12-2018

Methodologies for Evaluating Security Risk and Safeguards for HEU to LEU conversion of a Miniature Neutron Source Reactor (MNSR) using SCALE and ORIGEN

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Recommended Citation

Dahunsi, Stephen Olumuyiwa, "Methodologies for Evaluating Security Risk and Safeguards for HEU to LEU conversion of a Miniature Neutron Source Reactor (MNSR) using SCALE and ORIGEN. " PhD diss., University of Tennessee, 2018.
https://trace.tennessee.edu/utk_graddiss/5314

To the Graduate Council:

I am submitting herewith a dissertation written by Stephen Olumuyiwa Dahunsi entitled "Methodologies for Evaluating Security Risk and Safeguards for HEU to LEU conversion of a Miniature Neutron Source Reactor (MNSR) using SCALE and ORIGEN." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Energy Science and Engineering.

Howard L. Hall, Major Professor

We have read this dissertation and recommend its acceptance:

G. Ivan Maldonado, Brandon Prins, Lee Riedinger

Accepted for the Council:

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Methodologies for Evaluating Security Risk and Safeguards for HEU to LEU conversion of a Miniature Neutron Source Reactor (MNSR) using SCALE and ORIGEN

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Stephen Olumuyiwa Ariyo Dahunsi
December 2018

Dedication

To God almighty from whom all blessing flow.

"Lord and savior, true and kind"

To my late parents Deacon and Mrs. Dahunsi, may the Lord bless your souls. To my godmother and a "super-woman," the late Mrs. Ndubuisi-Offor; what a painful exit, I miss that voice, "my son."

Acknowledgement

My deepest gratitude to my major Prof. Howard L. Hall for finding me worthy of support and kindness at all times. I MOST APPRECIATE YOUR SUPPORT.

Prof. Lee Riedinger (Director of the Bredesen Center), thank you for this wonderful opportunity. This would not have been possible without your support.

I am forever indebted to you both, Prof. Brandon Prins and Prof. G. Ivan. Maldonado for your contributions and direction.

Most of all, my gratitude goes to **my best friend, lovely wife** (Adenike) and **our lovely children** (Oluwakorede, Ololade and Olukolade) Dahunsi for their support, endurance and patience throughout the duration of this program.

And to my mentor Jeffrey A. Chapman who saw the potentials in me and asked that I proceed on this journey. Thank you and you are very much appreciated.

A very special acknowledgement and appreciation to Bruce Patton, how can I ever repay your kindness? Even in retirement, you are never tired of guiding me with your subject matter expertise.

A very big thank you to you Dr. B. I. O. Dahunsi, “Solid pillar,” you have always been there. May God continue to bless you.

To my all-time supper supporters, Engr. and Mrs. H. H Ngadda, you promised to always be there and have remained constant as a shining example, father and mother to an orphan. This is the culmination of what you started, I am forever grateful.

Prof. M. N. Agu, who made sure my dream did not wade, I tremendously appreciate you.

To my very good friend and brother, Patrick D. Lynch, I cannot thank you enough for your encouragement and support through difficult times and terrain.

Hannah Hale, “mum,” you have been there for me in critical times since the very first day of this journey. God bless you for your kind assistance all the time.

Thank you, Dr. Heilbronn, you made sure I never lost interest in studying at University of Tennessee.

Prof. S. A. Jonah and Dr. Yakub Viva Ibrahim of the Center for Energy Research and Training, thank you for your support and the opportunity to use the NIRR-1 facility as a case study for this research.

Abstract

Rising global opinions on security of vulnerable nuclear materials at research reactor facilities against misuse and acquisition by terrorist or violent groups has led to the implementation of the enrichment reduction program focused at reducing enrichment in fuel from about 90% to less than 20%. This program has provided an extraordinary prospect of improving international security to counter the fears of direct use of HEU materials acquired from these facilities for non-peaceful purposes. Ongoing efforts by the United States Department of Energy (DOE) through the Reduced Enrichment in Test and Research Reactors (RETRR) and the International Atomic Energy Agency (IAEA) supports countries to develop and adapt better technical capabilities targeted towards this program. This research enumerated and compared the amount of weapon-usable materials that the reactor produced in both the HEU and LEU fuel at varying time intervals of operation from a simulated neutronic model of the Nigeria Research Reactor (NIRR-1) developed with SCALE and ORIGEN code. Consequently, result obtained showed that weapon-usable ^{239}Pu balance for LEU fuel compared to HEU increased linearly about 10-fold as the number of days of operation increases. This ^{239}Pu growth was strongly considered for the ongoing conversion of Miniature Neutron Source Reactors (MNSR) as a case study because of the concern that out of the nine licensed prototype MNSR worldwide, four are in China, the origin of the design but the other five are in Ghana, Iran, Nigeria Pakistan and Syria. These five countries have well organized terrorist or violent groups that could potentially acquire nuclear materials or sabotage these facilities to disperse radiological materials which should be a call to more action for more security as well as international safeguards and accounting for nuclear materials. Additionally, based on the outcome of this simulation, as well as the vulnerability assessment carried out that included seeming capabilities of terrorist groups operating near the

NIRR-1 facility, security risk and safeguards were evaluated, and suggestions were made on security risk of the increasing quantity of weapon-usable ^{239}Pu isotope.

Preface

All the work presented in this research is original research conducted by Stephen Dahunsi in consultation and support of faculty and subject matter experts.

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Acronyms

ABU - Ahmadu Bello University
CERT - Centre for Energy Research and Training
CIAE - China Institute of Atomic Energy
CRP - Collaborative Research Project
FOM - Figure of Merit
FPED - Full-Power-Equivalent-Days
GHARR-1 - Ghana Research Reactor - 1
HEU - High Enrich Uranium
IAEA - International Atomic Energy Agency
INS - Institute for Nuclear Security
KUCA - Kyoto University Critical Assembly
LEU - Low Enrich Uranium
MK - Reactivity worth
MNSR - Miniature Neutron Source Reactor
NAS - National Academy of Science
NED - Nuclear Explosive Devise
NIRR-1 - Nigerian Research Reactor - 1
NNRA - Nigeria Nuclear Regulatory Authority
NPT - Nonproliferation Treaty
ORIGEN - Oak Ridge Isotope GENeration
ORNL - Oak Ridge National Laboratory
PARR-1 - Pakistan Research Reactor-1
RDD - Radiological Dispersal Device
RERTR - Reduced Enrichment for Research and Test Reactors
SCALE - Computer Analyses for Licensing Evaluation
SQ - Significant Quantity
SRR-1 - Syria Research Reactor – 1
SSAC - State System of Accounting and Control
UNODC - United Nations Office on Drug and crime
MCNP - Monte Carlo Neutron Particle

Chapter 1

INTRODUCTION

The global resolve to reduce the use of highly enriched uranium (HEU) fuel and the eventual elimination of such material from research reactors altogether is seen as an approach at reducing risk and the perceived possibility that nuclear materials from one or more of these research reactor facilities may one day be advertently acquired and used by any terrorist group known or operating on a global pedestal [1] to produce nuclear weapon or construct a radiological dispersal device (RDD). Though, the use of HEU in research and test reactors has raised security concerns, even though they are considerably smaller in terms of power and waste generation than power reactors [2] [3]. Beside the security concerns, research reactors are considerably smaller in terms of energy output, operation, and waste generation [4], but there have been concerns due to the extent of security and safeguards applicable to nuclear materials and the facilities globally compared to those obtainable at power reactor facilities. Nevertheless, under the IAEA guidance, [5] it is a requirement that all member states must implement relevant and objective measures to secure, safeguard, and counter all credible perceived risks of non-peaceful application of nuclear technologies and associated materials in all its ramifications. This includes efforts by the agency to support, develop, and adapt better technical capabilities targeted towards converting all HEU fueled reactors with lower enriched uranium (LEU) fuels of less than 20% enrichment. HEU is defined as the uranium type in which the isotopic concentration of ^{235}U is 20% or higher (natural uranium ore consists of 0.7% ^{235}U) [6]. The term research reactor includes critical and subcritical facilities [7] used in stimulation and measurement of effects of radiation on metals in the nuclear rocket environment [8], generation and production of neutron flux, ionizing radiation and related experimental instruments [9]. ^{239}Pu is the most suitable isotope used in weapon production [10], the isotope is produced by transmutation of ^{238}U isotope that is exposed to neutron radiation at lower kinetic energy. The ^{238}U is subjected to two β^- decays, and as the isotope loses electron, the initial β^- decay transmutes the ^{239}Pu isotope to ^{239}Np while the second β^- transmutes the ^{239}Np into ^{239}Pu [10].

$$ {}^{238}_{92}U \; + \; {}^{1}_{0}n \rightarrow {}^{239}_{92}U \rightarrow \;^{\beta^-}\; {}^{239}_{92}Np \rightarrow \;^{\beta^-}\; {}^{239}_{92}Pu \tag{\textit{equation 1.1}} $$

Meanwhile, the core of the NIRR-1 MNSR is projected to be converted to LEU fuel with UO_2 Zircalloy, it is expected that the initial 9.0 wt% of ^{238}U isotopic content in the HEU fuel will substantially increase to about 87.05 wt% in the UO_2. As it is anticipated, the reasonable amount of ^{238}U isotope present in the LEU fuel matrix can produce plutonium isotopes including the ^{240}Pu, but when the quantity of ^{240}Pu exceeds 7% measure of the total plutonium isotope, such matrix is said to be bad and not good enough weapon material.

Correspondingly, the vulnerability and proliferation of nuclear materials in research and test reactors can be exploited due to the high volume of ^{239}Pu that may be produced in the spent fuel from such a facility by any proliferant state. In view of the vulnerability evaluation of research reactor facilities as mostly located in developing countries like Nigeria, it may as well attract a very high consequence in terms of environmental hazard from the fall-out of radioactive dispersal in case of attack by violent or terrorist groups, since ^{239}Pu produces high and energetic radioactivity with a half-life of 24100 years.

Furthermore, the production of high-purity weapon-usable ^{239}Pu metal grade is best when lower enriched fuel is exposed for a few days of reactor operation, after which the chemical separation methodology process could be used to separate the ^{239}Pu from the other elements [10]. It is worthy to note that even though the NIRR-1 MNSR facility used as a case study is a compact core model, the production of ^{239}Pu from a lower enriched fuel is still technically a well-intentioned subject matter since the research reactor operates an average of 2.5 hours per day every week. This situation puts the facility in the class of reactor that can produce more amount of high-purity weapon-usable ^{239}Pu metal grade based on the quantity of ^{238}U present in candidate LEU fuel.

1.1 General Concept and Approach for Safeguards and Security of Nuclear Materials

The international safeguards application takes measures to prevent the spread, and timely detection in case of theft or diversion, of a significant quantity (SQ) of nuclear materials through full implementation of the non-proliferation treaty (NPT) agreement. This has been one of the cardinal objectives of the IAEA international safeguards and verification regime. The IAEA makes sure that all commitments to the NPT agreement are adhered to by verification and safeguards of nuclear materials and technology to accomplish nuclear disarmament. The NPT agreement came into force in 1970 and has been ratified by 190 state parties with the responsibility to promote strict adherence to the agreement on non-proliferation of nuclear materials. Accordingly, Article III of the NPT requires the applicability of the IAEA safeguards to all sources or special fissionable materials within the member state's territory, jurisdiction, and control [11]. For all IAEA safeguards and verification, complying with the requirements may also involve measures to fulfil the Additional Protocol (AP) if it was ratified by the state. This measure entails the collection of design information and environmental samples at different locations even beyond the facility [11] as deemed fit by the inspectors.

Establishing the inventory and having full knowledge of the strength of materials and the facility under the IAEA safeguards is of the utmost importance to all the cardinal oversite of the agency. The information on elements and their isotopes contained in the inventory is referred to as the source term, and this presents a gateway to understanding the extent, needed level(s) of protection, vulnerabilities, and safety of operations needed at any facility. Besides the importance of the source term to safeguards, the IAEA guidance and Safety Report Series No. 53 also recommends that it is important to analyze and determine the source term including its radiological consequences for all nuclear and radiological facilities to guarantee safety of people, materials, and the environment [4].

1.2 Limitations of existing control and accountability for safeguards and security of nuclear materials in research reactors

The IAEA verifies compliance to safeguards using non-destructive assay to corroborate all reactor data provided by the facility through the state, as well as physical inspection at intervals for inventory of different nuclear materials. A state proliferating or planning to proliferate may hide data from inventory transmitted to the IAEA.

Beside the application of international safeguards as a measure of compliance to the protection of nuclear materials and facilities, varieties of strategies have been proposed centered around enrichment reduction. Nevertheless, material attractiveness at lower enrichment may increase due to enrichment reduction. Non-state actors with less capability but with the intention of creating panic, disrupting, or acquiring materials to produce RDD, may easily be attracted to the facility. The attempt to divert materials by disgruntled personnel may also increase due to the perceived lowering of risk associated with the new enrichment.

There is also increasing concern that most strategies put forward by DOE, IAEA, and other stakeholders failed to place emphasis on the risk some of these facilities face operating in certain regions of the globe irrespective of the level of enrichment obtainable in those facilities. Consideration of the role that human elements play in security, risk mitigation, and management will be an asset to global security. Furthermore, the express understanding of uniqueness in culture in terms of tradition, ethnicity, nepotism, corruption, religious beliefs, administrative process, administration of justice system, policy, and legal framework that supports the sustenance of global strategies in these regions will go further to appreciate facility risks and other misunderstandings.

But there are concerns about assigning strategic value to the risk at all levels of enrichment and the notion that such material becomes more attractive even at lower enrichments, which now raises more concerns about material vulnerabilities attributes attached to nuclear materials at different enrichment levels and projected elevated proliferation risks as the fuel transits from HEU to LEU. According to a "Risk Metric" developed by Glaser which established that "***very roughly, a reduction of the fuel enrichment from 93 % to 45 % cuts the attractiveness by about 40 %, while a reduction from 93 % to 20 % cuts the attractiveness by almost 70 %, compared to W-HEU,***" as well as the fact that the technical requirements will make it practically impossible to manufacture nuclear weapons at enrichment levels below 20% [12]. The Glaser metric, however, failed to evaluate the increase in weapon-usable ^{239}Pu in LEU fuel materials after reducing the enrichment from 93% to 20% as well as the justification of the scale of difference in the ^{239}Pu balance between HEU and LEU.

