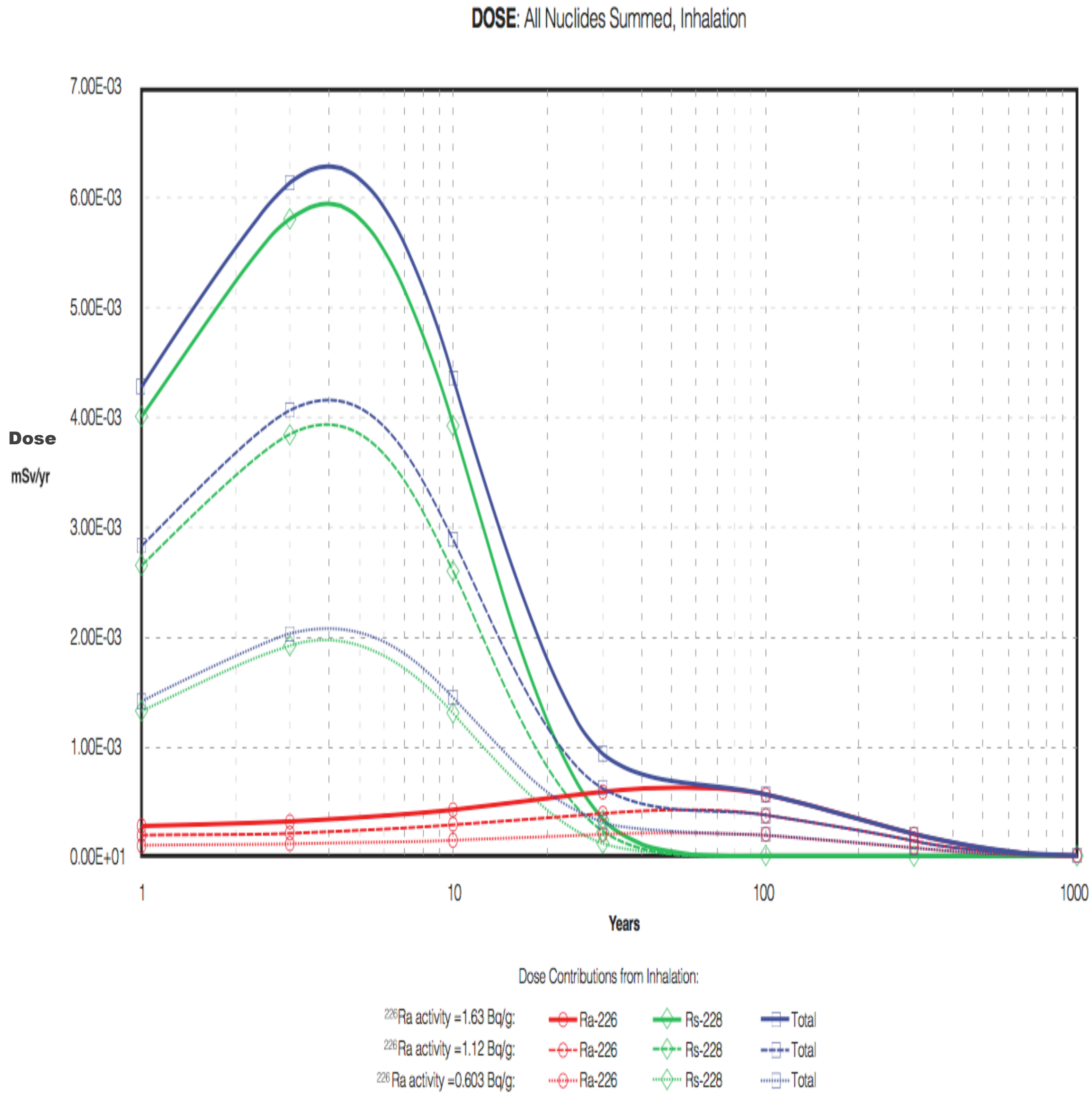


Figure 4.7 Doses contribution from inhalation exposure pathway ($^{226}Ra/^{228}Ra$ activity concentration 0.603, 1.12 and 1.63 Bq/g).

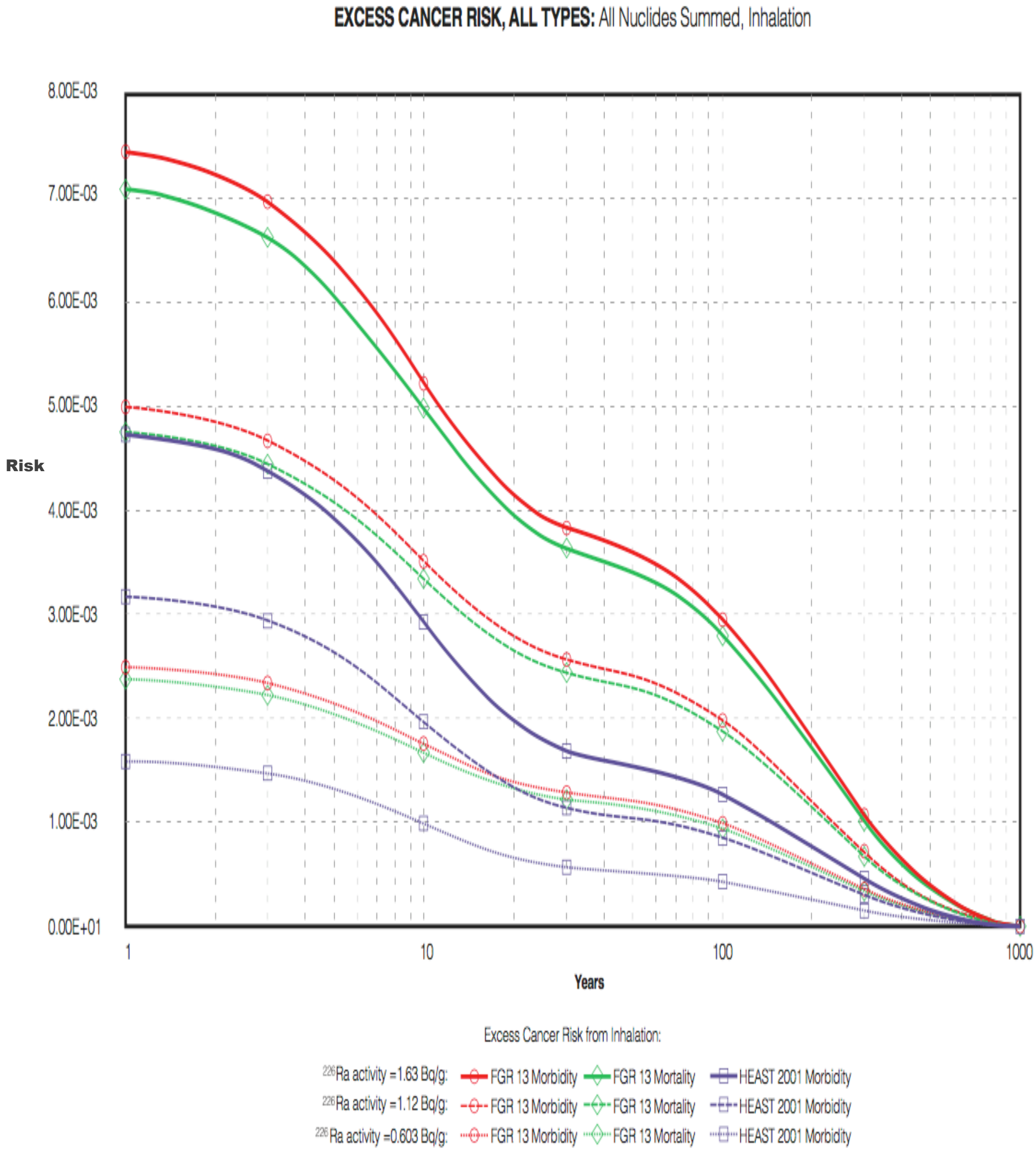


Figure 4.8 Excess carcinogenic risks from inhalation exposure pathway ($^{226}Ra/^{228}Ra$ activity concentration 0.603, 1.12 and 1.63 Bq/g).

4.4 TENORM Risk Assessment benchmarking with other literature

4.4.1 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 modelled 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 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 to 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 42323, 13578 and 9236 Bq/Kg and for Th-232 were 36100, 12180 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 x 10^{-5} mSv/yr and 0.732, 0.244 and 0.150 mSv/yr 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 x 10^{-9} and 6.0 x 10^{-5}, 2.0 x 10^{-5} and 1.2 x 10^{-5} for soil categories I, II and III respectively. Results are described in greater detail in subsequent sections of Figure 4.9.