The enrichment reduction program has provided an extraordinary prospect of improving international security as well as relieving the fears of direct use of HEU materials acquired from these research reactors for non-peaceful purposes. However, bearing in mind the increase in ^{238}U isotopic content in HEU from 9.0 wt% to 87.05 wt% in LEU and the fact that this noticeable increase will give rise to weapon-usable ^{239}Pu in spent fuel of the LEU should be a big source of concern for the enrichment reduction program as well as international safeguards and accounting for nuclear materials.

Granting the understanding that technical requirements will make it nearly impossible to manufacture nuclear weapons as enrichments reduces farther below 20%. At this point, it may be easy to assume that reducing fuel enrichment from 93% to 20% cuts the material attractiveness by almost 70%, but, alternatively, it is also believed that reduced enrichment may warrant lesser or easier adversary capabilities to obtain nuclear materials as the extent of required safety and security protocols for such materials diminishes. Cutting material attractiveness by almost 70% will not eliminate in entirety the possibility that material could be accessed in whatever form or shape by (i) a disgruntled employee acting for self or in collusion with an outsider, (ii) a terrorist invasion of susceptible secured facility and (iii) other material vulnerabilities.

Nonetheless, to an adversary or non-state actor, obtaining materials in any form or shape and accessing or disrupting facility operations with the attendant media attention is a success. To date, widely held global opinions on security of vulnerable nuclear materials at the research reactor facilities from misuse and acquisition by terrorist organizations worldwide has led to the implementation of the conversion program focused on reducing the enrichment in fuel from about 90% to less than 20%. Since the conversion program is an extensively accepted initiative worldwide, all the requisite risk assessment, material attractiveness, and vulnerabilities associated with each materials type, enrichment, facility, location, and the general adherence to both national and international regulations on material control and accounting for all levels of enrichment should be standardized to the extent practical when planning or implementing global nuclear material security.

Essentially, risk and material attractiveness, including their figure of merit (FOM), must be assigned to materials based on local, regional, and international threats to each facility. Additionally, more comprehensive methodologies, as well as adequate information gathering techniques for benchmarking procedures that cuts across the conduct for safety, security and safeguard for the stockpiled vulnerable nuclear materials at research reactor facilities worldwide, must established as a means of promoting global nuclear materials security.

The safeguard and security objectives in the context of this research are expected to develop capabilities that helps to avert the stealing or diversion of nuclear material, compare risk inherent in the reduced enrichment, as well as the safety of personnel and environment within and outside of the research reactor facility through the inventory of source term that will be obtained by utilizing the *O*ak *R*idge *I*sotope *GEN*eration (ORIGEN) capabilities in the Standardized *C*omputer *A*nalyses for *L*icensing *E*valuation (SCALE) code suite.

1.3 Importance of source term inventory to international safeguards and security of nuclear materials for research reactors

Nuclear materials inventories are measured using different techniques like counting physical items, detectors, on-site measurements, analysis of environmental samples, and many more [13]. Nevertheless, the enumerated techniques may not be enough to prevent clandestine operations by any facility when a total commitment and proof of adherence to international safeguards, including securing nuclear materials against clandestine operations, is desirable.

Apart from the importance of source term inventory to safeguards and security, the acquisition and potential threat of dispersal of small amounts of plutonium in the air in the form of dust or aerosol by an adversary or terrorist group would be politically and economically impactful without the fore-knowledge of its radiotoxicity and characteristics that can inform emergency response and the eventual clean-up.

A more detailed source term inventory, then, becomes very important and strategic to the ongoing conversion programs worldwide. The inventory will provide more detailed elemental and isotopic parameters that could make diversions, deviations, or accidents more easily detectable when further environmental and elemental analysis are carried out. Source term is the quantity of radioactive material expected to be released during normal reactor operations. It is reported on a ***per isotope*** basis, and the knowledge plays a critical role in safety analysis of reactors during and after normal operations. The extent, composition, and pattern of activity release can be simulated under different conditions to understand the degree of challenges that radiological hazards may present [14], or to detect any deviation from normal operations that may lead to non-peaceful application. Additionally, the conduct and evaluation of source term is a requirement to establish a national system of control, accounting, emergency response plan, and safety and security of nuclear materials. Furthermore, it is used for the conduct and postulation of radioactive releases for design base accident (DBA) analysis. The information contained in the analysis can provide evidence of operational consistency or otherwise when compared with initial information provided by state or facility during on-site or off-site evaluations of trace elements in environmental samples, as well as during accident analysis.

For research reactors, the knowledge of source term became very significant in safeguards and security of materials because of the several irradiation channels in the design that could accommodate clandestine and undeclared materials processing. Even though international safeguards permit the use of the tamper indicating device (TID) for facilities under the IAEA safeguards, it is challenging to have TIDs on the all the irradiation channels for regulatory oversite. Additionally, the usage patterns of research reactors are much less regular than power-producing reactors, which complicates analyses.

Nigeria is one of the countries operating an HEU fueled research reactor. The reactor is a Chinese manufactured MNSR that can produce weapon grade material, though in a very small quantity. The Nigeria Research Reactor (called NIRR-1) is undergoing conversion from HEU ($UA1_4$-A1) to LEU (UO_2, Zircalloy). The conduct and evaluation of source term and inventories for NIRR-1 are very significant for operational safety, amendment of legislation, and the eventual renewal of the operating license of the new LEU fuel. Additionally, the evaluation of source term from the NIRR-1 facility will reveal the composition pattern of radioactivity release under different conditions that can help plan for the readiness and the prevention of radiological hazards as the HEU core is removed from the reactor. The knowledge of source term inventory will help develop the HEU core shielding with the respective safeguard's expectation for storage and secure transportation of unirradiated and irradiated HEU at the end of the present HEU core life.

1.4 Background

According to the IAEA database shown in (Figure 1.1), there are about 273 research reactors in 59 countries around the world used for teaching and training purposes; there are 14 sited in Africa and they are expected to continue to play a leading role in advancement as well as improvement of human wellbeing [15]. Additionally, they will remain influential to the growth of nuclear technology use in agriculture engineering [16], education and training, basic science, materials development, and radioisotope production for medicine, industry, computer code validation, elemental analyses, and radiochemistry [17] [18] [19] [20]. The term research reactor includes critical and subcritical facilities [7] used in stimulation and measurement of effects of radiation on metals in the nuclear rocket environment [8].

Globally, the direct impact of utilization of research reactors are seen in the expansion of basic scientific systems, advancement, and enactment of viable research and technology policies that supports the transition of breakthrough from theory to reality. Research reactors are also used to generate neutron flux as well as experimental radiation for research and development [21]. A typical research reactor core has a small volume with powers less than 5 MW(t). In most cases, research reactors utilize higher fuel enrichments than typical power reactors [22]. Some of the reactors operate with HEU fuel that may be as high as 93% and are cooled by natural or forced cooling with pulsing capability. Their challenges range from housing stockpiles of both unirradiated and irradiated HEU materials with quantities ranging from grams (g) to metric tons (MTU) [23] and the need to have a credible ability to secure these nuclear materials.

Aside from the earlier efforts by the US and the IAEA to assist in providing technical capabilities to reduce enrichment levels in research reactor utilization, the importance of total elimination became obvious after the September 2001 terrorist attacks [24], and thereafter the inquest and increase by terrorist group seeking nuclear materials for malevolent acts. In addition to the efforts by the RERTR program, the National Academy of Science (NAS) recently published two reports to review the status of HEU to LEU conversion for both reactor fuel and targets: 1)

"Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors,"[1] and 2) "Molybdenum-99 for medical imaging"[2] These studies revealed that conversion of research reactors has the potential to improve performance understanding of the operating characteristics[3], contribute to further decision-making processes on the scientific evaluation, and most importantly, reduce proliferation risk[4].

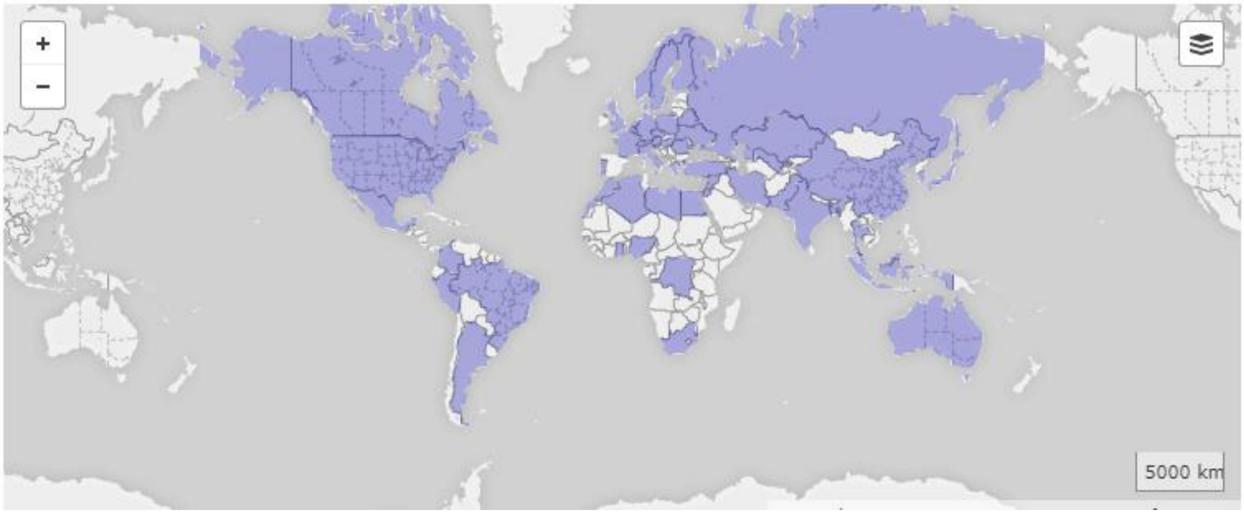

Figure 1.1. IAEA database of Research Reactors

Source: *[15]*

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[1] "Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors," Committee on the Current Status of and Progress Toward Eliminating Highly Enriched Uranium Use in Fuel for Civilian Research and Test Reactors, National Academy of Sciences, March 2016

[2] "Molybdenum-99 for Medical Imaging," Committee on State of Molybdenum-99 Production and Utilization and Progress Toward Eliminating Use of Highly Enriched Uranium, National Academy of Sciences, October 2016

[3] "National Research Council, Progress, Challenges, and Opportunities for Converting U.S. and Russian Research Reactors, Washington D.C: National Academies Press, 2012.

[4] Schickler, R. A., W. R. Marcum, and S. R. Reese. "Comparison of HEU and LEU neutron spectra in irradiation facilities at the Oregon State TRIGA® Reactor." *Nuclear Engineering and Design* 262 (2013): 340-349.

1.5 Study goals and objectives

The objectives of this research are aimed at setting international standards of evaluation in measuring security, risk and material attractiveness, and threat assessment. Presently, no existing confirmation measurements have been conducted to evaluate or confirm the NIRR-1 source term inventories. Hence, the operational source term of the facility will be simulated for postulated accidental release of radionuclides from an MNSR using the NIRR-1 as a study facility. These objectives will be achieved by performing the reactor physics analysis to evaluate the threats, dose calculations, burnup, and power distribution for security and safeguards of materials, including its implications for storage and transportation using SCALE and ORIGEN Monte Carlo code.

For this research, further emphasis is placed on using the TRITON tool of the SCALE code to understand the strength of the postulated inventory of releases and how it will affect technical requirements for assuring that the state has not embarked on a clandestine activity, or for an adversary to acquire nuclear materials from the facility. The result from the SCALE simulation will also be applied to developing an acquisition pathway analysis (APA) which is a requirement for designing a state level approach (SLA) to safeguards.

Apart from the Glaser risk metric, the capabilities, strength, and mode of operation of non-state actors within Nigeria and the region based on the past and present activities will be used to develop risk and material attractiveness to address the vital question of an appraised value of risk or attractiveness of nuclear materials, specifically at less than 20% enrichment at the NIRR-1 facility.

The schematic diagram of a typical MNSR and the various parts as are shown in (Figure 1.2) 1. Reactor vessel, 2. Reactor Base, 3. Lower Orifice, 4. Bottom Reflector, 5. Annular Reflector, 6.

Upper Orifice, 7. Upper Shim tray, 8. Lower Grid plate, 9. Fuel Elements, 10. Upper Grid plates, 11. Tie Rods, 12. Control Rods, 13. Control Rod clad, 14. Inner Irradiation site, 15. Outer Irradiation site, 16. Reactivity Regulator, 17. Core cover

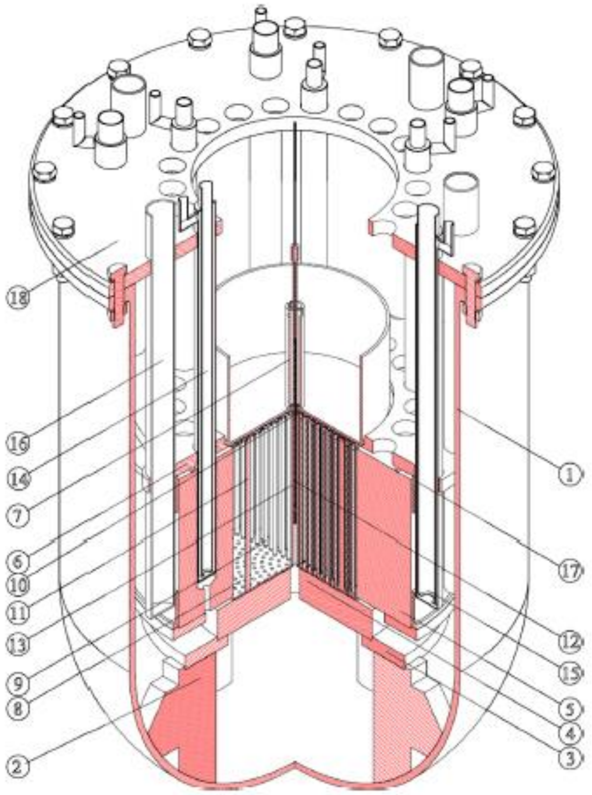


Figure 1.2. The schematic isometric diagram of a typical MNSR

Source: [25]

1.6 Research justification and study benefits

During normal operations, radioactive fission products accumulate in the primary coolant systems, pipes, and pumps, as well as in the contamination on exterior cladding material with fission trace uranium. It becomes important to postulate the extent that radioactive contamination and possible on-site exposure could potentially lead to severe deterministic effects (death) or off-site ground contamination that could affect the public and the environment. Besides this, postulating accident and unexpected initiating events from inventory of source term can help prepare for any unexpected accidents as the core of the NIRR-1 is removed and transported back to the manufacturer in China. On the other hand, the conversion program is expected to bring about a new safeguards challenge that this research will equally address as an important component of international security. The IAEA safeguards program was established as part of the international security architecture to detect the diversion of significant quantities of fissile nuclear materials against purposeful non-peaceful usage to produce nuclear weapons and explosives as well as radiological dispersal devices [26].

When accounting for nuclear materials, a potential weakness is inadvertent or deliberate gross over/under estimation of nuclear materials depending on the analytical methods used. The methodology applied for the accounting of plutonium balance and elemental source term evaluation, as well as the risk analysis in this research, will benefit the IAEA and give credible assurance of peaceful and protected core conversion, as well as the assurance of the ability to adhere to nuclear safeguards, NPT and pragmatic verification of design, and nuclear materials in Nigeria.

Equally, the completion of this research will provide answers to the following fundamental safeguards questions to draw conclusions and accomplish the set objectives of this work:

- What are the additional verification challenges to be faced by the NIRR-1 facility due to the HEU core removal and the new LEU core replacement, considering the reactor operating data history including storage of fuel materials?
- What quantity of plutonium will be left at the NIRR-1 facility after the conversion and how is such being accounted for?

- What are the international and domestic safeguards protocols to be met by the NIRR-1 facility for verification and regulatory oversite?
- What significant changes will the conversion have on the application of safeguards and material accounting within the facility and country at large?
- What are the potential proliferation risks and theft pathways in the ongoing conversion process and the probability of detection by either the facility or IAEA in case of theft or malicious attempt?
- What are the potential inventory management issues and regulatory challenges due to the conversion?
- What are the new safeguards challenges based on the sensitivity and uncertainty measurements of nuclear data for the NIRR-1 facility safeguards?
- What are the probable scenarios that should be used as guidelines to accomplish when designing State Level Approach (SLA) for the HEU, as well as the candidate LEU?
- What are the safeguards measures in place for continuous monitoring and storage of spent fuel?
- What are the safeguards methodologies in place to check undeclared irradiation or potential intent of diversion of spent fuel elements?
- What are the safeguards protocols in place for the eventual repatriation of the HEU fuel to its origin?

Nigeria is a signatory to the NPT for the universal, total, and irreversible elimination of nuclear weapons [27]. Well-understood source term inventories can be used as a tool for assurance that Nigeria's nuclear program follows the international verification regime. Based on the inventory, any unrelated radioactivity detection can indicate that a facility is potentially involved in a clandestine operation or activity.

The inventory result from this research is expected to provide a resource of basic information needed for the shielding calculation for core removal, storage, and transportation. A more detailed elemental and isotope outline that could make diversions, deviations, or accidents easily detectable based on the inventory data will be evaluated. It also provides the IAEA and national regulators baseline ideas of elemental expectation from facility operations when further environmental analysis is required. In addition, the evaluation of source term from the NIRR-1 facility will reveal the composition and postulated pattern of radioactivity release under different conditions that can help plan for the readiness and the prevention of radiological hazards as the HEU core is removed from the reactor.

Some of the existing MNSRs operate in countries (e.g. Nigeria, Syria, and Pakistan) where ongoing conflicts or security challenges of deadly terrorist groups have become a serious global concern. Moving forward, all countries like Nigeria operating research reactors must be able to demonstrate that the country can provide adequate security assurance using the research reactor as a measure of the ability to fulfill the requirements in the IAEA nuclear security series (NSS) 19 implementation guide. Furthermore, the guide stipulates security as a crucial requirement for state level nuclear program and all Member States must ensure that nuclear and radioactive materials are protected from people with malicious, criminal, and terrorist, as well as those with intentions to sabotage, within the facility and during transportation [28].

Therefore, burnup simulations for both HEU and LEU will provide information on the expected plutonium balance at different power levels to ascertain the quantity of plutonium expected from facility operations per period. At the same time, the proposed LEU will require an increase in normal operating power from 30kw in HEU ($UA1_4$-A1) to 34kw in LEU ($UO_{2,}$ Zircalloy) to have an equivalent flux [29]. The data from the burn-up will be used to assess the worth of the conversion process for MNSRs based on the plutonium balance, as well as rationalize the need to develop ***facility-specific*** risk and material attractiveness including their figure of merit (FOM) based on a global standard, while still recognizing local, regional, and international threat assessments of each facility devoid of general assumption. At the completion of this research, the idea generated will be used as a training support and complement to the ongoing efforts by the DOE and IAEA with subject matter contribution to the enrichment reduction program.

1.7 Methodology

Many computational tools have been used to simulate the likelihood of radiological release into the reactor containment and the environment, as well as to generate data for the verification of facility operations. But each tool presents different challenges about accuracy, and this is a limitation for the precision of output needed for the overall objectives of the conversion program. Evaluation of source term involves efforts in tracking several core physics parameters, operational times, and enrichment levels.

In this research, the ORIGEN capabilities of the SCALE code suite were employed to carry out reactor physics analysis and to generate the core inventory of source term for both the HEU and the candidate LEU. Dose calculations, plutonium balance, burnup, and power distribution important for safeguards were carried out using the Transport Rigor Implemented with Time-dependent Operation for Neutronic depletion (TRITON) code.

Even though the engineering and design drawings of the facility were not available, an MCNP input deck created at the Argonne National Laboratory (ANL) as part of the effort to convert the NIRR-1 core from HEU to LEU was *obtained through a private communication* and used as a guide to develop a new SCALE input used in this research. The choice of SCALE suite is based on its ability to generate K_{eff} more precisely and with more accuracy than [30] MCNP.

Using the MCNP input as the starting point, a computational SCALE model was initiated on *G*raphically *E*nhanced *E*diting *W*izard (GeeWiz) platform of the SCALE 6.1. version. This version of SCALE was chosen for the initial code development due to the availability of the windows user interface, its user friendliness, and its ease of navigation to new code users. The windows interface allows a step-by-step data input in a form format that can be viewed in a 3-dimesional output that helps visualize complete shape of input geometry. The input file from GeeWiz was opened in Fulcrum, a component of SCALE 6.2.3 suite, available with a graphical user interface (GUI) that provides a modular workspace which allows the user to drag-and-drop files. The autocompletion feature in Fulcrum helps to determine quick visual input, though the present version of SCALE only offers a 2-dimesional view of geometry.

The results obtained at various levels were analyzed and used to develop risk and material attractiveness and recommendations for implementing the outcomes of the research and future works.

Chapter 2

REACTOR DESIGN AND OPERATION OF THE NIRR-1

2.1 Description of the Nigeria Research Reactor

The Nigeria Research Reactor NIRR-1 is operated by the Center for Energy Research and Training (CERT), Zaria, Nigeria. The reactor is a Miniature Neutron Source Reactor (MNSR) licensed to operate at 31.1KW thermal power and 1.2 x 10^{12} neutron flux (n/cm^2/s). The reactor is a tank-in-pool type reactor with light water as moderator and coolant, and with metallic beryllium as a reflector. The reactor has a rated design of a maximum of 4.5 hours per day at full power [31], although it is operated for 2.5 hours daily for 5 days per week [32].

The NIRR – 1 fuel is an HEU UA1$_4$-A1 enriched at 90% with a burnup estimate of less than 1% of fuel after 200 days of operation, corresponding to 11 years [33]. The depletion of fuel and control of excess reactivity for the NIRR – 1 operation is done by the addition of Beryllium shim plates to maintain the reactivity worth (mk) at 4mk at the beginning of operation [33] [34]. The core of the reactor is a 230 mm x 230 mm square cylinder with 347 fuel pins and three Al dummies in the fuel lattice [35] [36]. Each fuel pin consists of 2.88g of ^{235}U loading with 1 central control rod (CD) and made up of 266 mm long cadmium absorber, 3.9 mm in diameter, covered with stainless steel 0.5mm thick [29]. The NIRR-1 is presently used for neutron activation analysis (NAA), research, soil elemental analysis for agriculture, identification of solid minerals, and training, but the conversion to LEU is expected to improve the operational performance to production of radioisotopes for cancer treatment as well as developing competencies towards the Nigeria nuclear power program. Nigeria has received support under the IAEA Coordinated Research Project (CRP) for the conversion of the NIRR-1 fuel from HEU to LEU as well as the RERTR program.

2.2 The NIRR-1 Core Design

The NIRR-1 core is made up of a 350-lattice position space, out of which 347 are fuel elements containing $UA1_4$-A1 enriched at 90% and covered in an aluminum cladding while the remaining lattice positions are made of dummy aluminum elements laid out in 10 organized cylindrical formations of varying diameter in the fuel cage and surrounded by an annular beryllium reflector. The cage is covered by a top shim tray of beryllium as well as another beryllium reflector below the cage. The fuel cage is held together by 2 grid plates, each placed above and below the cage, as well as 4 number tie-rods and the guide tube that controls the control rod movement.

2.3 Proposed LEU core design

An initial design specification for the candidate LEU core was initiated by a group of experts and coordinated by the IAEA with a preliminary enrichment benchmarked at 12.5% by simulating the reactor's design parameters such that there would be approximately the same number of fuel rods, water fissile ratios, negative reactivity, and power coefficients that will compensate for the expected penalties of core replacement [37]. Apart from this initial specification, several other experts have engaged the use of different computer codes to simulate the LEU core replacement. Previous computational studies have suggested that a 19.75% UO_2 [38], as well as U_3Si, U_3Si_2, and U_9Mo [39] fuel, will be a good replacement for the present HEU core and can appropriately match the parameters of the present HEU after the conversion. A Generic Base parameter for both the HEU (UAl alloy) versus LEU (UO_2) candidate fuel is enumerated in Appendix 1

Nonetheless, the generic number of LEU fuel is 348, and this work utilized 347 in reference to the SAR for NIRR-1. As well, (Table 2.1.) highlights the uranium isotopic for both the HEU (UAl alloy) and the LEU (UO_2) candidate fuel.

Due to the difference in thermal power between the HEU at 30 Kw and the LEU at 34 Kw, the increment in the macroscopic cross section of fission is inevitable with a constant flux and core volume to pay for the penalty of conversion depicted by Equation 2.0.

$$P = \frac{\emptyset_{th}\, \Sigma_f V}{3{\cdot}12\times 10^{10} \frac{fission}{watt-sec}} \qquad \textit{equation 2.0}$$

where,

P = Power
$\emptyset_{th}$ = thermal neutron flux
Σ_f = the macroscopic cross section of fission
V = the core volume

Table 2.1. Uranium isotopic for both the HEU (UAl alloy) and the LEU (UO_2) candidate fuel pins

Uranium Isotopes	HEU (wt%)	LEU (wt%)
^{235}U	90.0	12.5
^{238}U	9.0	87.05
^{234}U	1.0	0.2
^{236}U	0.0	0.25
Total	100	100

Chapter 3

LITERATURE REVIEW

3.1 Preliminary Conversion Concept

This research took advantage of several literatures, methodologies, and processes previously established on research reactor enrichment reduction to establish the importance of further benchmarking the codes used in simulating postulated accidents, as well as the need to update security and safeguards requirements at these facilities in accordance with the threat level identified from the facility assessment. A greater amount of the existing literature laid more emphasis on safety of these reactors during conversion and the implementation of adequate protection when HEU is converted or reduced to LEU. But, according to the IAEA, an aspect of state's fulfilment of international obligations is the protection of personnel and the environment from exposure to the harmful effects of radiation including safety practices in all its ramifications, whereas security as a state international obligation seek to prevent, detect, and protect nuclear facilities and nuclear and radiological materials from theft, sabotage, and unauthorized access.

Source terms and the quantity of radioactive materials expected to be released into the environment during normal and shutdown operations on a per isotope basis is one of the most important technical projections of the conversion program. This research was able to identify and review challenges from previous literature about university-based research reactor conversion programs, especially simulated events concerning γ, α, and β radiation, as well as postulated challenges that may arise in prospective detonation of radiological dispersal devices (RDD) like ^{60}Co, ^{90}Sr, ^{137}Cs, ^{192}Ir, ^{238}Pu, ^{241}Am, and ^{252}Cf produced from medical and industrial isotopes

[40]. Any of the sources listed above may be obtained by terrorist or malicious personnel but acknowledging the strength of damage from the sources with high activity content is important to the facility level security awareness and planning.

New ideas were generated based on these reviews which further laid credence to the need to consider security of nuclear materials even at enrichment below 20% that could be denoted as LEU. In addition, a new methodology for benchmarking parameters for all levels of enrichment reduction that looked outside safety to a more engaging security and safeguards of nuclear materials, mostly in regions of the world where definable threats exist, that could result in proliferation or malicious use of nuclear material was developed.

The Oak Ridge National Laboratory (ORNL) was the first to carry out the viability of a replacement LEU for research reactors with the conversion of the Oak Ridge Research Reactor (ORR) in 1987 using the mixed-core approach [41]. After this, several operating research reactors have been converted from HEU to LEU. More than a few methodologies and codes have been used to postulate operational safety of nuclear materials for various conversion activities, and the deployment of these codes and methodologies have also helped to identify conceptual challenges from the obtained results necessitating further studies.