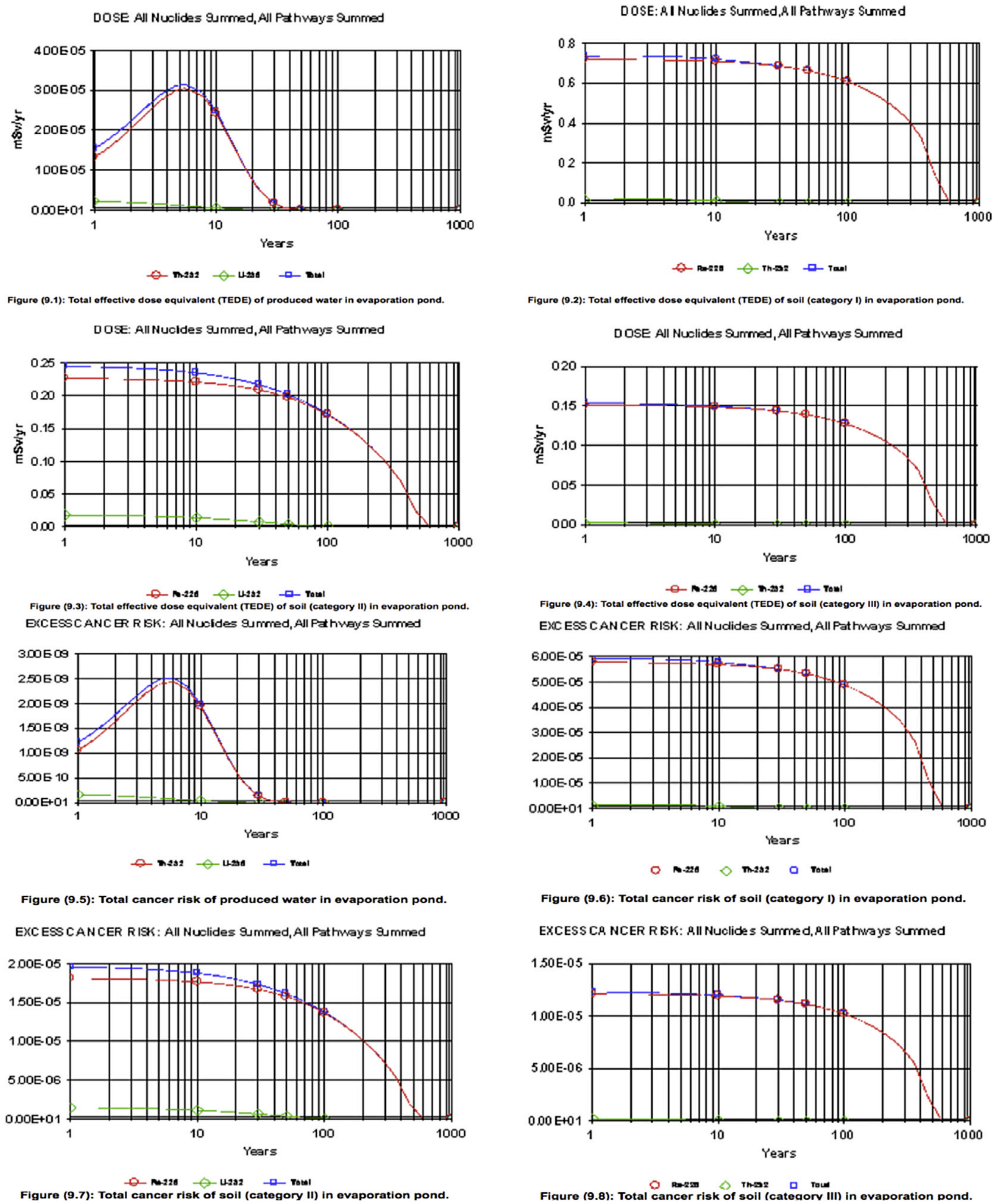


Figure 4.9 Total effective doses equivalent (TEDE) from U-238 and Th-232 radionuclides and total carcinogenic risk for industrial workers exposed to produced water and contaminated soil in the evaporation pond (Othman and Hassan, 2013).

4.4.2 *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 modelled 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 re-suspended 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 4,050 m^2 (1 acre) with a contaminated zone 20 cm thick. Three soil concentrations were measured and modelled. The concentration ratio of 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 EPA, 1993a; US EPA, 1993b). 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).

Figure 4.10 shows the total doses from all exposure pathways over 100.00 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 3,000 mrem/yr 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 Figure 10 below.

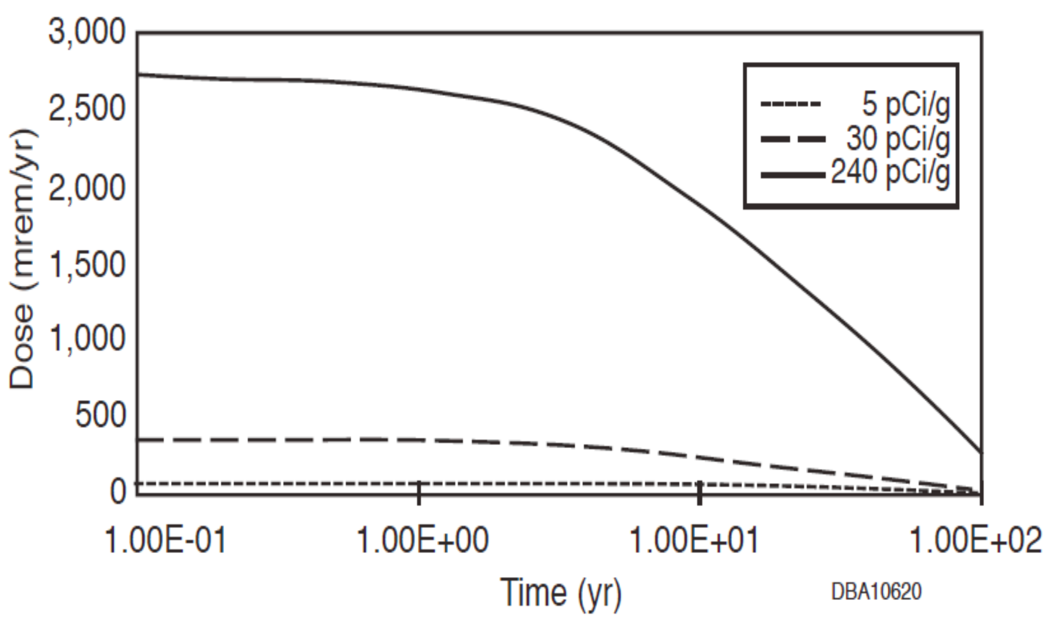


Figure 4.10 Total doses over time summed over all pathways for land spreading with dilution (Smith et al., 1996)

4.5 Analysis and discussions

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. Unfortunately, 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 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 instance in 1991, the International Commission on Radiological Protection (ICRP) recognized that workers' exposure to TENORM doses exceeding an average of 1mSv/yr 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/yr. 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 (Khan et al., 2003). Such uncertainty can arise from the following factors:

- Inaccurate input data or assumptions, or default input made by the simulator.
- 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 the limitation 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/ dis- equilibrium /in-growth for each sample.
- Each series may contain 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 modelling 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, and accumulated intake doses are factors that have a great impact on the biological effects of radiation exposure, which are not yet being considered by available simulation programs.

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, genetic structure, accumulated intake doses, and 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 analysed 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 (any doses, no matter how small, involves 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 (BEIR VII, 2006) and is accepted also by the US National Research Council. Based on this model, it has been confirmed that even the very lowest doses of radiation 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 approach 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 thirty years that some workers in the oil and gas industry are at great risk of being exposed to technologically enhanced levels of natural 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 next chapter.) 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 (2005) 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 where 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.

4.6 Conclusions

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. Crucial factors such as radiation source, types, doses rate, doses effects, doses frequency, tissue type/cell and genes are not being considered in the current TENORM radiological occupational risk assessments in the oil and gas industry, making it difficult to estimate with high accuracy the health risks from low-doses radiation. As a result, estimates remain controversial. Therefore, 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.

Chapter 5

The Importance of public participation in legislation of TENORM risks management in the oil and gas industry

Authorship and contributorship

This work has been completed by Khalid ALNabhani, Prof. Faisal Khan, and Dr. Ming Yang in 2016. This work has been accepted and published in volume 102 of *Journal of Process Safety and Environmental Protection*, at pages 606-614. Full details of this article can be accessed through the following link:

https://www.researchgate.net/publication/302554748_The_Importance_of_public_participation_in_legislation_of_TENORM_risks_management_in_the_oil_and_gas_industry

The first author (Khalid ALNabhani) and co-authors (Drs. Faisal Khan & Ming Yang) formulated the research problem. The first author structured the approach based on current knowledge gaps found in related literature reviews and available regulations and standards. The co-authors (Drs. Faisal Khan & Ming Yang) critically reviewed the developed approach and provided further suggestions to improve both the approach and the manuscript.

Preface

The great debate about incorporating public participation in the legislative process of oil and gas regulation is contentious and triggered by the political game theory whereby states focus on building a strong economy and full sovereignty at the expense of public health and the environment. The relationship between politics and the economy in oil and gas producing states often politicized to increase oil and gas production. This has led to increased technological risks, where harmful radioactive materials are co-produced during oil and gas production. Furthermore, the co-produced radiological materials pose a serious radiological risk to workers in the oil and gas industry through direct radiological exposure. 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, as has been discussed earlier in the previous chapter. Incidentally, these disposal sites that are later developed into residential sites, commercial premises or industrial sites, can amplify the radiological risk to us and our grandchildren and their descendants. Radiological risks from the oil and gas industry therefore threaten public health and the environment, and are thus a matter of public concern. This chapter focuses on the relationship between the legislation and politics related to the oil and gas industry and the laws associated with the oil and gas industry that are inadequate to provide sufficient protection to both human health and the environment. This chapter aims to emphasize the importance of public participation and activate its role in the formulation of legislation that strives to strike a balance between the interests of government and industry and the interests of the public.