The conversion of research reactors is based on comparing the operating parameters of HEU with a matching LEU substitute, as well as meeting all required regulatory standards including facility specific commitment to the safety, safeguards, and security for both the unirradiated and irradiated fuel. Equally, the projected fuel replacement must be estimated comparing the data of both mass per element ratio and enrichment ratio. Conversion of the research reactor increases the ^{238}U content which is the dominant isotope in LEU, the difference in the weight fraction, as well as the nuclear cross sections and the reactor power must be compensated for. This gap is referred to as the “penalty factor” and denoted as $f_{penalty.}$ This factor varies in different reactors but is generally between 1.2 – 2.0.

The ratio of mass per element is defined as:

$$\frac{M_{LEU}}{M_{HEU}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textit{equation 3.0}$$

where, M_{LEU} = mass of LEU
M_{HEU} = mass of HEU

While the enrichment ratio is defined as:

$$\frac{e_{LEU}}{e_{HEU}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{equation 3.1}$$

where, e_{LEU} = enrichment of LEU
e_{HEU} = enrichment of HEU

Aside from finding a LEU replacement with matching operating parameters, information obtained from source term provides both the regulators and operators with an estimate of postulated radioactivity release and the capability the facility requires for accident mitigation. Correspondingly, the knowledge aided the development of scenarios to overcome the extent of the challenges identified based on the elements and their corresponding daughter isotopes. In addition, it also provided the technical information required for shielding, cask design, storage, and eventual transportation of both the unirradiated and irradiated fuel including for emergency planning and response.

It is required that any facility undertaking a facility redesign be subject to conducting and evaluating operational accident source term (AST) and the investigation of uncertainties in measured and calculated quantities to determine safety margins with associated consequences for the management of severe accidents [42]. For the NIRR-1, the result from the AST provides a starting point for the SAR update including the methodologies used in evaluating the technical requirements for safety and security.

The NIRR – 1 fuel is an HEU UA14-A1 enriched at 90% with a burnup estimate of less than 1% of fuel after 10 years. To perform a feasibility search for suitable LEU for the conversion of NIRR-1, an MCNP model of the current HEU core was developed and benchmarked by experimental data [43]. A uranium dioxide (UO_2) LEU option with 12.5% enrichment was initially identified as a suitable replacement for the HEU core with minor changes to the core configuration [44]. However, the manufacturer of the reactor, China Institute of Atomic Energy (CIAE), recommended a 13% enriched UO_2 fuel rather than the initial 12.5% enrichment projected for the conversion of all MNSRs per the collaboration between the RERTR and the IAEA's CRP. Results obtained from the re-evaluation suggested that a UO_2 LEU fuel with 341 pins containing nine Zircalloy claddings can provide about the same cold core excess reactivity of 4.91 mk comparable to the present HEU core at 4.97 mk. This contrasts with the 12.5% enriched UO_2 core requirement of 348 fuel pins and two Zircalloy claddings that was initially projected. Aside from that, there is a departure in the value of simulated prompt neutron lifetime (l_f) quoted by the manufacturer using 'EXTERMINATORS' diffusion code to the result obtained by Ibikunle et al (2016) when compared to calculated kinematics parameters obtained for the present HEU and three other reference LEU alternatives [39] In another related work that was motivated by the identified discrepancies in the enrichment proposed by the manufacturer at 13% compared to the initial proposal of the SAR, data at 12% enrichment for the LEU replacement, Jonah et al found out that two different options each with 12.45% and 12% [45] enrichment will suffice for an LEU substitute.

As well, Ibikunle et al further investigated the core physics analysis for a suitable LEU replacement with three different dispersed LEU fuel (U_3Si, U_3Si_2 and U_9Mo) replacements at 19.75% enrichment highlighted in (Table 3.0) Ibikunle further reported a discrepancy in the reactor in simulation and submitted that the power level of any of the three measured LEU fuels must be increased from 31kw to 34 kw to obtain an equivalent flux compared to that of the present HEU fuel [46].

Table 3.1. HEU versus three proposed dispersed LEU fuel parameters

	Fuel type	Enrichment %	Density of meat/U (g/cc)	Fuel meat diameter (mm)	Clad material/ thickness (mm)	No of fuel pins
	HEU - UAl4	90.2	3.456/0.92	4.30	Al/0.60	347
1	LEU - U_3Si	19.75	7.394/5.49	4.30	Al/0.60	347
2	LEU - U_3Si_2	19.75	6.409/4.42	4.74	Al/0.38	347
3	LEU - U_9Mo	19.75	8.210/5.95	4.30	Al/0.60	347

Source: [46]

The evaluation of source term in different research reactors is used in the analysis and behavioral understanding of radionuclides' dispersal pattern at each facility and emergency preparedness planning. It can provide information significant to securing such materials and preventing unauthorized access to the facility. However, the data collected from each reactor are not identical in any two identical reactors operating with the same burnup rates.

Accordingly, data collected as source term from the analysis of core physics parameters form part of a significant requirement for license application and provide information on the changes to the facility including design information in fulfillment of the IAEA Comprehensive

Safeguards Agreement (CSA). It also provides the baseline information required for the IAEA verification. It is used as the activity reference point which assures that a facility is operating according to design specification while also assisting the facility's modelling of radioactive dispersal pathways and the volatility of identified nuclides.

In previous research directed towards establishing core physics parameters of a replacement fuel for NIRR-1, Rabba et al [33] estimated the burnup rate using the BUNRER Code VENTURE with a UO_2 LEU fuel and found out that the LEU substitute fuel has a burnup rate of about 1% for 200 days of reactor operation at 9 hours per week. This is an equivalent usage of 0.49 Kg of ^{238}U. However, only the plutonium isotope (^{239}Pu, ^{240}Pu and ^{241}Pu) generated in the core of NIRR-1 were recorded by the code [33]. On the contrary, the need for security and safeguards warrants that all radioactive content expected to be released in form of source term from the core of the reactor into the pipes, coolant water, and the environment are significantly important. Additionally, the work did not establish or evaluate the source strength, or the physical characteristics of radioactive materials in terms of half-life and its deposition velocity [47] from the generated source term.

Generally, irradiation and fuel burnup lead to fissile nuclide consumption by fission which results in the formation of fission products directly or by radioactive decay. However, some of these fission products have their **significant merits and demerits** in terms of health and safety of personnel, the public, and the environment due to the range of their half-lives. In operational planning, the protection of health and safety of personnel and of the public from radiological and non-radiological hazards associated with radioactivity [48] is important in practices and services associated with reactor technology. Hence, the knowledge of their decay period and the ability to be able to control the spread of the hazards it may present to personnel, the environment, and to the larger population during accident situations is worth devoting attention to evaluate their release using appropriate depletion code.

The NRC enumerated the expected release fraction using the ORIGEN isotope and depletion code for all low burnup and low enrichment as highlighted in (Table 3.2) [42], and the resultant IAEA assessment accordingly in (Table 3.3) [49]. In this work, the evaluation was carried out using ORIGEN isotope generation and depletion computer code from the most recent update of SCALE 6.2.3. to generate the NIRR-1 core inventory and the postulated source term from the HEU and LEU core.

Table 3.2. Source term grouping and their expected release fractions (US NRC)

Groups	Noble Gases	Halogens	Alkali Metals	Tellurium	Ba-Sr group	Noble metal	Cerium group	Lanthanide
Expected release fraction	1.0	0.4	0.3	0.05	0.02	0.0025	0.0005	0.0002

Source: USNRC Regulatory Guide 1.183

Table 3.3 Source term grouping and their expected release fractions (IAEA))

Groups	Noble Gases (%)	Halogens (%)	Particulates (%)
Expected release fraction	100	50	1

Source: IAEA-TECDOC-643

The result from several conversion efforts enumerated below showed diverse challenges assumed to have been caused by the transfer of data between codes and the RUN time of the codes.

3.1.1 Pakistan Research Reactor-1

Shoaib et al [50] modelled the atmospheric dispersion and estimated accidental airborne radionuclide release from the Pakistan Research Reactor-1 (PARR-1) for the power upgrade of the PARR – 1 to a 10 MW based on the US Nuclear Regulatory Authority guide 1.183 to determine the atmospheric dispersion and the source term for the fission product inventory in the reactor core for the PARR-1, and to plan for evacuation during an emergency [50]. The importance of Shoaib's work was seen in the discovery that the dose rate obtained from his work was more than the permissible committed effective dose (CED) at 500 m from the downwind distance away from the reactor, according to the scenario result obtained from the released fraction calculation for PARR-1. The result further laid credence to the importance of estimating facility-specific source term of radioactive accidental release from the core of any reactor during operations as a requirement for license renewal for any facility modification.

3.1.2 Syria Research Reactor

Dawahra et al [51] used the GETERA code to calculate fuel burn up and radionuclide inventory for the 30 KW Syria Research reactor (SRR-1) including the output of activities of fission products and actinides after 200 days of burn up time. In his result, the atomic density of LEU was found to have decreased compared to that of the HEU for the same number of burn up times, hence the need for a higher density LEU fuel material. However, the result obtained by Dawahra showed that the conversion of the SRR-1 from HEU to LEU presents some overall advantage in terms of cost [51], and further verified the reactors operational safety and site-specific security. Accordingly, Dawahra also estimated postulated radiological hazards associated with the operation of SRR-1 and the concentrations of fission products and actinide radionuclides in the core by investigating the source term due to all operations within the facility. The result obtained clearly outlined the importance of source term. Consequently, the outcome of the SRR-1 core inventory for both the HEU and the LEU fuel became an important consideration for modelling spent fuel management scenarios [52] for safe operations. This inventory is significant because the NIRR-1 core will be removed as irradiated spent fuel, thus the need to postulate different scenarios of events that may be dangerous to the personnel and the public due to an unexpected radionuclide release.

3.1.3 Ghana Research Reactor (GHARR-1)

The GHARR-1 is a tank in pool reactor that utilizes HEU as fuel. The GHARR-1 has 344 fuel elements dispersed in 27.5% aluminum in U-Al matrix with enrichment of 90.2%. The reactor was designed with a 10-year HEU core and it was operated at its maximum core flux for 2.5 hours in a day for 5 days in a week. The GHARR-1 is one of the research reactors recently converted from HEU to LEU. Neutronic analysis based on MCNP transport was carried out for both the candidate LEU and the operating HEU based on the scheduled core conversion program. Equally, a comparative core performance assessment was carried out for both fuels. As part of the conversion efforts, Abrefah et al used ORIGEN2 and REBUS3 codes to estimate the end-of-cycle isotopic inventory for the design of the spent fuel cask [53] [54] for the transportation and HEU core repatriation back to the manufacturers in China. Abrefah asserted that the result obtained was consistent with literature for the HEU core when similar calculations were carried out using different methods. The GHARR-1 initial safety analysis report (SAR) also projected a UO_2 enriched at 12.5% and confirmed by the IAEA's CRP project on MNSR conversion. A further work by Odoi et al also confirmed that the rated power of the LEU core must be increase from 31KW to 34KW as well as increase the fuel pins from 344 in HEU to 348 to retain the core excess reactivity at 4.0mk including the flux at 1.0×10^{12}n.cm^2.s [54] [55]. However, there were slight discrepancies between the manufacturer's calculated parameters as compared to the postulations from other simulated reactor core physics. According to the CIAE, the manufacturer of the MNSR prototype, a UO_2 LEU core enriched at 13% was simulated to be the replacement fuel for the core of the NIRR-1 MNSR reactor.

Eventually, the GHARR-1 was shut down for core cooling in 2016, and finally, removed and repatriated back to China. The present LEU core for GHARR-1 now consists of a zircaloy-4 alloy of UO_2 fuel elements enriched at 13% based on the manufacturer's recommendation, at a total cost of about 20 million USD [54]. The LEU core is expected to operate for about 25 years. (Figure 3.1 and 3.2) shows the vertical cross section of GHARR-1 core and the of cask containing the GHARR-1 HEU core

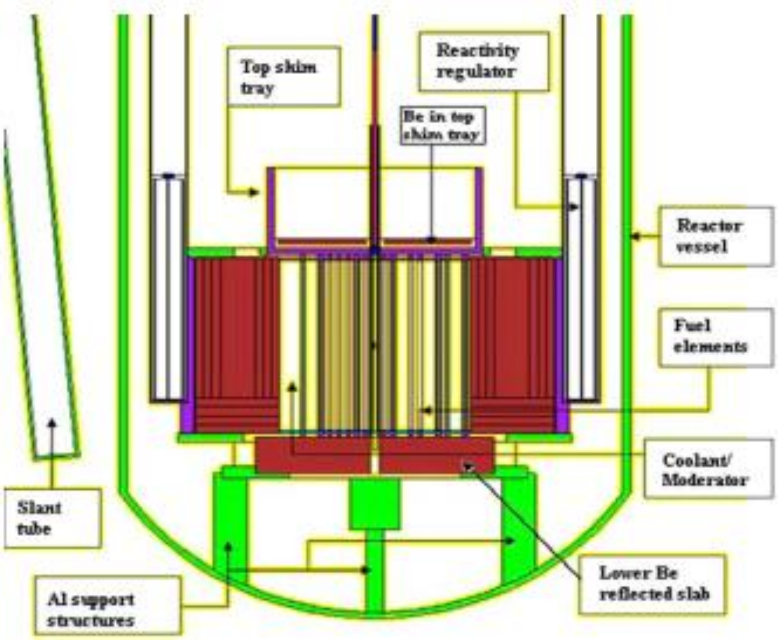


Figure 3.1. Vertical cross section of GHARR – 1 HEU core

Source: Abrefah et al

Figure 3.2. Gamma dose rate monitor of cask containing the GHARR-1 HEU core

Source: iaea.org

3.1.4 The Kyoto University Critical Assembly (KUCA)

The KUCA has a unique feature due to the combination of different core types and neutron sources. The KUCA is a multi-core type thermal spectrum critical assembly devoted to fundamental research and education on reactor physics. KUCA consists of two solid moderated (dry) cores and one light water moderated (wet) core loaded with HEU fuels. In 2012, the DOE and the Argonne National Laboratory (ANL) conducted joint scientific research for the substitution of the HEU fuel to a LEU based fuel, the outcome of which presented some drawbacks in core performance safety and validity of academic research results of the LEU fuel candidate. U-MO fuel was selected for consideration with varying thicknesses to match up the performance of the HEU fuel. But from the result of safety analysis obtained, the scientific understanding, including the performance of fuel used in the conversion at the KUCA facility was inadequate [56]. The initial studies done on the conversion indicated that a U10Mo with foil thickness of 12 mils was inadequate due to the technical challenges of the high accuracy demand in fabricating the foil thickness of the replacement LEU fuel which offered a total dependence of core reactivity on the fabrication tolerance. This type of technical challenge is not typical and has not been witnessed in any previous conversion. As such, an alternative fuel U7Mo with 19.75% enrichment in a mixture of aluminum matrix density 6gU/cc was proposed by a joint research between the Kyoto University Research Reactor Institute (KURRI) in Japan and the Argonne National Laboratory (ANL) in the US under the auspices of US DOE Material Management and Minimization (M3) program [57]. The collaboration will afford further US-Japan strategic promotion of a much-needed opportunity to share technical experience, as was announced jointly by both countries during the 2014 nuclear security summit as part of the US-Japan Nuclear

Security Working Group (NSWG) [58], to be part of the continuous effort to resolve the technical challenges encountered in down-blending the HEU fuel to a lower enrichment.