5.1 Introduction

Since the eighteenth 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 for such states, generating a significant return on the investments of the state. 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.

The production of oil and gas has increased greatly due to increasing global demand. This has led to increased technological risks as a result of the adoption of new technologies to increase oil and gas production, such as Enhanced Oil Recovery Technologies (EORTs). Some of the risks include TENORM (technologically enhanced naturally occurring radioactive materials) wastes, which pose a radiological risk to workers, the general public and the environment and therefore, it become 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 are increasingly politicized and highly contentious. While this is 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. 5.1). The significance of trust and the link between national participation and the dynamics of the political systems have serious implications in regard to 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 is capable of protecting workers in the oil and gas industry, the general public, and the environment from radiological exposure.

Figure 5.1 Political conflicts and public distrust.

5.2 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," when in fact TENORM are nuclear in nature, as explained earlier. TENORM are present in the natural nuclear isotopes produced by radioactive decay from thorium-232 and uranium-238series. In the oil and gas industry, they are enhanced technologically due to the physical and chemical processes used to enhance oil and gas production (Kolb and Wajcik, 1985; Baried et al., 1996; Jonkers et al., 1997; O'Brien and Cooper, 1998; ALNabhani et al., 2015). The major source of radiation exposure for the public and the environment is TENORM, either through direct exposure pathways or through ingestion and inhalation pathways from contaminated water and soil in which TENORM wastes are disposed. 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, because of regular 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" is explained by many economical and political reasons. Legislation related to nuclear issues is the most important reason. Further, due to the importance of having detailed and safe legislation to accommodate large amounts of TENORM 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 general public will oppose them. Knowing that, the radioactive waste disposal methods currently available pose serious health and safety risks, such as direct radiation to the public and industrial workers, as well as contamination of water resources, soil, plantations, the food chain, and the atmosphere.

If we look at the history of British politics, the legislative and decision-making processes in relation to technological risks such as those 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 at that time. 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 were 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 against 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*, 1983). Later, in May 1988, the UK Energy Secretary announced the decision of the government to stop dumping nuclear waste into the sea (Hansard, 1988). Despite this announcement, the government wanted to continue disposing large items arising from operations of sea disposal into the sea.

In the United States of America, political opposition concerning nuclear waste disposal develops when policies of waste management move to site-specific proposals in greenfield locations. Political disagreements have developed between eastern and western states in the US concerning nuclear waste disposal. Controversy typically occurs during the process of selecting the sites (or host states) for nuclear waste disposal. After the sites of nuclear waste disposal are identified, the level of opposition to these decisions intensifies. The TENORM situation is a political quagmire that it is difficult to extricate ourselves from. The government authorities try to convince the public that TENORM are 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 are 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 by 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 US 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 towards scientists or US policy-makers. Moreover, the presence of many agencies that deal with the protection of workers and the public from radiation in the US also contributed to inconsistencies in the regulations and policies. These include the National Council on Radiation Protection and Measurements (NCRP), Nuclear Regulatory Commission (USNRC), Department of Energy (DOE), US Environmental Protection Agency (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 (US National Research Council, 1999). Furthermore, the presence of many agencies would leads 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). Furthermore, the law as it is 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).

5.3 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; finally, 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 labour 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). The main risk factors of TENORM identified in the oil and gas industry, which 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., ground-water contamination, plant and food contamination).

(5) 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) 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.

5.4 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 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 have the ability to 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 US, 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 have to 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 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 acknowledgement 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. Indeed 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.

5.5 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 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; Cole and Caputo, 1984; 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 dilemma persists when policy-makers 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 in order 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, taking into account public fear in order 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 surpasses lack knowledge of legal and legislative matters.

5.6 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 USA, 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. Moreover, the resulting convolution presents challenges in strategic planning for 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, policy issues are similarly complex, facing municipal, provincial, and federal government challenges. In relation to the US, Canada regions benefit at the expense of local jurisdictions, where negative effects are most significant across several government layers (Council of Canadian Academies, 2014). By contrast, in the US, the decision to allow exploitation and exploration is made by landowners rightfully owning the subsurface rights. 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.

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 (Theodoriet 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, such as TENORM risks in the oil and gas industry, public participatory approaches to policy development have been applied in various fields. 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 multi-criterion decision-making approaches (Greening and Bernow, 2004) and a post-normal 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. 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 public panel system. 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 socio-economic 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 on the potential risks and benefits of TENORM in oil and gas production must be shared, discussed, and agreed upon with the public or their nominated representatives. The final outcomes 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.

5.6.1 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.

5.6.2 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 in the formulation of technological risk policy in the oil and gas industry 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; environmental damage; air pollution; and the radiological effects of TENORM on future generations. Moreover, proper public engagement should thoroughly address all issues, from the distribution of risks and benefits to the significance of developments for future generations, citizens, and residents. Finally, the process must be made more transparent and open to the public

5.6.3 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. Conversely, potential exposures to the radiological risks of TENORM and toxic materials may occur via the contamination of drinking water sources, soil, and the atmosphere, especially during periods of more intensive surface disposal of nuclear radioactive wastes. Consequently, these radiological risks of TENORM can lead to chronic carcinogenic diseases in the public, extending even to future generations. 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 nuclear 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 in the oil and gas industry. Well integrity including well design, construction, operation procedures, completion type, geological formation structure, casing quality, cementing quality, hydraulic fracturing, chemical types, and volume are 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 well 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 modelling of risks. In order 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 and cause cancer.

5.7 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 UK and the US heed public demands to change their nuclear radioactive policy, in particular the management policies of radioactive wastes, given the serious risks to health, the environment and natural resources, and the economy. Indeed 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. These assessments also include management practices for drinking water and soil quality, focusing on potential contaminants arising from nuclear radioactive waste disposal methods such as surface disposal and underground injection disposal. The panel also would investigate the integrity of oil and gas well design, TENORM emissions into the atmosphere from oil and gas fields, processing facilities, and impacts during the full life cycle of production. Finally, they would investigate and validate whether governments have a radiological exposure emergency response plan in place.

In conclusion, it is a prerequisite of a mature and healthy democracy that the public be engaged in policy-making directed at mitigating crucial and sensitive issues. Therefore, supporters of deliberative democracy must endeavour to convince political regimes and legislatures to engage the public in decision-making related to nuclear radiological policy so as to minimize radiological risks at the local and international levels. Moreover, Some political regimes or nuclear industries wish to develop effective nuclear programs, may find TENORM coproduced from the oil and gas industry as excellent, abundant, and cost-effective sources. Therefore, public participation in the legislative process associated with nuclear radioactive material is the optimal strategy to achieve much-needed protections that aims to mitigate technological risks as well as avoid any misuse of political power.

Chapter 6

Conclusions

Preface

This chapter provides conclusions and findings based on the proposed framework and the developed methodologies presented in this study about TENORM risk assessment and management in the oil and gas industry. Based on the conclusions and findings obtained in this chapter, set of recommendations and directions for future research in this domain will be proposed in the next chapter.

6.1 Conclusions

Radioactivity accompanying the recovery of petroleum products has become an area of concern to the oil and gas industry. Thirty years of research have addressed this issue, but still some confusion remains between NORM and TENORM. This review has demystified and redefined TENORM from technical and nuclear scientific perspectives, it has explained how NORM's activity concentration is enhanced by processes associated with the recovery of oil and gas to create TENORM. This study also concluded that naturally occurring radioactivity is used as a key indicator of the presence of hydrocarbons, which therefore helps to predict and quantify radiological risks at an early stage of hydrocarbon exploration, drilling and production. Most of the literature in this area has focussed only on quantifying the presence of TENORM in oil and gas with virtually no statistical or quantitative risk assessment based on a review of available data in describing TENORM in oil and gas production. The precursory conclusion drawn from available literature reviews is that there is an urgent need for extensive research to bridge current technical and knowledge gaps related to the management of TENORM risks in the oil and gas industry. In this thesis, this was achieved by developing following new approaches that are considered as main contribution of this study:

(1) Quantitative risk assessment and dynamic accident modelling of TENORM occupational exposure in the oil and gas industry using SMART approach.

(2) Scenario-based risk assessment of TENORM waste disposal options in the oil and gas industry based on fate and transport model and extrapolation of results from medical and engineering the perspectives.

(3) The introduction of a new approach emphasizing the importance of public participation in the development and legislation of TENORM risk management policy in the oil and gas industry.

(4) Scientific and technical recommendations that help to safely manage and contain TENORM issues in the oil and gas industry.

Based on the available data and the analyses of various crude oil, gas, and produced water samples, as well as equipment and waste collected from several oilfields and upstream, midstream and downstream processing facilities, it has been acknowledged that TENORM poses a serious problem in the oil and gas industry. Higher exposure to TENORM affecting workers was confirmed to be associated with areas such as drilling rigs, production and gathering stations, flow lines, refineries and associated equipment. Results also demonstrate that the oil industry often exhibits higher radiation levels than the gas industry, but in both cases, radiation poses serious health risks whether in high or low doses, according to medical opinion.