3.2 Stages and Timeline for HEU to LEU conversion

According to the National Academy of Science, the conversion of HEU to LEU follows some predetermined technical and non-technical steps [59]. The technical steps may be related in all facilities in terms of the benchmarking of codes and the involvement of multiple international organizations. However, the nontechnical steps may be different for each facility and/or country owing to variance in policy and international relations. Because understanding the cultural influence on the application of best practices, building of nuclear security culture, cultivating safeguards culture, and the implementation process of a nuclear infrastructure is crucial [1] and country specific, the implementation structures and stages may not be the same, but the goal remains enrichment reduction targeted towards global security.

The technical steps depicted in (Figure 3.2) and bounded by thick lines consists of stages in the conversion program that require or are subject to constraint in fuel performance and the general geometry of the new core design while the nontechnical, represented in dotted lines, are stages in the conversion program that are related to funding, economics, and general policy within the facility or country.

Although the National Academy of Science steps in (Figure 3.2) take care of the safety parameters and most of the technical requirements for the conversion, most of the MNSRs considered for conversion are in areas presently known to be volatile and prone to terrorist attacks. Then, security becomes an issue of utmost consideration in operation, storage, and transport. As well, it is significant to carry out threat assessment and to note the inherent risk at enrichment below 20%, including the attractiveness in storage and transport. As such, this research recognizes the importance of security culture in the application and implementation of policies that support technical innovations that vary from country to country. Importantly, the fuel of NIRR-1 will be shipped back to the country of origin (China), adequate security and transport security plans must be recognized for licensing purposes and be put in place. Hence the addition of the two more stages to the recommendation of the Material Management and Minimization (M3) program colored in green in (Figure 3.3).

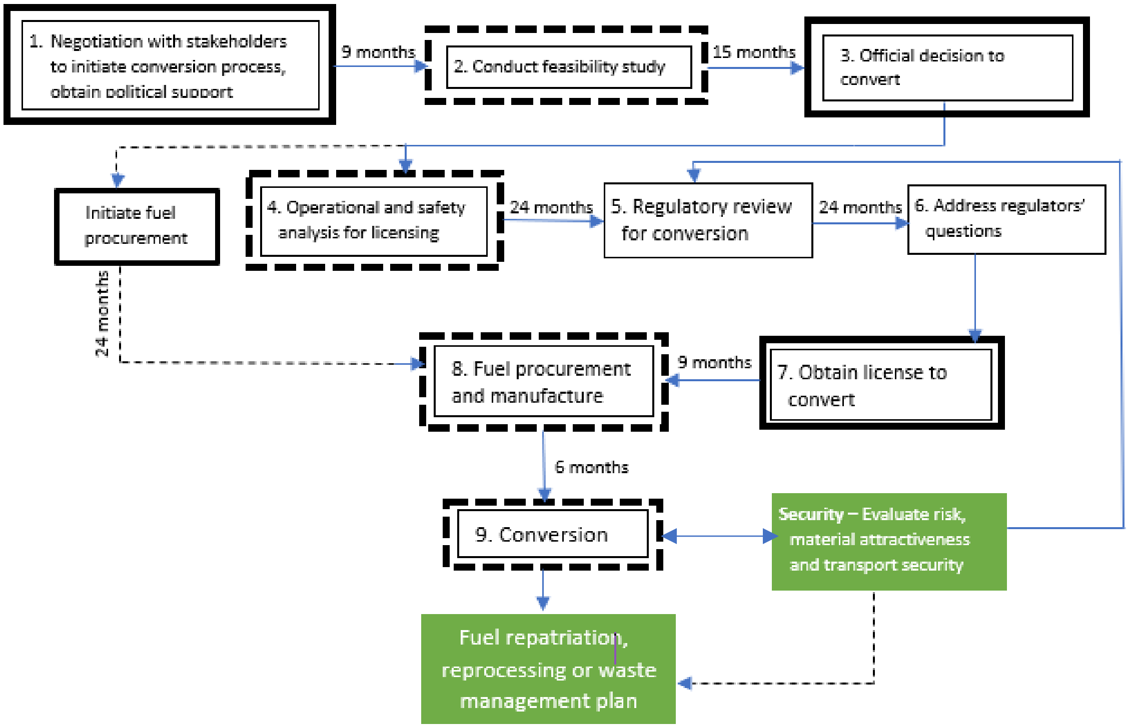


Figure 3.3. Stages of HEU to LEU conversion including timeline

Source: Adapted from the National Academies

Chapter 4

THE REACTOR PHYSICS MODELING APPROACH

4.1 Reactor Physics Modelling

This chapter details the procedures for the simulation of the NIRR-1 core and the general modelling of the hypothetical MNSR reactor representation used in this work. It also highlights the modeling approach and the methodologies adapted for the analyses of lattice and reactor core physics, HEU and LEU fuel assessments, radionuclide nuclide inventories, and the associated operational source term. It must be pointed out that for converting or lowering enrichment in any reactor, there must be adequate adjustment to the technical specifications of the original core, most especially for the excess core reactivity and the shutdown margins, as well as the identification any operation constraint [60].

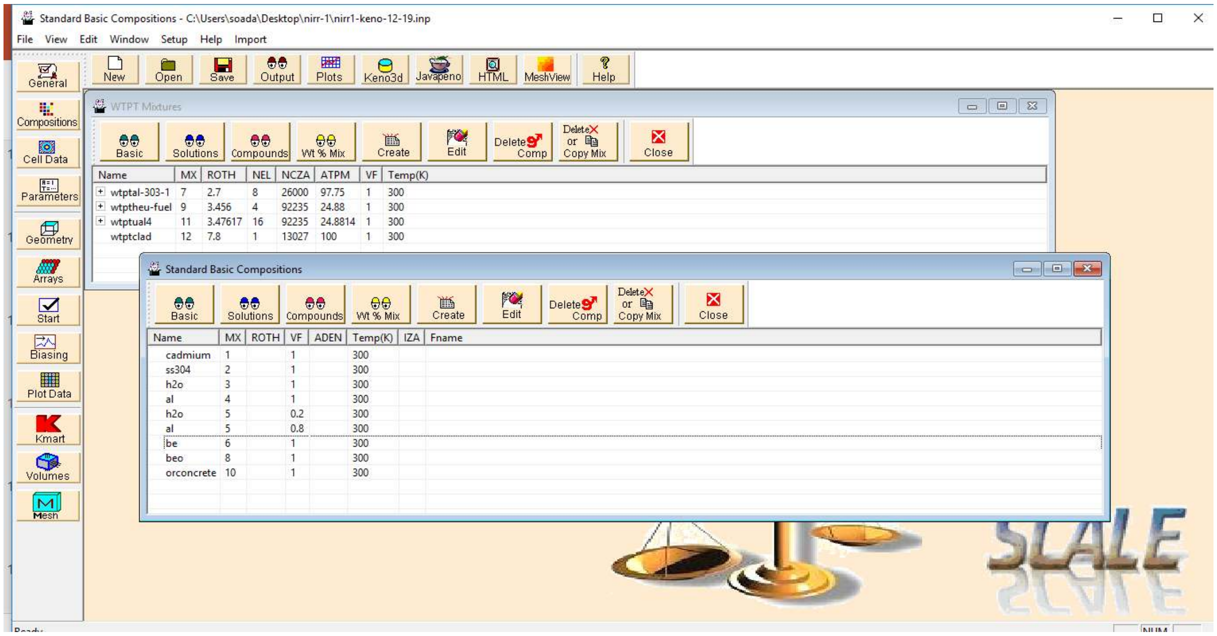
Though engineering and design drawings were not available at the commencement of this work, an existing MCNP input was used as a guide. The choice of SCALE package was because of its capability to generate K_{eff} more precisely and with more accuracy [30] than MCNP, as well as its all-inclusive capabilities for depletion and activation, and for the advantage of having an updated library that contain up to about 2200 nuclides including about 1470 pre-generated burnup libraries. However, starting with a lower version of SCALE, the ***G*raphically *E*nhanced *E*diting *W*izard** (GeeWiz) is shown in (Figure 4.1) due to its user friendliness in executing, plotting, and viewing results in 3-D [61], the composition and geometry of the reactor were initiated.

Figure 4.1. SCALE 6.1 GeeWiz toolbars

4.2 Code description

A wide range of physical parameters were considered to correctly represent reactor physics parameters to simulate the characteristics of the HEU, as well as the equivalent parameter of the candidate LEU fuel, taking into cognizance safety restrictions that must compensate for the penalties of converting from a higher to a lower enrichment. The core of the NIRR-1 reactor is comprised of 350 units of lattice rod position out of which 347 contain the fuel elements and three dummy rod positions. For the existing HEU, the fuel elements are made up of 90% enriched uranium-aluminum alloy, ordered in layers of ten multi-concentric circles at a pitch distance of 10.95 mm operating at 31 KW (th). At the same time, the candidate LEU fuel projected for the conversion program was designed such that it retained the same size and shape of the outbound HEU core. However, the LEU fuel element is made up of 12.5wt % uraniumoxide pellets with zircaloy-4 clad with simulated and expected operating power of 34 KW (th). Both, the HEU and LEU core simulated design, are located inside an annular beryllium reflector, resting over another lower beryllium reflector plate. The fuel pins are held together by a combination of two grid plates, guide tube, and four tie rods located in opposite ends of the pin bundle [32]

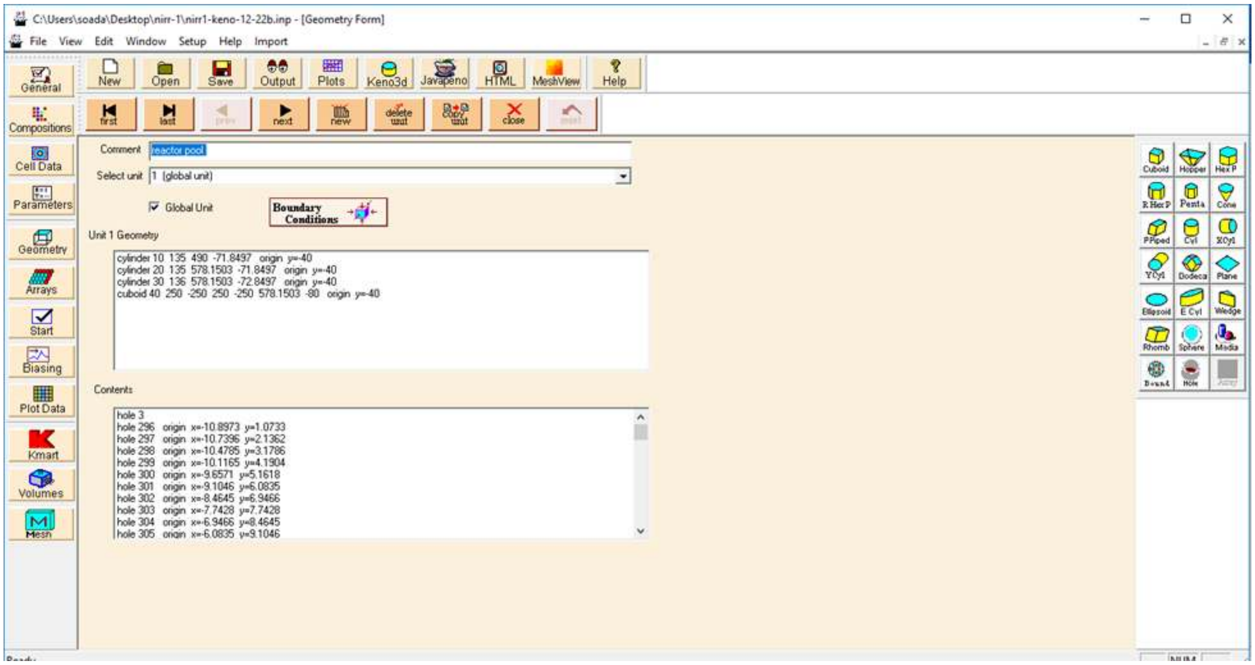
The code input was initiated, as mentioned above, by entering parameters into the GeeWiz platform using the composition window shown in (Figure 4.2). Equally, the geometry for the fuel lattice structure of the reactor core was manually generated into the user-friendly windows shown in (Figure 4.3).