To assess radiation exposure risk to workers, a new methodology of quantitative and dynamic modelling scenario based risk assessment was proposed. This model was based on the SMART approach that integrates the SHIPP methodology and rational theory. The SMART approach provides a systematic and comprehensive risk assessment framework for modelling, predicting, updating, and managing the TENORM exposure risk during oil and gas production based on safety barrier performance evaluation and analysis. This approach consists of three main phases. In the first phase, basic events failure data were derived from academic and technical experts' opinion that were found to be consistent with reality and considered, as the initial believes. The rational prediction and Bayesian updating theorem adopted in the second phase of the SMART approach were utilized to predict the failure likelihood and update the prior failure probabilities of the identified six safety barriers over the ten-year period. Finally, 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 obtained from SMART approach demonstrated that system degradation causes the end-state probability (consequence occurrences probability of radiological exposure) to change dramatically over the ten-year period. This degradation could be attributed to many factors, the most important being a dearth of TENORM awareness and radiological risk assessment studies. Other factors include some of the legislation, and the fact that TENORM producing industries are reluctant to admit the presence of radiological risks in their operations despite avoiding any association with the word "nuclear" for political and economical reasons. Nevertheless, some government authorities (such as the case in the United States of America) try to convince the public that TENORM are not as harmful as nuclear radiation exposure by separating the radiation standards for NORM/TENORM from the radiation standards of the nuclear industries. (ALNabhani et al., 2016a). Furthermore, some industries consider exposure to TENORM as a low dose and therefore safe exposure, despite the medical community considering it unsafe according to epidemiological studies (ALNabhani et al., 2016b). The implementation cost is also a potential barrier for acknowledgement and action toward TENORM risks and inhibits safety barrier improvement. Accordingly, no action yet has been taken by the industry to introduce or bolster safety barriers for its activities. As a result the system will continue to degrade.

On the other side, Technologically Enhanced Naturally Occurring Nuclear Radioactive Materials (TENORM) waste in the petroleum industry has become another 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 waste during oil and gas 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 modelling system. The main purpose of this approach was to measure doses and excess carcinogenic risks through different pathways of exposure using real input data that are dynamically updated. 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 input data that are dynamically updated and related assumptions affect the results and the degree of confidence we should have in them.

This approach also attempted to fill the current knowledge gaps on radiological risk assessment of TENORM exposure. It was concluded that it might not be appropriate to evaluate the safety performance of TENORM waste disposal methods and to draw final 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, biological factors such as tissue type/cell and genes 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. 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 of radiation and eventually increase the chance of developing cancerous diseases. 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.

Finally, it has been argued that radiological risks from TENORM are a public issue, and that greater public participation is needed in policy-making related to technological risk. Such a development would indeed be regarded as a sign of openness and transparency in a democratic society. This study has explained how public participation is an important way to confer legitimacy on public institutions and a remedy to the syndrome of the "truncated democracy". Indeed public participation made nations like the UK and the US respond to public demands by changing their nuclear radioactive policies, in particular the policies for the management of radioactive wastes. These policies were changed because the public felt it was exposed to serious risks regarding their health, the environment, the economy and natural resources.

The conflicts within political regimes and the related challenges involved in legitimizing nuclear risk management have been seen as a problem of truncated democracy. Thus, there was an urgent need for a framework that would be designed to engage public participation in the process of legislation capable of protecting people's health and environmental safety from radiological risk associated with oil and gas production. Therefore, this study presented a systematic approach that aims to maximize the efficiency of public engagement in the processes of policy and decision-making related to important public issues caused by TENORM risks in the oil and gas industry. This approach calls for a voluntary, independent, and multidisciplinary community panel. This panel is comprised of academic and technical experts charged with examining the scientific and technical evidence and related legal issues in order to mitigate the radiological risks associated with TENORM in the oil and gas industry. The mandate of this panel extends to state-of-the-art assessments of the range of impacts of TENORM risk in the oil and gas industry and its associated technologies. The areas of concern are the health and safety fears of workers and the public, management practices of drinking water, soil quality with specific reference to potential contaminants arising from enhanced nuclear radioactive waste disposal methods, which include surface disposal and underground injection disposal, investigation of oil and gas well integrity design, TENORM emissions into the atmosphere from oil and gas fields, processing facilities and impacts during the full life cycle of production. Finally, the panel would determine whether governments have a reliable radiological exposure emergency response plan in place or not.

In conclusion, in order for decisions related to TENORM to be truly democratic and able to meet the needs of all who are affected, it is necessary to engage more public participation. Therefore, supporters of deliberative democracy still have much work to do in convincing political regimes and legislatures to engage the public in discussions about technological risks and in nuclear radiological policy-making in order to minimize radiological risks at the local and international levels. It is also worth keeping in mind that some political regimes aspiring to have a strong nuclear system may find technologically enhanced nuclear material co-produced from the oil and gas industry as an excellent abundant and cost effective source to be developed and exploited in non-peaceful purposes. Therefore, public participation in democratic societies in the legislative and policy-making processes with the aim of mitigating technological risk associated with nuclear radioactive material is the best option.

On the other hand, there is also lack of uniform international safety standards to address TENORM safety in the oil and gas industry. Many of the available regulatory radiological safety standards are inconsistent with each other about a precise characterization of a safe exposure to low radiological doses, and there is no commonly agreed standard. This was obvious with the International Commission on Radiological Protection (ICRP) and the Canadian Nuclear Safety Commission (CNSC). The International Commission on Radiological Protection (ICRP) recognized that workers' exposure to TENORM doses exceeding an average of 1mSv/yr is unsafe and that a full system of radiation protection control over TENORM-sources is needed, while the Canadian Nuclear Safety Commission (CNSC) recommended a formal safety program including personal dosimetry if occupational workers are exposed to 20 mSv/yr.

Chapter 7

Science-based solutions & Recommendations

Authorship and contributorship

This work has been completed by Khalid ALNabhani, Prof. Faisal Khan, and Dr. Ming Yang in 2017 and has been published in the of *Journal of Loss Prevention in the Process Industries*, at pages 161-168. Full details of this article can be accessed through the following link:

https://www.researchgate.net/publication/315437625_Management_of_TENORMs_produced_during_oil_and_gas_operation

The first author (Khalid ALNabhani) identified the research problem, developed the conceptual design of the proposed technologies as a part of TENORM risk management system, and finally drafted the manuscript. The co-authors (Drs. Faisal Khan and Ming Yang) supervised the research and development phase, critically reviewed the developed the design and theoretical principles, and provided valuable comments to improve the manuscript.

Preface

This chapter provides novel thinking and techniques to the fields of TENORM risk management in the oil and gas industry. It offers an important contribution to both the scientific community and the industry through the invention of new approaches of special personal protective equipment shielded with an effective and lightweight layer of leaded material (LPPE), to prevent radiological occupational exposure in the oil and gas industry, and a new eco-friendly technology of Thermo-chemi-nuclear Conversion Technology (TCT). This new technology able to optimally manage and dispose safely of TENORM wastes, and exploits them to engender renewable energy and synthesis fuel.

7.1 Introduction

Enhanced oil and gas production activities have resulted in the increased production of Technologically Enhanced Naturally Occurring Nuclear Materials (TENORM). This has raised a radiological concern for workers, the public and the environment. The available studies have focused on identification and assessment of TENORM; no attention is given to the safe handling and management of produced TENORM. This chapter attempts to present set of recommendations and conceptual understanding of a technology to manage TENORM concerns. The recommendations presented in this chapter are part of system development program of TENORM risk management in the oil and gas industry. These recommendations stress the importance of new approaches of special personal protective equipment shielded with an effective and lightweight layer of leaded material (LPPW). It also introduces a novel Thermo-chemi-nuclear Conversion Technology (TCT) to treat TENORM. This technology is designed to manage TENORM wastes along with household, sewage, industrial effluent, and hazardous wastes, and eventually convert them into fuel and renewable energy.

7. 2 Science-based solutions and Recommendations

7.2.1 TENORM occupational exposure prevention in the oil and gas industry

Oil and gas companies can predict the presence of TENORM at early stages of oil and gas exploration and production activities. They do this by gathering information via radioactivity measurements collected from well logging databases such as spectral gamma logs and oilfield correlation logs of oil and gas wells in different oilfields (ALNabhani et al., 2015). Correlation of well logging data make it possible to calculate expected radioactivity levels in the planned well and therefore get a good indication of the level of TENORM presence in that oilfield (ALNabhani et al., 2015). However, there could be some uncertainty associated with such predictions, so precautionary measures should be adopted, especially for drilling activities. These measures include but are not limited to the following: safety prevention barriers identified in chapter three; uniform international safety standard addresses TENORM safety and management in the oil and gas industry; workers' awareness of being exposed to radiation risks and the necessity to undergo TENORM safety courses and training; the implementation of working permits; minimization of exposure duration; provision of personal radiation detectors; and the use of an emergency response plan, high sensitivity radiation sensors and early warning detection systems in the up-stream, mid-stream and down-stream facilities including drilling site, flow lines, production / gathering stations and refineries, and associated equipment. In addition, the use of special personal protective equipment shielded with an effective and lightweight layer of leaded material (LPPE) should be in use. A special design is currently under development to combine a high quality of personal protective equipment, which refers to protective clothing, helmets, goggles, hand gloves, safety boots and facemask. This design will be blended with a mixture of a certain percentage of leaded material, Barium and Polyethylene in order to have a strong cloud of electron density with a strong ability to scatter the energy in order to prevent gamma emission and other associated radiation from penetrating the body. Accordingly, radiation protection procedures must be applied to all workers involved in the oil and gas industry, including drilling crew members, work-over crewmembers, well services and intervention crew members, workshop technicians, flowline crew members, workers in production, gathering and refinery stations, and workers involved in petrochemical or related industries relying on hydrocarbon products.

7.2.2 TENORM waste management based on Thermo-chemi-nuclear Conversion Technology (TCT)

The handling of TENORM with newer technologies of disposal methods is slowly becoming more efficient. Oxidation-reduction reaction chemicals, solids/fluids separation and gasification 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 generate energy and other synthesis fuels. Low to intermediate radioactive waste can be treated via gasification, which can minimize its volumetric size, however, cannot provide complete treatment of radiation risk. However, this study proposed a new technology as an extension of the working principle of gasification that will enable the safe management of TENORM waste as well as other different types of hard, liquid and gases wastes with zero emission to the environment. This technology is called Thermo-chemi-nuclear Conversion Technology (TCT). The TCT provides an excellent option for recycling different types of waste simultaneously, and this could be a tremendous asset to help bolster the environmental image of the oil and gas industry. In contrast, the current practices used in oil and gas industries, such as plug and abandonment methods, only decrease large transportation costs and temporary out-of-sight storage. These methods attempt to solve problems, however, it enhances the activity concentration of NORM that already exists in the underground formation and contaminates soils and aquifers. While surface storage and land farming may be the cheapest options available, it is important to remember the long-term ramifications associated with this method. In particular, we need to consider that our grandchildren and their descendants will have to live with TENORM for 1600 years in the area where TENORM was disposed, and that there food and water resources will be contaminated. On the other hand, the proposed TCT allows for the prevention of environmental pollution resulting from TENORM disposal methods. Additionally, TCT will help to enhance protection for workers, the public, and safely manage and recycle TENORM alongside many other types of waste with no impact on the environment. It doses so by converting these wastes into renewable energy and fuel, as described in greater detail in the following section.

The Working principle of Thermo-chemi-nuclear Conversion Technology (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. Figure 7.1 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 US energy department, and the second process is nuclear treatment of TENORM waste, which considered as the most important part of this process

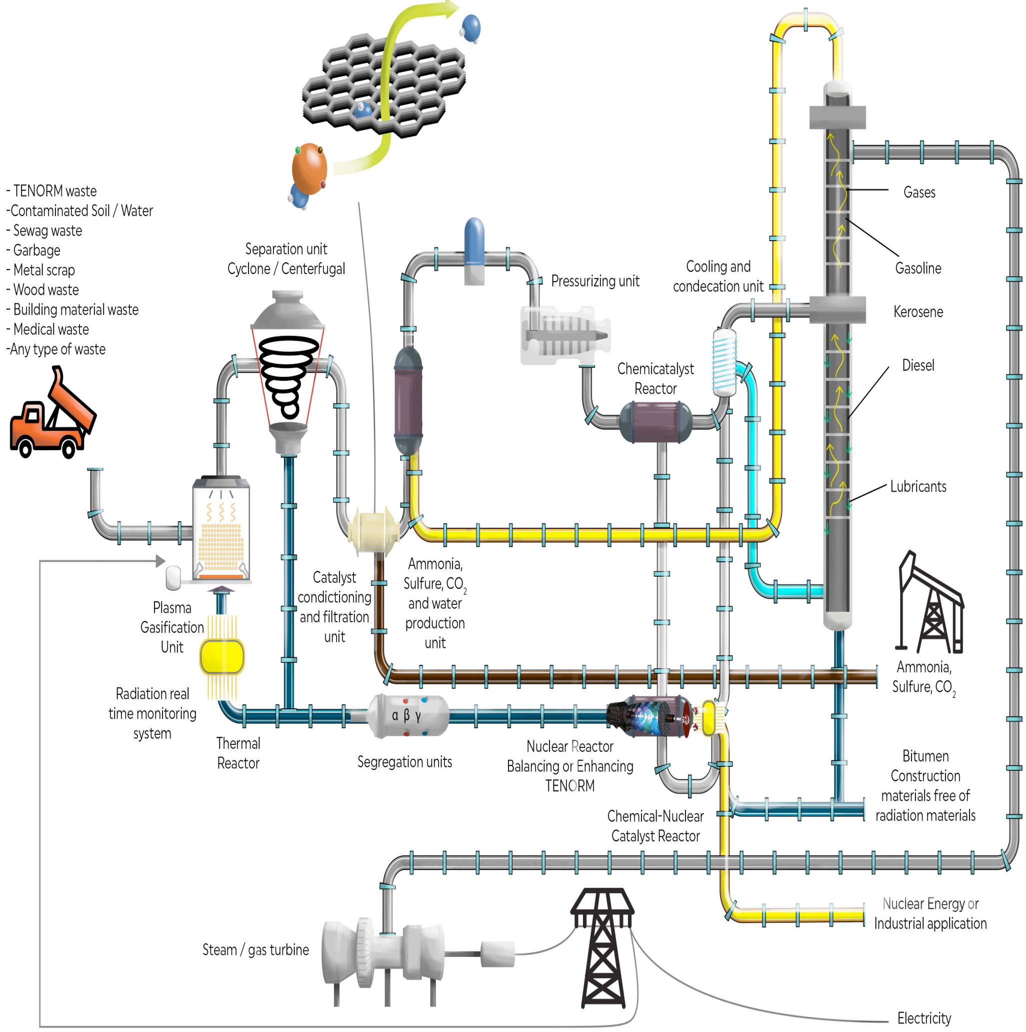


Figure 7.1. Process flowchart of Thermo-chemi-nuclear Conversion Technology (TCT).

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 Figure.7.2. This is because it can provide the optimal utilization of a tremendous volume of produced TENORM waste from gathering and production stations, such as separated contaminated formation water from production stations, contaminated soil 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.

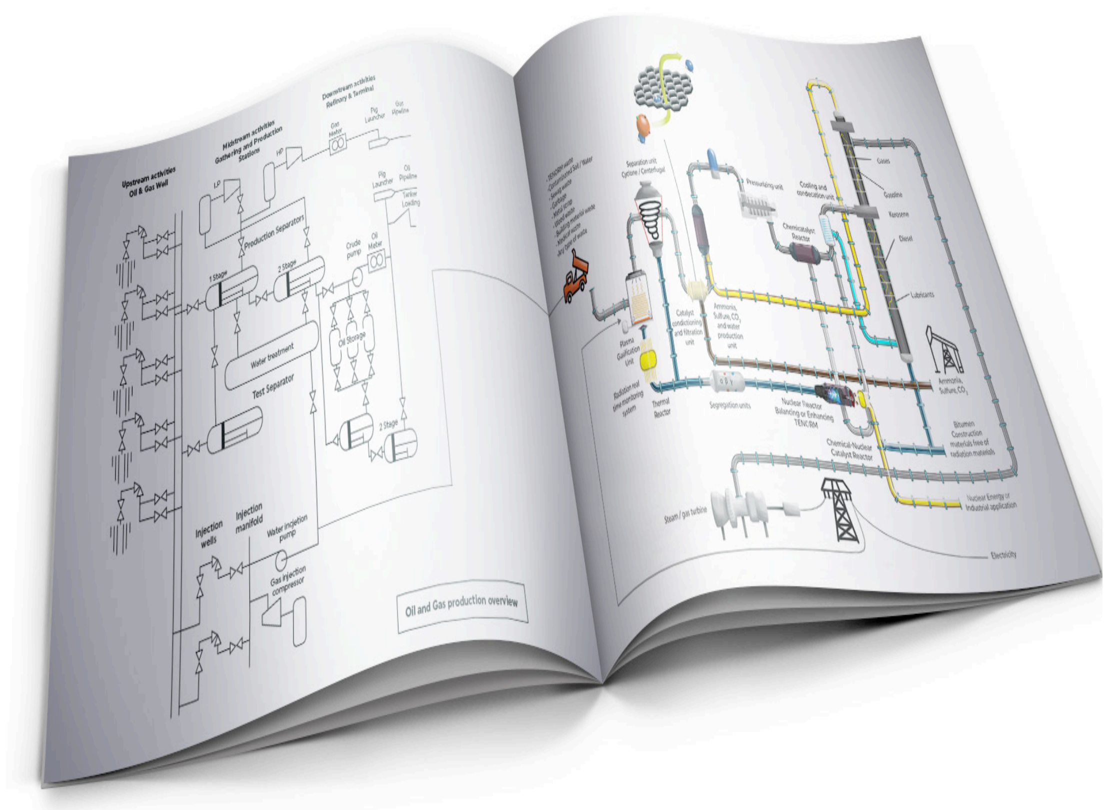


Figure 7.2 Combined process flow chart of production station and Thermo-chemi-nuclear Conversion Plant.