Name	MX	ROTH	NEL	NCZA	ATPM	VF	Temp(K)
+ wtptal-303-1	7	2.7	8	26000	97.75	1	300
+ wtptheu-fuel	9	3.456	4	92235	24.88	1	300
+ wtptual4	11	3.47617	16	92235	24.8814	1	300
wtptclad	12	7.8	1	13027	100	1	300

Name	MX	ROTH	VF	ADEN	Temp(K)	IZA	Fname
cadmium	1		1		300		
ss304	2		1		300		
h2o	3		1		300		
al	4		1		300		
h2o	5		0.2		300		
al	5		0.8		300		
be	6		1		300		
beo	8		1		300		
orconcrete	10		1		300		

Figure 4.2. SCALE 6.1 GeeWiz composition window for NIRR-1 model



Comment: reactor pool

Select unit: 1 (global unit)

☑ Global Unit

Unit 1 Geometry

```
cylinder 10  135  490  -71.8497   origin  y=-40
cylinder 20  135  578.1503  -71.8497   origin  y=-40
cylinder 30  136  578.1503  -72.8497   origin  y=-40
cuboid 40  250  -250  250  -250  578.1503  -80   origin  y=-40
```

Contents

```
hole 3
hole 296   origin  x=-10.8973  y=1.0733
hole 297   origin  x=-10.7396  y=2.1362
hole 298   origin  x=-10.4785  y=3.1786
hole 299   origin  x=-10.1165  y=4.1904
hole 300   origin  x=-9.6571   y=5.1618
hole 301   origin  x=-9.1046   y=6.0835
hole 302   origin  x=-8.4645   y=6.9466
hole 303   origin  x=-7.7428   y=7.7428
hole 304   origin  x=-6.9466   y=8.4645
hole 305   origin  x=-6.0835   y=9.1046
```

Figure 4.3. Developing the geometry for fuel lattice

Additionally, the windows interface in GeeWiz allows a step-by-step data input menu in a form format that can be viewed in a 3-dimesional output; this is another advantage the GeeWiz hold over the more recent SCALE 6.2.3 version. Additional adjustments were made on fulcrum, the platform that serves as the graphic user interface (GUI). The KENO3D function helps to intermittently visualize complete shape of input geometry [62] as the model progresses in a way that ensures that the output is exactly what is being anticipated as shown in (Figure 4.4). One of the aims of this research is to be able to use the outcome as a training model to support the ongoing efforts of the DOE and the IAEA with subject matter contribution to the enrichment reduction program.

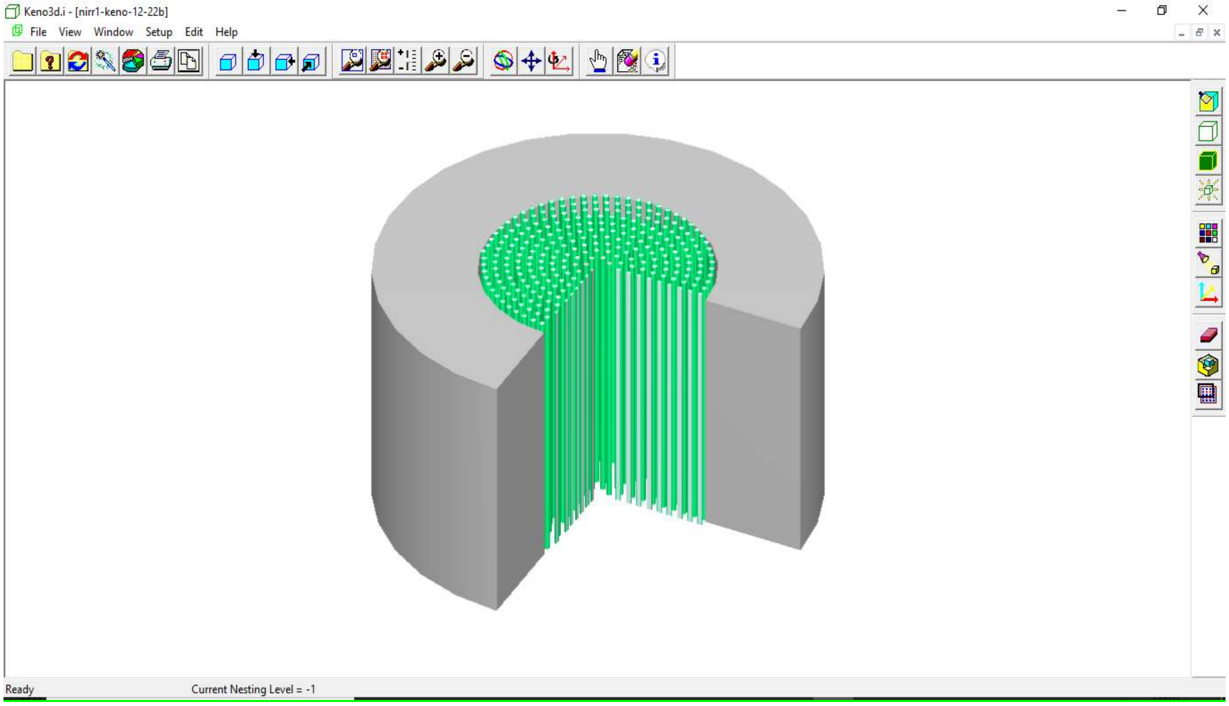


Figure 4.4. SCALE 3-D model view of NIRR-1 core inside Beryllium reflector

The initiated lattice physics model on GeeWiz was opened in fulcrum, a component of SCALE 6.2 suite available with a graphical user interface (GUI) that provides a modular workspace. Fulcrum allows a user to drag and drop generated files for analysis. Despite the user friendliness using the window menu format for input in GeeWiz, the SCALE 6.2 version is an improvement over the 6.1 version because of the enhanced capability in the analysis of continuous energy (CE) Monte Carlo, radiation shielding, depletion, and the fulcrum window, as well as the ENDF/B-VII.1 nuclear data libraries inclusion of an improved group structure.

The autocompletion feature in fulcrum helps to determine quick visual input for creating, editing, validating, and visualizing inputs. Though this version is a newer model, it only offers a 2-dimesional view of geometry that includes a user interface that automatically connects with other SCALE embedded resource.

Presently embedded in all the versions of SCALE suite code are several built-in geometry designs for various reactor cores; LWR, BWR, etc., as seen in (Figure 4.5), which can be generated automatically as an array when dimensions are specified as input to the code. However, going by this, the design pattern of the NIRR1 core must be painstakingly entered manually for all the 350 lattice positions.

The input data as well as the depletion model was set up on fulcrum at intervals of time according to the operating history of NIRR-1, with respect to the decaying continuous operational power of the reactor using the *T*ransport *R*igor *I*mplemented with *T*ime-dependent *O*peration for *N*eutronic depletion (TRITON). The simulated input was depleted, using the "*=t6-depl*" command for the Monte Carlo depletion KENO-VI.

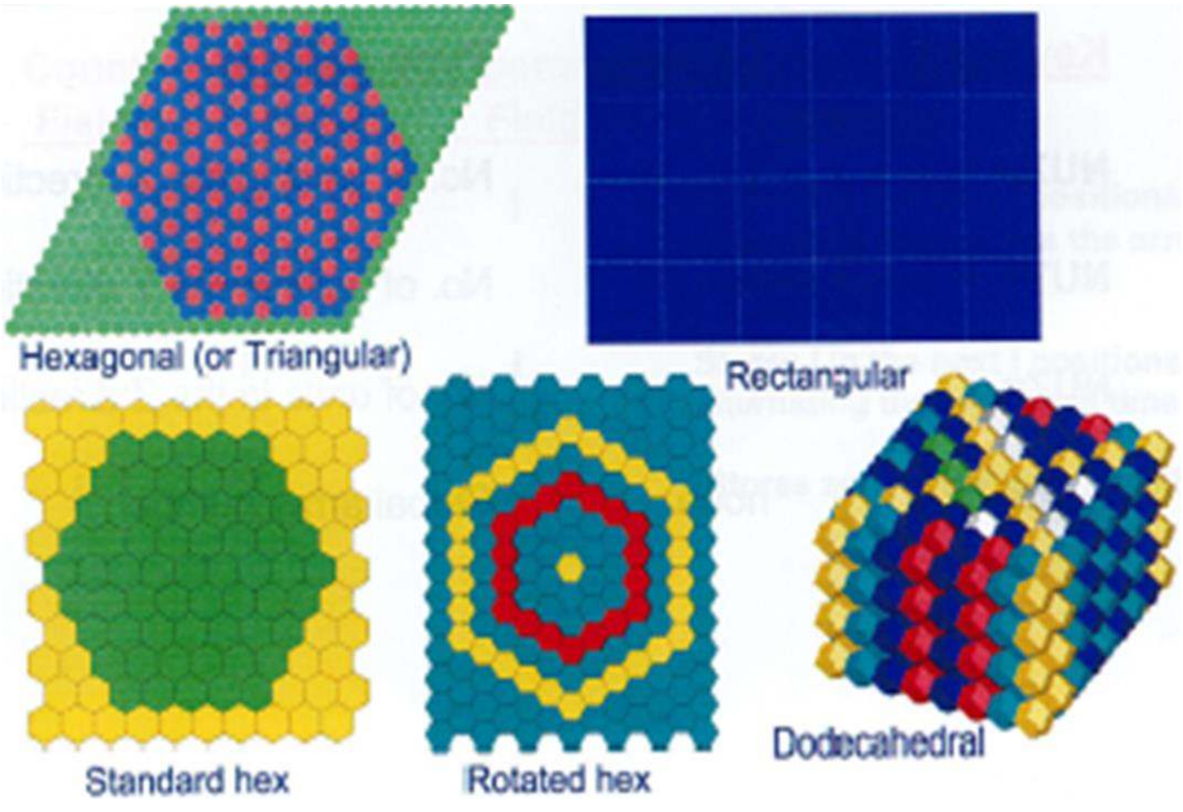


Figure 4.5. Samples of existing fuel design with SCALE (Array types)

4.3 Execution of Code

4.3.1 General depletion equation

The ORIGEN uses a type of depletion equation resulting from the solution to the system of ordinary differential equation (ODE) in solving for the production and loss rate of nuclides, as well as the effective multiplication factor known as K_{eff}. The depletion equation measures the rate of change in nuclide concentration.

$$\frac{dNi}{dt} = \sum_{j=1}^{m} l_{ij}\lambda_j N_j + \Phi \sum_{k=1}^{m} f_{ik}\sigma_k N_k - (\lambda_i + \Phi\ \sigma_i + r_i)\ N_i\ F_i \qquad \textit{equation 4.0}$$

If we consider the equation above as A = B + C – D
where,

A represents; Rate of change in Nuclide *i*

B represents; Decay into Nuclide *i* in order *j*

C represents; Production of Nuclide *i* from irradiation and

D represents; Loss of Nuclide *i* through decay, irradiation, or other means

Considering the transmutation equation above in matrix form

$$\dot{N}(t) = AN(t) \qquad \textit{equation 4.1}$$

where,

$$\dot{N} = \frac{dN}{dt}$$

Nonetheless, the nuclide vector solution can be written in the form;

$$N(t) = exp\ (At)\ \ N(O) \qquad \textit{equation 4.2}$$

where,

N(O) = Vector of initial atom densities

A = N x N transition matrix containing rate coefficients for radioactive decay, neutron capture and fission

A matrix of transition elements (S^{-1}) will look like;

$$A = -\lambda - \Phi\sigma \qquad \textit{equation 4.3}$$

The exponential matrix solution above can also be expressed to solve the coupled differential equations for the 2600 nuclides in as fast as 0.02 seconds when the initial nuclide concentrations, neutron flux (derived from power), nuclear decay data, and neutron cross sections are known. It must be recognized that the accuracy of nuclear data determines how best the ORIGEN output will become.

The code was executed on the Nuclear Engineering Cluster, “NeCluster”. The Necluster is a combination of 60 computational nodes tightly synchronized and linked together like a single computer. The outputs from the RUN are broadly analyzed and discussed in chapter 7.

Chapter 5

GENERALIZED RISK MODEL, MATERIAL ATTRACTIVENESS AND VULNERABILITY ASSESSMENT

The elevated concern over the utilization of HEU in research reactors has prompted several international initiatives to strengthen nuclear security and nonproliferation. Prominent among the strategies adopted is reducing enrichment and stockpiling of weapon-usable materials globally. It is assumed that reducing inventory of such materials is a prerequisite to risk reduction, especially after the September 2011 terrorist attack in the US. Aside this, there are several indications that the level of security at research reactor facilities may not be as robust as that which is obtainable at power reactor facilities [63].

The recognized challenges further raised the probability of preeminent risk in the continuous utilization of weapon-usable materials in research reactors. Nonetheless, it is also envisaged that lowering the enrichment in such reactors increases the attractiveness in terms insider ability to initiate material theft or sabotage. Even though the emission of dangerous gamma rays from research reactor spent fuel makes it self-protecting, nuclear material becomes a source for proliferation concern as the radioactive fission products in this spent fuel reduces due to its decay over a period [63]. Essentially, the longer the decay period, the lesser the risk of acquisition by an adversary and the higher the attractiveness and material vulnerabilities that could be attributed to such material for malicious or non-peaceful applications.

In the past, risk communication methodologies heavily relied on categorization of the safe level of enrichment in research reactors using individual preferences and personal perception representations rather than situational and evidence based. According to the US homeland security, the first significant step to understanding risk is to be acquainted to the risk environment, in addition to considering the policy and political climate [64] associated with the subject matter to be investigated, including vulnerabilities and the corresponding consequences which the occurrence may impose on a facility, country, or the international community [65] rather than using a single technical or safety occurrence. Identification of threats and vulnerabilities, followed by the analysis of risk to be posed by the identified vulnerabilities and their individual contribution to the challenges, is the first step to safeguards and security of nuclear materials. Equally, there must be policy guidelines with adequate regulatory framework to sustain the application of safeguards and security.

5.1 Risk and material attractiveness in research reactors

Apparently, the use of both the HEU and LEU in research reactors raises obvious proliferation risk of theft and nuclear material misapplication. HEU, on one hand, is a direct weapon-usable material while the LEU precipitates higher plutonium yield because of its neutron capture in uranium-238 [66] as the operating thermal power of the reactor increases.

The variation due to enrichment reduction was measured in the Ghana Research Reactor (GHARR-1), and it was found that the conversion of HEU to LEU will require increasing the fuel pins from 344 to 348 to arrive at the same reactivity as the outgoing HEU. Additionally, the reactor nominal power must be increased from 31 kW to 34kW to retain the neutron flux at 1×10^{12} n.cm^2.s inside the irradiation sites [67]. Doing this will compensate for the conversion penalties and safety margins required to retain the same operating parameters equivalent to the outgoing HEU.