TENORM waste, contaminated formation water, and sand 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 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 ^{O}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 KW 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. Carbon, for instance, forms a large number of compounds due to its willingness to bond with other materials; carbon dioxide accordingly plays a 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 favour 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 take place between approximately 800 and 1000 ^{O}C. Hence, the gas is cooled down further to a temperature of approximately 600 – 400 ^{O}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 through 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 in order 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. Meanwhile, solid wastes such as metals, contaminated scraps, soil, and sand will melt down and will be collected at the bottom of the thermal gasification reactor unit as slag. This slag containing any radioactive material will be segregated according to its type of radiation emissions and components, and will then be further treated through series of nuclear transmutation reactions in a nuclear reactor. The reactor contains particle accelerators in which energetic subatomic particles are bombarded toward a target nucleus, based on common modes of nuclear decay reactions described in below equations (Averill and Eldredge, 2011). Resulting product nucleus will either be stabilized so that slag can be used safely later for any industrial application as road construction materials, or it will be further enhanced to generate more energy according to the principle of energy production from the radioactivity (Kumar, 2015) that can be used for energy generation.

- Alpha decay

$${}^{A}_{Z}X \rightarrow {}^{A\text{-}4}_{Z\text{-}2}X' + {}^{4}_{2}\alpha \xleftrightarrow{\textit{(Nuclear Transmutation Reactions)}} (X'' : Satable / Enhanced) \qquad (1)$$

- Beta decay

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta \xleftrightarrow{\textit{(Nuclear Transmutation Reactions)}} (X'' : Satable / Enhanced) \qquad (2)$$

- Gamma emission

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z}X' + {}^{0}_{0}\gamma \xleftrightarrow{\textit{(Nuclear Transmutation Reactions)}} (X'' : \text{Energy Enhancement}) \qquad (3)$$

- Spontaneous fission

$${}^{A+B+C}_{Z+Y}X \rightarrow {}^{A}_{Z}X' + {}^{B}_{Y}X' + C\,{}^{1}_{0}n \xleftrightarrow{\textit{(Nuclear Transmutation Reactions)}} (X'' : Satable / \text{Energy Enhancement}) \qquad (4)$$

This work is intended for a patent application. Therefore, further theoretical details on scientific principle, technology, its implementation and/or effectiveness can be provided on personal contact bases with the author for the purpose of licensing and granting rights to develop, use or transfer the intellectual property of invented technologies into diverse applications including, but not limited to, scientific development, commercial or industrial applications.

7.3 Future research needs

The available studies related to TENORM issues in the oil and gas industry have focused on identification and analysing the distribution of TENORM throughout oil and gas activities; no attention has yet been given to the safe handling and management of radiological risk associated with TENORM. Unfortunately, these lack any detailed analytical assessment with regards to radiological risks for the workers, the public, and the environment. Therefore, this study presented new approaches that serve as a road map for extensive research to bridge current technical and knowledge gaps related to the management of TENORM risks. The following recommendations are provided for future research:

- *Quantitative risk assessment and dynamic accident modelling of TENORM exposure in the oil and gas industry from economic perspectives*

More approaches for quantitative TENORM risk assessment and dynamic accident modelling to prevent and control radiological exposure accidents from economical perspectives are required to be considered for future research needs. For instance, the accident modelling and risk assessment framework using the SMART approach proposed in this study is a good example of an innovative approach of dynamic, quantitative accident modelling and risk assessment. The SMART approach proposed here with more focuses on identifying and quantifying the risk to provide an integrated framework for predicting and updating TENORM occupational exposure risk assessment. Using this methodology, efforts were made to better understand the cause-consequence behavioural mechanism of TENORM exposure by investigating the performance of existing safety barriers and conceptualizing the predictive capabilities and updating methodologies using a hybrid of SHIPP methodology and rational theory. Therefore, it is very important to continue further researches and studies to evaluate TENORM risks in the oil and gas industry from economical perspectives as well, which is not covered by this study at this stage.

- *Eliminate regulatory conflicts and establish a consistent set of international safety standards for TENORM issues in the oil and gas industry*

Risks posed by TENORM in oil and gas production are significant enough to warrant immediate actions to develop governmental regulatory control and maximize public participation. Future studies are also required to standardize an international safety guideline for TENORM issues in oil and gas industries. The main challenges are to come up with appropriate regulations that are able to mitigate or eliminate TENORM risks associated with oil and gas production, and to minimize the inconsistencies between different safety standards with regards to TENORM safe exposure.

- *Current practices of TENORM waste management*

TENORM waste management, including handling and disposal methods of TENORM wastes that currently exist are all short-term solutions. Current TENORM disposal practices are either surface disposal, such as landfill, land-spreading or subsurface burial (excavated pit, or abandoned mine), or down hole injection (abandoned wells or disposal wells), or direct disposal into seabed. Improper disposal of TEORM waste may contaminate food (for instance, fish, marine and coastal life are under direct threat of direct disposal of contaminated produced water from offshore activities into the sea), soil and water resources (as a result of surface and subsurface TENORM waste disposal). Thus, current practices may cause chronic cancerous diseases. Such practices must be examined in greater detail due to unforeseen hazards that pose future risks to human health and the environment. Emphasis should be placed on developing new technologies that are able to minimize uncertainty of predestination of TENORM effects on the environment, waste volumes, and radioactivity level. TCT is one of the new technologies proposed in this study to safely manage TENORM waste in the oil and gas industry. Thus, further studies and innovations of other new technologies are urgently required to safely and economically manage TENORM waste generated from oil and gas industries, taking into account the conversion of this waste into alternative renewable energy to maintain the sustainable development of countries and economies.

- *TENORM as alternative renewable energy*

Results from TENORM surveys collected from several oilfields indicate that radionuclide concentration can vary from an undetectable range to an extremely high level of radiation emission. For instance, according US EPA (1993) and Smith et al. (1996), it has reported that activity concentrations in waste sludge can reach as high as 25900 Bq/g. Moreover, the survey conducted in 1992 by the Michigan Department of Public Health that reported high radium concentrations were measured in produced water, as high as 159,000 pCi/l. According to the study conducted by Suhas Kumar in 2015 about energy from radioactivity, it has been confirmed that such radiations have energy and there is new interest in energy from radioactivity, including natural and waste radioactive materials. Therefor, the potential of energy optimization produced from radioactive nuclides contained in TENORM coproduced with oil and gas may provide a very promising area for future research due to the fact of its longevity where the life of radioactive energy is a strong function of the half-life of the material used, which can be in the order of many decades, also its high energy density, up to five orders higher than conventional energy. Energy generated by TENORM could be assessed directly or by investigating data collected from well logging and correlation data that are able to quantify the content of radioactive material, energy released in each particle, abundances, rock source types, energy emission strength, radionuclide's half-lives and many other factors required to calculate energy from radioactivity in term of decay constant that depends on half-life of nuclei, number of nuclei and energy per particle emitted by radiation. Furthermore, research in this promising area will provide valuable insight into how to manage TENORM from the source in a safe, efficient manner.

Bibliography and References

References

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

Aberbach, J. D. and Rockman, B., A. (1978) Administrators' beliefs about the role of the public: The case of American federal executives. Western Political Quarterly, 31 (December). 502-522.

ACIR -Advisory Commission on Intergovernmental Relations. (1979) Citizen participation in the American federal system. Retrieved 10/12 2015 from: http://www.library.unt.edu/gpo/acir/Reports/brief/B-3.pdf.

Adams, M., Wheeler, D. and 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.

AEC. (1972) Grand Junction Remedial Action Criteria. 10 CFR 12.Atomic Energy Commission, D.C Washington

Ajay, K., Karpe, Rupali, K., Sabyasachi, R., Usha, N., Ravi, P.M. (2012) A comparative Study of Distribution Coefficients (Kd) for Naturally Occurring Uranium (U) and Thorium (Th) in Two Different Aquatic Environments.

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

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, 2015 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. Isotopes. (63), 457–463.

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

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), 71-4.

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. (99), 237–247, Available from: http://www.psep.ichemejournals.com/article/S0957-5820(15)00177-9/abstract

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. (102), 606-614. Available from:

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. Journal of Loss Prevention in the Process Industries. (40), 55-66. Available form: http://www.sciencedirect.com/science/article/pii/S0950423015300838

API. (1987) Measurement Protocol for the Occurrence of LSA Material. API, Dallas, Texas.

AP1. (1989) A National Survey on Naturally Occurring Radioactive Materials (NORM) in Petroleum Producing and Gas Processing Facilities. API, Dallas, Texas.

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. (1992) Bulletin on Management of Naturally Occurring Radioactive Materials (NORM) in Oil and Gas Production, 1sted. API Bulletin E2. (BULE2).

APPEA (2002) Guidelines for Naturally Occurring Radioactive Materials.

Averill, B., Eldredge, P. (2011) General Chemistry: Principles, Patterns, and Applications.V(1.0).

Avwiri, G. O and 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. 572-580. Retrieved 02/16, 2015from: http://www.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 Progr. (42), 502.

Bareja, E. (1984) Geology. Quart. (28), 353–366.

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,1996). 1 (1), 5-18.

Batt, T. (1992) Nevada Claims Victory in Yucca Deal. Las Vegas Review-Journal, pp. 1A-3A.

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

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

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

Berry, J., M., Portney, K., E. and Thomson, K. (1989) Conflict, Alienation and Delay: Is Citizen Participation Poison? Study 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 M. A. Burns (ed.), Low-Level Radioactive Waste Regulation: Science, Politics, and Fear (Chelsea, Michigan, Lewis). 193-213.

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. Retrieved 03/25, 2015from: http://www.earth.ox.ac.uk/~gideonh/pdffiles/Intro.pdf

Bradley, F., J. (2003) Risk-Based Classification of Radioactive and Hazardous Chemical Wastes. Health Phys. 85 (6), 759–760, NCRP Report No. 139.

Burkart, W. (1999) Ethics and Science in Radiation Protection, SSI news. Swedish Radiation Protection Institute Newsletter. (7), 1.

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

Clarke, R. (1999) Control of low-level radiation exposure: time for a change? Journal of Radiological Protection. 19 (2), 107-115.

CNSC. (2014) Fact sheet Naturally Occurring Radioactive Material. Retrieved 02/27, 2015 from: http://www.nuclearsafety.gc.ca/pubs_catalogue/uploads/NORM-factsheet-eng.pdf

Cole, R., L., and Caputo, D., A. (1984) The Public Hearing as an Effective Citizen Participation Mechanism: A Case Study of the General Revenue Sharing Program. American Political Science Review. (78), 404-16.

Cooper, M., 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.

Council of Canadian Academies. (2014) Environmental impacts of shale gas extraction in Canada: The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction. Ottawa.

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

Cupps, D., S. (1977) Emerging Problems of Citizen Participation. Public Administration Review. (37), 478-87.

Dicus , G., J.(1998) Why we need to harmonize radiation protection legislation. Presented at the 1998 "Women in nuclear " global annual meeting. Taipei, Taiwan. 24 April, Study. 5, 98-13.

Dodge, E. (2008) Plasma-gasification of waste clean production of renewable fuels through the vaporization of garbage. Cornell University. Ithaca.

Dresel, P., E , Arthur W., R. (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 p. Retrieved 03/17, 2015 from: http://www.marcellus.psu.edu/resources/PDFs/brines.pdf

DuraiRaj, P., Thamilarasu, P., Krishnadas, K. (2014) Gamma rays from nuclear propulsion annihilation of matter. IJMRD 2014. 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) Naturally Occurring Radioactive Material (NORM). Chapter 2. Jackson,Mississippi, USA.

Efendi, Z. and Jennings, P. (1994) An assessment of the environmental radiation dose for residents of the Perth metropolitan area. Radiation Protection in Australia, 12, 8-12.

El Afifi, E., M., Awwad, N., S. (2005) Characterization of the TENORM 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 enthalten ist. Phys. Z 5 (1), 11–20.

E&P Forum. (1988) Low specific activity scale: origin, treatment and disposal. The oil industry international exploration & production forum report. London.

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. Petroleum Geologists Bull. (38), 2200–2218.

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 Rev. 21, 1.

Fiorino, D. (1989) Technical and Democratic Values in Risk Analysis. Risk Analysis. (9), 293-299.

Fisher, R., S. (1995 a) Naturally Occurring Radioactive Materials (NORM) in Produced Water and Scale from Texas Oil, Gas and Geothermal Wells: Geographic.

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.

Flynn, J., Kasperson, R., Kunreuther, H. and Slovic, P. (1992) Time to Rethink Nuclear Waste Storage. Issues in Science and Technology (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.

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

Gesell, T., F. (1975) Occupational rad. exposure due to Rn222.H.Physics. 29 (5), 681.

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

Godoy, J., M., R., Petinatti da Cruz, J. (2003) Environ. Radioact. 70-199.

Gopalakrishnan, R., K. (1998) Basic nuclear physics (radioactivity). 31-41. Available from:

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

Graham J., Higson D., J., Mitchel, R., E., J., Kobayashi, S. (1999) Low doses of ionising radiation incurred at low dose rates. 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, France, 25th October 1998; reprinted in the J Aust Radiation Protect Soc. (16), 32-47.

Greening, L., A., Bernow, S. (2004) Design of coordinated energy and environmental policies: use of multi-criteria decision-making. Energy Policy. 32(6), 721–735.

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

Hamlat, M., S., Kadi, H., Fellag, H. (2003) Precipitate containing NORM in the oil industry: modelling and laboratory experiments. Appl. Radiat. Isotopes. (59), 95–99.

Hansard - Great Britain-Parliament. (1988) Radioactive Waste (Disposal). Official Record 26 May 1988,Col. 233. HMSO, London.

Held, J. (2012) Gasification - status and technology. Rapport SGC 240•1102-7371•ISRN

SGC -R-240-SE. Swedish Gas Centre.

Himstedt and Burton, E., F. (1904) Petroleum radioactive gas. Phys Zs. (5), 511–516.

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, March 16–20. Available from: http://www.2412.org/orders/463/10.1016_S0969-8043(01)00042-2-Assessment-of-radiation-exposures-from-naturally-occurring-radioactive-materials-in-the-oil-and-gas-industry.pdf

Hood, A., Gutjahr, C., and Heacock, R. (1975) Organic Metamorphism and the Generation of Petroleum: American Association of Petroleum Geologists Bulletin. (59), 989-996.

IAEA (International Atomic Energy Agency). (1994) Classification of Radioactive Waste .A Safety Guide. SAFETY SERIES No. 111-G-1.1

IAEA (International Atomic Energy Agency. (2002) Technologically Enhanced Natural Radiation (TENRII). VIENNA.

IAEA (International Atomic Energy Agency. (2003a) Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry. Safety Series, No. 34. ISBN 92-0-114003-7.

IAEA (International Atomic Energy Agency. (2003b) Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and

Technological Options for Mitigation. Technical Reports No 419. ISBN 92-0-112503-8.

IAEA (International Atomic Energy Agency. (2008) Radiotracer Residence Time Distribution Method for Industrial and Environmental Applications. Vienna.

IAEA (International Atomic Energy Agency. (2013) Management of NORM Residues. TECDOC, 1712. Vienna.

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.

ICRP. (1991) Recommendations of the International Commission on Radiological Protection. Recommendations, Pub. no. 60 .Pergamon Press, Oxford.

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

Jackson,R., B.,Vengosh, A., Carey, J., W., Davies, R., J., Darrah, T., H., O'Sullivan, F., Pétron, Jacob, G. (1990) Site Unseen: The Politics of Siting a Nuclear Waste Repository (Pittsburgh, Pennsylvania, University of Pittsburgh).

Jamall, I., S., and Willhiteb, C., C. (2008) Is benzene exposure from gasoline carcinogenic? Journal of Environmental Monitoring. (10), 176–187.

Janssen, M., P., M., Blaauboer, R., O., and Pruppers, M., J., M. (1998) Geographical distribution of radiation risks in the Netherlands, Health Physics. 74 (6), 677-686.

Jasanoff, S. (1986) Risk Management and Political Culture. (New York, Russell Sage Foundation).

Jasper, J., M. (1990) Nuclear Politics: Energy and the State in the United States, Sweden, and France (Princeton, New Jersey, Princeton University Press).

Jefpreyg. Zukin, Douglas, E. Hammond,T, Lungku, E., H.-and Elder, W. (1987) Uranium-thorium series radionuclides in brines and reservoir rocks from two deep geothermal boreholes in the Salton Sea Geothermal Field, southeastern California. Pergamon Journals Ltd. (51), 2719-2731.

Jonkers, G., Hartog, F., A., Knaepen, W., A., I. (1997) Characterization of NORM in the oil and gas production (E&P) industry. Proc of Int. Symposium On Radiological Problems with Natural Radioactivity in the Non-Nuclear Industry. Shell Research & Technology, Netherlands. Amsterdam, September 8-10, 1997, 23-47. Retrieved 03/09, 2015 from: http://i.iv.7.eu-norm.org/index.pdf

Kasperson, R., E. (1986) Six Propositions on Public Participation and Their Relevance for Risk Communication. Risk Analysis. (6), 275-81.

Kasperson, R., E, Golding D. and Tuler, S. (1992) Social Distrust as a Factor in Siting Hazardous Facilities and Communicating Risks. Journal of Social Issues. (48), 161-187.

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.Ch. 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, NewYork.

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.

Kumar, S. (2015) Atomic Batteries: Energy from Radioactivity Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA.

Kvasnicka, J. (1996) Radiation Protection in the Offshore Petroleum Industry. Proceedings of the International Congress on Radiation Protection, IRPA 9, International Radiation Protection Association, Vienna, Austria, (4), 621-623.

Langmuir, D. (1978) Uranium solution mineral equilibria at low temperatures with applications to sedimentary ore deposits.Geochim. Cosmochim. Acta. (42), 547–568.

Langton, S. ed. (1978) Citizen Participation in America. Lexington, MA: Lexington Books.

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 andiron in stratiform aquifers. Geol. Rev.13 (5), 744–751.

Matta, L., E., Godoy, J., M., Reis, M., C. (2002) 226Ra, 228Ra, and 282Thin scale and sludge samples from the campus basin oil field E&P activities. Radiat. Prot. Dosim. (102), 175–178.

Michigan Department of Public Health. (1992) Interm 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 Mich.) to. Smith K., P (Argonne National Laboratory, Lakewood, Colo.), Aug. 30.