According to the IAEA, risk of nuclear materials acquisition to manufacture NED, risk of acquisition of nuclear materials to produce a radiological dispersal devices (RDD), and total facility sabotage are the three main types of risk that must be considered when planning to secure nuclear materials [68]. Besides this, it is important that all security risk analysis and calculation be consistent with associated vulnerability, threat assessment, environmental factors, and the state regulations. Notably, the combined knowledge of threat motives of non-state actors and the increasing threat itself can help provide effective and strategic national and foreign security policy [69].

Consequently, a wide range of initiating events leading to a step-by-step approach to securing nuclear materials at these facilities must be considered from factors that could lead to or contribute to nuclear terrorism, material attractiveness, as well as their corresponding figure of merit (FOM) and the likelihood of an insider or any non-state actor with global reach acquiring nuclear materials from any facility directly or by proxy to make dirty bombs or RDDs. With the knowledge of factors known, the development of facility physical security from the evaluation of possible pathways for material acquisition must also be considered.

5.2 The Glaser "Risk Metric"

The Glaser Metric concept was described in chapter one and it postulated that the reduction of enrichment from 93% to 45% cuts the attractiveness to about 40%, while the reduction from 93% to 20% cuts the attractiveness by about 70%. Glaser evaluated risk to the use of HEU and the justification for the conversion of fuel in research and test reactors to LEU based on the methodology of strategic value (SV) to quantify material attractiveness and risk value of uranium and plutonium in two scenarios. His assumption relied on an adversary having either basic or advanced capabilities as enumerated in equation 5.1 and 5.2 with fuel burnup rate at 40% to arrive at a risk metric for an MTR type reactor geometry operated at 30MW and varied at different enrichments and periods of operation to arrive at the 70% percentage attractiveness reduction "***making inevitable ad-hoc assumptions***" [12]. Acknowledging the model with the assertion of the increase challenges to be faced by adversaries to manufacture weapon-useable materials as the enrichment decreases from higher to lower percentages.

Glaser used equation 5.1 quantitatively to derive the capability of an adversary's skill to produce a gun type weapon with a direct use of uranium recovered from spent fuel using mathematically derived equation 5.1 to arrive at SV. Which technically depends on the ability of an adversary's ability to reprocess and recover the much-needed material from a spent fuel.

$$CM_A^* = \eta_1(\epsilon_{FF})\frac{m_{FF}}{M_B(\epsilon_{FF})} + \eta_1(\epsilon_{SF})\frac{m_{SF}}{M_B(\epsilon_{SF})} \qquad \textit{equation 5.1}$$

where,

CM_A^* = Total strategic value of material

M_B = One bare critical mass of uranium

η_1 = Weighting factor

FF and SF = mass

ϵ = Enrichment level

While in equation 5.2 quantitatively measured the scenario where the extent of an adversary capability can manufacture an implosion type weapon from the combined worth of uranium and plutonium of critical mass 4 kg in equation 5.2

$$CM_{B_1}^* = \eta_2(\epsilon_{FF})\frac{m_{FF}}{M_R(\epsilon_{FF})} + \eta_2(\epsilon_{SF})\frac{m_{SF}}{M_R(\epsilon_{SF})} + \frac{m_{Pu}}{4.0kg} \qquad \textit{equation 5.2}$$

Glaser performed his calculation using MCNP and his work relied on a result from a single rod/unit cell calculation rather than the whole core of the reactor MTR. His work emphasized proliferation concern and attributes measured based on (i) intermittent refueling of research reactors over the life time of the facility, (ii) fresh fuel shipment and (iii) the storage of same within the facility. However, combined attributes for the global enrichment reduction conversion of reactors utilizing HEU to LEU was based on the concern for security, vulnerability of materials, perceived misuse and the acquisition of the materials by terrorist group. If all these factors were realistically considered, material attractiveness and risk evaluation must therefore consider all environmental factors, vulnerability assessments, adversary type and capabilities peculiar to each of the facilities since they are operated under different conditions but the same and domesticated international standards.

Based on this study, it is worthy to note that most MNSR facilities, no refueling or fuel storage is particularly necessary because the reactor is built to operate for about ten (10) years made possible with the addition of beryllium plates as the fuel is consumed.

Again, the Glaser risk metrics identified strategic value for material attractiveness at different level of enrichment above and below 20% including the results obtainable from the two scenarios in equation 5.1 and 5.2. Nonetheless, assuming reducing enrichment from 93% to 20% reduces attractiveness by 70%. Even so, there is no perfect system, the state and the rest of the international community retains the liability of the remaining 30% attractiveness to nuclear materials. Hence, 30% risk is not best practice and cannot translate to an acceptable risk for licensing and regulatory requirements in safety, security and safeguards.

The theft of irradiated materials from the NIRR-1 facility may not be viable because of the self-protecting nature of irradiated materials from the reactor which is ascribed as a form of physical protection at nuclear facilities. However, terrorist groups may be willing to sacrifice self against the recommended limit of 1 Sv/hr standard of unshielded material at 1 meter [70] to obtain or expose irradiated material to the facility and cause environmental hazard. The core of NIRR-1 is designed and subject to removal and shipment to the manufacturer at the end of its useful core life which should have eliminated the perpetual storage of fresh fuel, on the contrary, 3 pins of fresh unirradiated HEU fuel is kept within the facility storage room. Intrinsically, our risk emphasis is placed on the risk of invasion or disruption by insider or any of the nonstate actors as well as the theft of one or more of the unirradiated fuel in storage.

Globally, non-state actors are recognized as an out-of-bound to all known security and the nonproliferation strategies, and according to the International Security Index (iSi), it is expected that the strength and the scale of their activities including the threat of nuclear war between countries [71] will generally be on the increase. In the light of these threats, securing nuclear materials becomes very imperative that the methodologies for estimating risk and materials attractiveness should neither be limited to technical inferences of enrichment reduction in the use of nuclear materials or a parallel assertion that does not consider the threats, vulnerability(s) and challenges peculiar to each country and facility as suggested by the Glaser risk metric.

Again, this rise will eventually at some point increase the attractiveness of nuclear materials above the 30% denoted by the Glaser estimates. As well, methodologies for risk allocation must consider the vulnerability, intensity, scale and consequences arising from acts of sabotage or terrorism.

The risk model in this research was carried out and compared with one of the prominent risk models used by the proponents of enrichment reduction in test and research reactors developed by Glaser. In addition, the evaluation of risk and material attractiveness in this work considered that any quantity or enrichment can be used for RDD. Therefore, information based on the type of element, isotope, quantity and irradiation were considered to plan for mitigation of any fallout from possible acquisition or attack at an imaginary facility designed in this research. Also, the type (i.e, plutonium, or uranium) including their fissile content, chemical and physical form, extent of dilution, level of material irradiation and quantity [68] as described in Appendix 2 (table of nuclear materials at different categories) were used as guide for the analysis carried out on the imaginary facility that represented the NIRR-1 facility.

5.3 Core physics parameters for risk evaluation

It should be pointed out that this research partially agreed with the Glaser Metric, the risk model for this work aggregated the physics parameters in terms of the core source terms, plutonium balance and burnup with their associated vulnerabilities to demonstrate how well the risk evaluation is important to security and safeguards as well as the assurance that the tampering or outright forceful removal of one or more of 345 fuel pins can be detected at all levels of enrichment as well as the level of physical security to protect the HEU replacement fuel in storage.

According to the Department of Homeland Security (DHS), risk is "*the potential for an unwanted outcome resulting from an incident, event as determined by its likelihood and the associated consequences*" [72]. Based on this definition, the likelihood of a terrorist attack on a nuclear facility has been postulated by many research [73] [74] [75].

5.4 Coefficient for calculating realistic risk and risk reduction for the NIRR-1 MNSR

A well-designed facility Physical protection System (PPS) must always be tested and reviewed and should be accurate initialize the response in action to interrupt any adversary action before the adversary task time. Using the security risk assessment process in (Figure 5.1) was used to evaluate the material attractiveness and the vulnerabilities of a hypothetical NIRR-1 facility. Measures of religious ideology, poverty and corruption were also considered for the Nigerian situation as a measure of the risk assessment in this work. The physical protection system of this hypothetical facility will be evaluated by an adversary sequence diagram (ASD) that will be discussed later in this chapter. The global enrichment reduction program must conceptualize the cost benefit analysis in the in terms of increasing the physical security of some of the facilities where the threat and target of the adversary may not be theft but disruption.

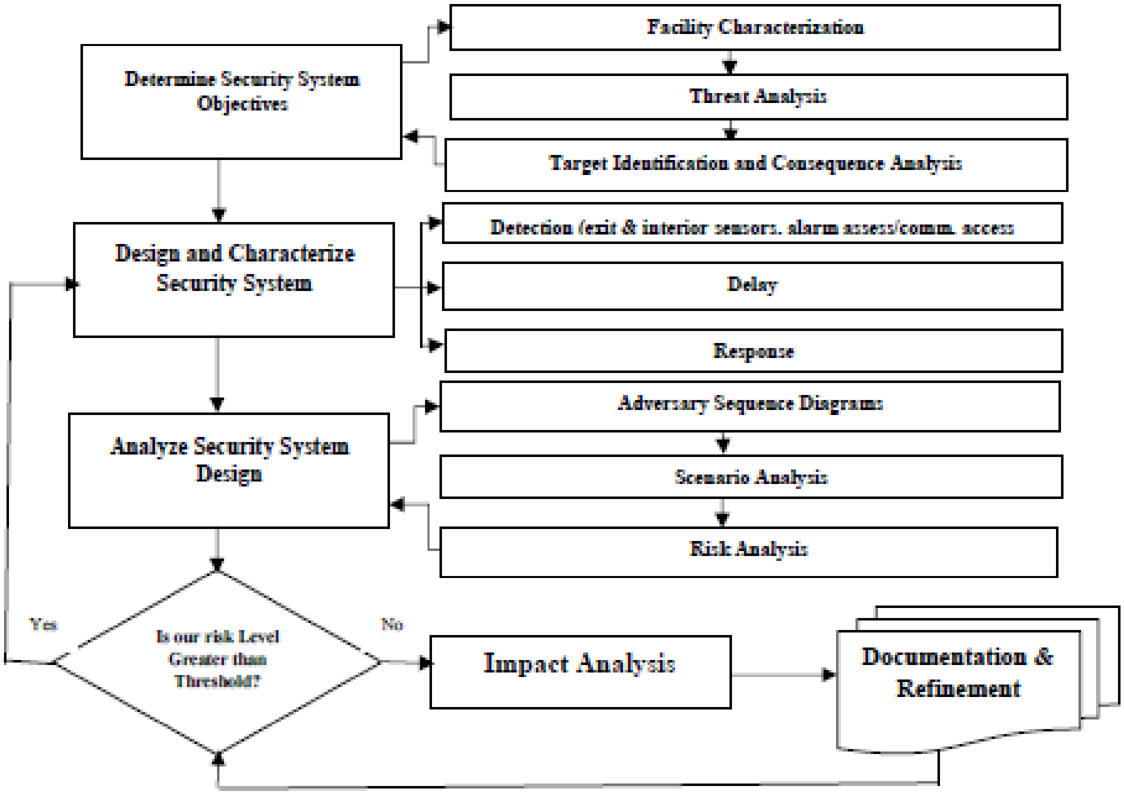


Figure 5.1. Security Risk Assessment Process

5.4.1 Material attractiveness by means of figure of merit (FOM)

Material attractiveness is the methodology used for the assessment of physical protection and international safeguards. It calculates the attractiveness and evaluates the usability of plutonium producing materials from fuel cycle [76] as well the amount or extent of material attractiveness that could advertently be required by a proliferant state or a non-state actor for non-peaceful purposes of weapon manufacture or production of RDDs. Material attractiveness is a guaranteed way to evaluate the risk posed range of nuclear materials; special nuclear materials (SNM), alternate nuclear material (ANM) and actinides with critical mass of fission products because it uses unique physical properties of such materials for assessment in a way that they are traceable and can be reproduced [77].

The extent of attractiveness derived as FOM defines the limits of usability of such materials while access and the sophistication of adversary determines the type of material sorted after. The value of usability of nuclear material can be derived from equation 5.3 when all conditions are met.

$$FOM_1 = 1 - log_{10} \quad \frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left(\frac{D}{500}\right)^{\frac{1}{log_{10} 2}} \qquad \textit{equation 5.3}$$

where,

M = bare critical mass of the metal (kg)

h = heat content (W/kg)

N = mass of a fuel assembly, fuel rods, or other sources of nuclear material (kg)

D = dose rate (of 0.2M or of N) evaluated at 1 meter from the surface (rad/h)

Equally, the result following equation 5.3 is used to categorize attractiveness for materials in form of alloys and metals as enumerated in (Table 5.1). Correspondingly, materials with FOM between one (1) and two (2) are said to be attractive, though it is more preferred when greater than two (2). But when the number reduces from one (1) to less than one (1), the materials becomes less attractive and non-weapon-usable. Nevertheless, such materials could advertently be used as RDDs when it is acquired by an adversary or any of the nonstate actors.

Table 5.1. Categorization of material attractiveness for alloys and metals based on FOM

FOM	Weapons Utility	Attractiveness
>2	Preferred	High
1 to 2	Attractive	Medium
0 to 1	Unattractive	Low
<0	Unattractive	Very Low

Source: [77]

5.4.2 Assessment of NIRR-1 facility location and vulnerabilities

Few non-state actors have been identified as having the capability to acquire weapon-usable materials to manufacture weapon of mass destruction, though in concept, it is difficult to assert the degree of their capabilities. It has further been suggested that the likelihood of a crude and low-level attack technique may be employed in trying to obtain these materials with an attendant disruptive rather than destructive [78] consequence.