Mohammad 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.

Morone, J. F. , Woodhouse, E. J. (1989) The Demise of Nuclear Energy? Lessons for a Democratic Control of Technology (New Haven, Connecticut, Yale University).

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.

Naqvi, S. (2012) enhanced oil recovery of heavy oil by using thermal and non-thermal methods (Master Thesis). Dalhousie University Halifax, Nova Scotia. Canada.

Nelkin, D. (1977) Technological Decisions and Democracy: European Experiments in Public Participation. Beverly Hills, CA: Sage.

Nelkin, D., Pollak, M. (1979) Public Participation in Technological Decisions: Reality or Grand Illusion? Technology Review. 55- 64.

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.

Nyanda, A., M., Muhogora, W., E. (1997) Regulatory control of low level radiation exposure in Tanzania :Low doses of ionizing radiation .Biological effects and regulatory control. Contributed studys. International conference held in Seville, Spain, 17-21 November1997, IAEA-TECDOC-976.308-311.

O'Brien, R., S. and Cooper, M., B. (1998) Technologically Enhanced Naturally Occurring Radioactive Material (NORM): pathway analysis and radiological impact, Appl. Radiat. Isot. 49 (3), 227–239.

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. Isotopes. (60), 779–782.

Organo, C., Fenton, D. (2008) Radiological Assessment of NORM Industries in Ireland – Radiation Doses to Workers and Members of the Public. Retrieved 17/03/2015 from : https://www.epa.ie/pubs/reports/radiation/RPII NORM Report 08.pdf

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.

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 Journal of Nuclear Science and Applications. (46), 172-179.

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.

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.

Pennsylvania Department of Conservation and Natural Resources (PaDCNR). (2008) Spring Pennsylvania Geology, (38), 1.Available from: http://www.dcnr.state.pa.us/topogeo/pub/pageolmag/pageolonline.aspx.

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. (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.

Rathnayaka, S., Khan, F., Amayotte, P. (2011) SHIPP methodology: predictive accident modelling approach. Part I: Methodology and model description. Process Saf. Environ. Prot. (89), 151–164. Available from: http://dx.doi.org/10.1016/j.psep.2011.01.002.

Rathnayaka, 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. 1–20.

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.

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.

Rosenbaum, W., A. (1976) The Paradoxes of Public Participation. Administration and Society. (8), 355-83.

Rosenbaum, W., A. (1983) The Politics of Public Participation in Hazardous Waste Management." In James P. Lester and Ann O'M. Bowman, eds. The Politics of Hazardous Waste Management. Durham, NC: Duke University Press.

Russell, W., L. (1945) Relation of Radioactivity Organic content and sedimentation. Bull. Am. Assoc. Pet. Geol. 29 (10), 1470-1493.

Schmoker and James, W. (1981) Determination of Organic-Matter Content of Appalachian Devonian Shales from Gamma-RayLogs. AAPG Bull. 65 (7), 1285–1298.

Schreiner, B. (2008) Use of industrial gases in petrochemistry. Hydrocarbon Processing 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

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. Isotopes. (55), 133–135.

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 in unconventional shale gas development. Environ.Sci.Technol. (48), 8289–8297.

Smellie, J. (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, G., E, Fitzgibbon, T., Karp, S. (1995) Economic impact of potential NORM regulations In: Proc of SPA/EPA Exploration and Production. Environmental Conference, 27–29 March 1995, Houston, USA.181–231.

Smith, K., P. (1992) An Overview of Naturally Occurring Radioactive Materials (NORM) in the Petroleum Industry. Report No. ANL/EAIS-7. Argonne National Laboratory, Argonne, Illinois.

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. (1980) Assessment of the radiation. TAEC Tech.Jour.7 (2), 55-65.

Steinhäusler, F. (2005) 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. 129-134.

Strand, T. (1999) Handling and disposal of norm in the oil and gas industry. WM'99 Conference, February 28 - March 4, 1999.

StrSchV. (2001) Verordnung¨uber den Schutz vor Sch¨aden durchionisierende Strahlen (Strahlenschutzverordnung). – Artikel 1der Verordnung f¨ur die Umsetzung von EURATOM-Richtlinienzum 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. USPATENT. (4), 071-744.

Swanson, V., E. (1960) Oil yield and Uranium Content of black shales. Geol. Survey. Study 356-A.

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 Physics. (67), 34-38.

The observer Newsstudy. (1983) Issue of 28 august.

Theodori, G., L., Luloff, A., E., Willits, F., K., Burnett, D., B. (2014) Hydraulic fracturing and the management, disposal, and reuse 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 definitely not normal :responding to wicked issues in the environment ,energy and health. Environ.Sci.Policy. 12(3), 347–358.

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

UNSCEAR -United Nations Scientific Committee on the Effects of Atomic Radiation. (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 -1137.

US Environmental Protection Agency (US EPA). (1993). Produced water radioactivity study. Office of water and Office of Science and Technology. Washington, DC, USA.

US Environmental Protection Agency (US EPA). (1993a) DRAFT Diffuse NORM Waste Characterization and Preliminary Risk Assessment. Office of Radiation and Indoor Air, Washington, D.C.

US Environmental Protection Agency (US 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, D.C.

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

US Environmental Protection Agency (US EPA). (2008) Technical Report On Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining. EPA 402-R-08-005 (1).Washington, DC. Retrieved 13/02/2015 http://www.epa.gov/radiation/docs/tenorm/402-r-08-005-voli/402-r-08-005-v1.pdf

US National Research Council. (1989) Improving Risk Communication. Washington, DC: National Academy Press.

US-National Research Council. (2003) Reactor concepts manual: Biological effects of radiation .USNRC technical training center . Retrieved, 01/09/2015 from: http://pbadupws.nrc.gov/docs/ML0230/ML023020586.pdf

US National Research Council. (1999) Evaluation of Guideline for exposure to

Technologically Enhanced Naturally Occurring Radioactive Materials. National Academy Press. Washington.

Vandenhove, H., Bousher, A., P., H. Jensen, D. Jackson, B. Lambers, T. Zeevaert. (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.

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.

Verma, M., K. (2015) Fundamentals of carbon dioxide-enhanced oil recovery (CO2-EOR)—A supporting document of the assessment methodology for hydrocarbon recovery using CO2-EOR associated with carbon sequestration: U.S. Geological Survey Open-File Report 2015. 1071-19.

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

Wilson, A., J., Scott, L., M. (1992) Characterization of Radioactive Petroleum Piping Scale with an Evaluation Subsequent Land Contamination. Health Phys. (64), 443.

Wilson, A., J., Scott, L., M. (1993) Characterization of Radioactive Petroleum Piping Scale with an Evaluation Subsequent Land Contamination. Health Phys. (63), 681.

World Health Organization (WHO). (2010) Preventing disease through healthy environments exposure to benzene: a major public health concern. Available from: http://www.who.int/ipcs/features/benzene.pdf

WPS. (2012) Plasma torches manual. Westinghous Plasma Corporation. Manual. USA.

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), 124–12.

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, Ill.

Zhu, Q. (2015) High temperature syngas coolers. IEA Clean Coal Centre. United Kingdom.

Zimmerle, W. (1995) Petroleum Sedimentology. Kluwer,Dordrecht, 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.

APPENDIX A:

MORBIDITY AND MORTALITY RISK COEFFICIENTS FOR EXTERNAL EXPOSURE[1]

Nuclide	Morbidity (1/yr)/(pCi/g)	Mortality (1/yr)/(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

(Cont.)

[1] US Environmental Protection Agency (US EPA). (1997, a) Exposure Factors Handbook. EPA/600/P-

Nuclide	Morbidity (1/yr)/(pCi/g)	Mortality (1/yr)/(pCi/g)
Cs-134	7.10E-06	4.83E-06
Cs-135	2.36E-11	1.58E-11
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

(Cont.)

Nuclide	Morbidity (1/yr)/(pCi/g)	Mortality (1/yr)/(pCi/g)
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
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
Te-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

(Cont.)

Nuclide	Morbidity (1/yr)/(pCi/g)	Mortality (1/yr)/(pCi/g)
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

NA[a] = not available.

Pb-210+D[b] and Sb-125[b] values listed are for a cutoff half-life of 30 days.

APPENDIX B:

MORBIDITY AND MORTALITY RISK COEFFICIENTS FOR INHALATION[2]

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-02	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
C-14 (dioxide)	G	1.00E+00	1.99E-14	1.36E-14

(Cont.)

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

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
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-02	1.28E-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-11
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	1.00E+00	2.50E-11	2.34E-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

(Cont.)

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
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
Co-60	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-02	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

(Cont.)

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
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
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

(Cont.)

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
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

(Cont.)

Nuclide	Type[a]	f_1[b]	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

(Cont.)

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
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
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

(Cont.)

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
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
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

(Cont.)

Nuclide	Type[a]	f_1[b]	Morbidity (1/pCi)	Mortality (1/pCi)
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

(Cont.)

Nuclide	Type[a]	f_1[b]	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 coefficients for particulate aerosols of type F, type M, and type S representing, respectively, fast, medium, and slow absorption to blood. 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 (f1) 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 and Sb-125 values listed are for a cutoff half-life of 30 days.