It should also be pointed out that the NIRR -1 facility is in the volatile North-Eastern part of Nigeria, where the Boko Haram terrorist group (now Islamic State of West Africa, ISWA) operates. It is well known that this group pledged allegiance to the Islamic State terrorist group (ISIS) and have increased their attacks on soft and vulnerable targets [79]. The Islamic State (ISIS) is one of the known terrorist organization seeking to obtain nuclear materials from Russia in exchange for access to oil fields captured in the Anbar province of Iraq [80]. In 2015, it was speculated from a recovered video evidence that the ISIS group was plotting to acquire nuclear materials by kidnaping a senior researcher from the BR-2 reactor at the Belgian Nuclear Research Centre or his family member as ransom to have access to the material [81]. Based on the nearness of the Nigerian research reactor facility, it is believed that the conversion of HEU to LEU core will be a good value added to the global risk and proliferation reduction. Besides Boko Haram's connection and declaration for ISIS, there are confirmed reports of a connection, offer of assistance and training support for Boko Haram by one faction of the al-Qaida terrorist group, al-Qaida in the Islamic Maghreb (AQIM) [82]

Other prominent non-state actors in this category interested in accessing nuclear materials to manufacture weapon of mass destruction are the Al Qaeda, Chechnya-based separatists, Lashkar-e-Taiba, and Aum Shinrikyo [83]. Nonetheless, the Aum Shinrikyo based in Japan have more than the other groups displayed intents and their capabilities for complex engineering efforts including overwhelming penchant to facilitate and deploy chemical weapons [84]. The NIRR-1 facility's vulnerability is not limited to terrorist attach scenario alone, the dwindling economic situation in Nigeria makes the facility and personnel vulnerable to elicitation from outsiders. Recalling that in 1992, 1.5 kg of HEU was stolen from a scientific facility by personnel at the Luch Scientific Production Association in Podolsk, due to worsening economic situation. Similarly, a plot by some personnel of the Chelyabinsk region's nuclear facilities was thwarted by the Russian Federal Security Service [85].

The NIRR-1 facility is rated according to the IAEA INFCIRC 225, Rev 5 as a category III [68] facility represented in (Table 5.2) this is based on the acknowledgement of the facility not having significant off-site risk but with the potential for accidents resulting in deterministic health effects on-site. Equally, (Table 5.3) enumerated level of materials, diversion that will be enough to develop NED as well as the IAEA categorization of nuclear materials based on INFCIRC 225, Rev 5 [86]. Based on these tables, no amount of materials acquired under Category III is enough to construct a nuclear explosive device. However, the risk inherent for Category III materials are that of theft for the purpose manufacture of RDD or the environmental consequence of attack on the facility that may inadvertently lead to death, injury and prolonged economic problem.

Table 5.2. Nuclear material categorization

Material	Enrichment	Category I	Category II	Category III
1.Plutonium	Any	≥2 kg	≥500 g and <2 kg	
2.Uranium-235 (^{235}U)	≥20% ^{235}U	≥5 kg	≥1 kg and < 5 kg	≥15 g and < 1 kg
	≥10% and <20% ^{235}U		≥10 kg	≥1 kg and < 10 kg
	≥0.71% and <10% ^{235}U			≥10 kg
3.Uranium-233 (^{233}U)	Any	≥2 kg	≥500 g and < 2 kg	≥15 g and < 500 g

Source: [86]

Table 5.3. Material requirements versus security categories

Security Category	**Thefts/Diversion**
Category I	Single theft/diversion of nuclear materials enough to build NED
Category II	At least two thefts/diversions of nuclear materials required to build NED
Category III	Many thefts/diversions of nuclear materials required to build NED
Less than Category III	Thefts/diversions of nuclear materials is insignificantly suitable to build NED

Source: [86]

5.4.3 Religious Ideology, Poverty and corruption as a measure of security risk

Regrettably, personnel working in the over 40 of the HEU operated research reactors may be susceptible to crime, corruption, financial inducement or blackmail in exchange for information and nuclear material or both. Most are especially in developing countries and areas where there is ongoing crisis. The NIRR-1 facility in Nigeria is government owned and operated and could be vulnerable to these challenges. According to a United Nations Office on Drug and Crime (UNODC) report on a nationwide household survey on corruption across all the states in Nigeria conducted in 2017, it was reported that 32.3% of the sample population in Nigeria paid or requested to pay bribes when in contact with public officials in Nigeria. It was further established in the same survey that corrupt practices are more prevalent with younger demography while an estimated 400 Billion NGN ($1.11 Billion) is paid yearly in cash bribes in Nigeria [87]. Essentially, the NIRR-1 facility is based in the Northern Nigeria with locally recruited personnel with different level of education, income and the challenges that come with economic situation in Nigeria.

With the account that Boko Haram fraternizes with other deadly terrorist groups, it is obligatory that Nigeria and all IAEA Member States put in place good policy and adequate technical safeguards and security protocols that is enough to meet the status of their nuclear program to protect nuclear materials from misuse and clandestine activities [88]. A basic challenge that could hamper governments initiative is the decline in public trust for government agenda and policy.

There will be no international terror organization without the involvement of locals. The measure of success in our counterterrorism activities should go beyond the understanding, planning to foil attacks, arresting and prosecuting terrorist to examining the conditions under which and why each of the groups thrive in recruiting members. In a joint research by the US and some Yemeni experts, it was discovered that poverty, low quality life and education are major drivers of locals joining or collaborating with terrorist organizations. Even though there are little empirical evidence to draw conclusion that poverty drives terrorism in some of these states where increasing number of such activities have been recorded, because of reported cases among wealthy communities [89]. Indications are that the attacks in poorest areas are becoming deadlier as shown in (Figure 5.2), the attack heat map generated by the National Consortium for the Study of Terrorism and Response to Terrorism [90]. In Nigeria, the inhabitants of the Northeastern part where the deadly Boko Haram extremist groups operates are among the poorest. A 2012 statistics on poverty profile in Nigeria showed that out of the estimated 163 million country population, 112.47 million representing 69% of the population are poor with the Northeast share of about 69% of the total estimated poor [91]. Based on the heat map of attacks, the cost conversion allocated to the conversion program must equally consider the physical facility upgrade of the facility.

Nonetheless, to complete the evaluation of security risk and the requisite vulnerability assessment of the NIRR-1 facility based on location, past incidences ascribed to restive and terrorist groups, this research assumed that enrichment reduction may sound as reduced risk from perspective of a nonprofessional or a non-scientist. To develop security policy, a better understanding of each groups' determination and capabilities in carrying out attacks as well as projected targets [92]. The data on (Table 5.4) was developed based on assumption using statistics from literature and information from well-established sources [90] on a format adapted from "Security Index^{TM}, Capabilities Rating"

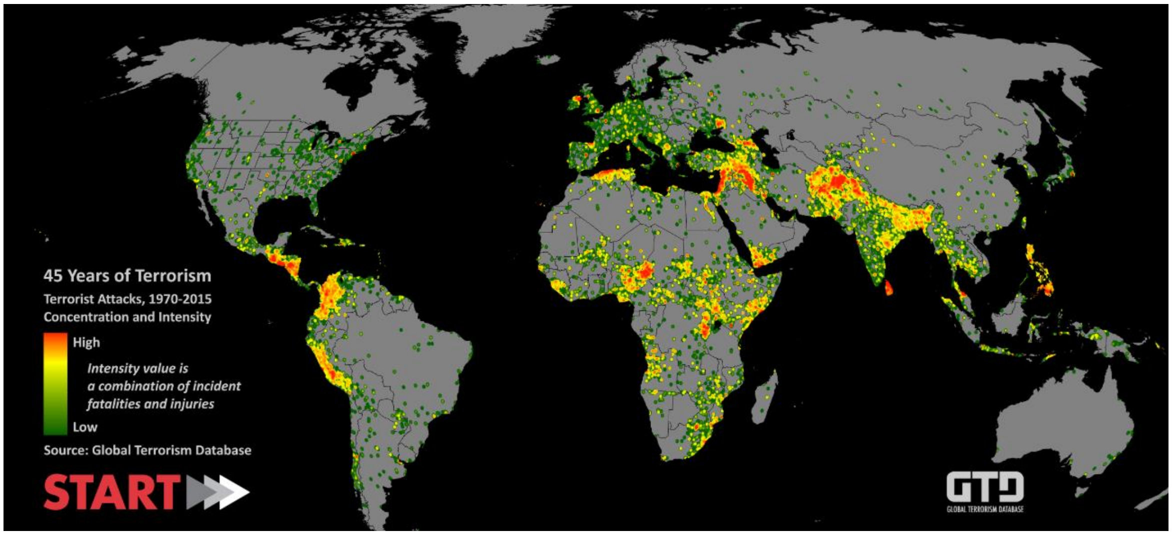


Figure 5.2. Heat map of global terrorist attacks

Source: [90]

Table 5.4. Threat capability and evaluation of non-state actors in Nigeria and affiliates

	Personnel	Intelligence Collection and Targeting	Command, Control and Target	Operational Planning Experience	Tactical Execution Experience	Logistical support and Infrastructure	Weapons and Munitions and Supply Lines	Propaganda and Information Operations	IT and Communications Capability	Financial Resources and Support
Boko Haram	4	4	5	3	4	4	5	5	4	5
Islamic Movement in Nigeria (INM)	2	4	4	2	2	4	3	3	2	3
Kala Kato	1	1	2	1	1	1	1	2	2	1
Izala Movement	1	2	1	1	1	1	1	1	1	1
The Islamic State terrorist group (ISIS)	4	5	4	5	4	4	5	4	4	4
Al Qaeda	4	4	3	4	3	4	5	4	3	4
Chechnya-based separatists	4	3	2	3	2	3	2	3	2	3
Lashkar-e-Taiba	4	3	2	3	2	2	2	3	2	3
Aum Shinrikyo	5	3	3	5	3	4	5	4	5	4
"Fulani Cattle rearers" (Herdsmen)	3	2	2	2	2	2	5	2	1	4

(1 – Non-Existent / Not Known, 2 – Immature / Non-Effective, 3 – Workable / Effective, 4 – Good, 5 – Excellent)

5.5 Potential proliferation risk, and theft pathways in enrichment reduction

Most of the recent efforts in in counterterrorism and protection of nuclear materials considers the interest and the ability of terrorist group to manufacture nuclear weapon from acquired SQ of nuclear material. But the present work takes the initiative to evaluate and evaluate risk using the NIRR-1 facility based on the outcome of a neutronic model developed from the operating parameters and history of the facility. The amount of fission products that can be released if the facility is attacked is the major interest because the amount of plutonium that can be produced throughout the life time of operation of the core cannot produce the quantity required to manufacture any weapon.

The assessment of capabilities of the non-state actors within the Nigeria territory, countries having established boarders with Nigeria and most especially those that have their operating base near the NIRR-1 facility are equally assessed.

Risk evaluation, communication and assessment cannot be completed without the assessment of critical factors for protection system. Physical protection system as well must consider the role an insider could playacting alone or in collaboration with a potential adversary.

5.5.1 Insider threat and mitigation

Trusted personnel remain the most dangerous and the greatest risk to any organization because of their knowledge and privileged access to equipment, document and the facility in general. They may use their position to carry out espionage, theft of intellectual property and sabotage [93] [94]. Because of peculiarity of the NIRR-1 facility in terms of location, there must be adequate culture of security and safeguards to prevent elicitation outside influence on the facility personnel

Undesirable consequences can result from the theft of a nuclear material from any facility that can have grave psychological impact, economic loss, environmental damage, and loss of critical infrastructure as well as loss of life may be in the process of responding and neutralizing the adversary there may be shot outs that could result to loss of life and secondly, if the response was not able to neutralize the adversary, they may intentionally use the stolen material as a weapon to produce; RDD or Radiological Emitting Device (RED) that could be used to cause maximum harm to the people and environment. It must be noted that the conversion program only reduces the enrichment in fuel but does not mitigate unauthorized access or damage to, and loss, theft or unauthorized transfer of radioactive sources. There the establishment of facility protection must come alongside the program to prevent the threat of unauthorized access by both insider and outsiders. A graded approach to prevent and protect against the insider was developed by the IAEA as shown in (Figure 5.3).

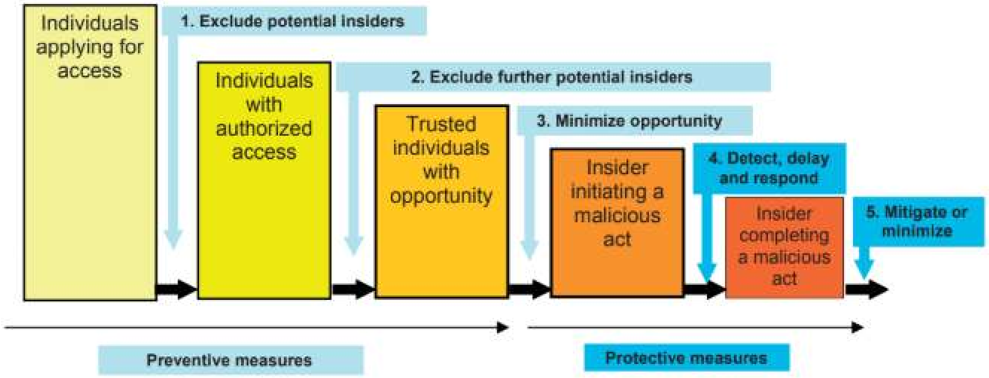


Figure 5.3. The IAEA graded approach for preventing and protecting against insiders

Source: [94]

5.6 Adversary Sequence Diagram

The security risk assessment and evaluation techniques for the hypothetical facility design in (Figure 5.4) was carried out using with the concept of adversary path to model the PPS, the assessment considered the fact that adversary from outside will transverse several layers of security.

The design breakdown echoed on timely identification of clandestine activities and the needed detection as well as delay elements up to the time when the guards must respond to interrupt as well as call for external backup if there is need for intervention before the adversary gets to the target. In addition, early detection elements were considered near the perimeter fence while equally adding delay elements near the target. (Figure 5.5) represents the timeline for an adversary to complete task (T_c) as well as the timeline for the facility protection system to be activated against the adversary (T_I). In this design, detection and response time is expected to be less than time it will take the adversary to complete any task through the Most Vulnerable Path (MVP). Beside this the PPS system must be such that can delay adversary timeline as soon as the first alarm (T_o) is heard and assessed (T_A). All actions and consequences are ranked and represented as the risk equation [95]. The ranking system is accomplished by accumulating the probabilities of all timely detection elements along a path and referred to as the probability of interruption (P_I). Consequently, all detection must occur before the Critical Detection Point (CDP), which is the point where the last timely detection element is located before an adversary completes action. Respectively, each of the elements is associated with a probability of detection as well as a non-detection probability represented by equation 5.4.

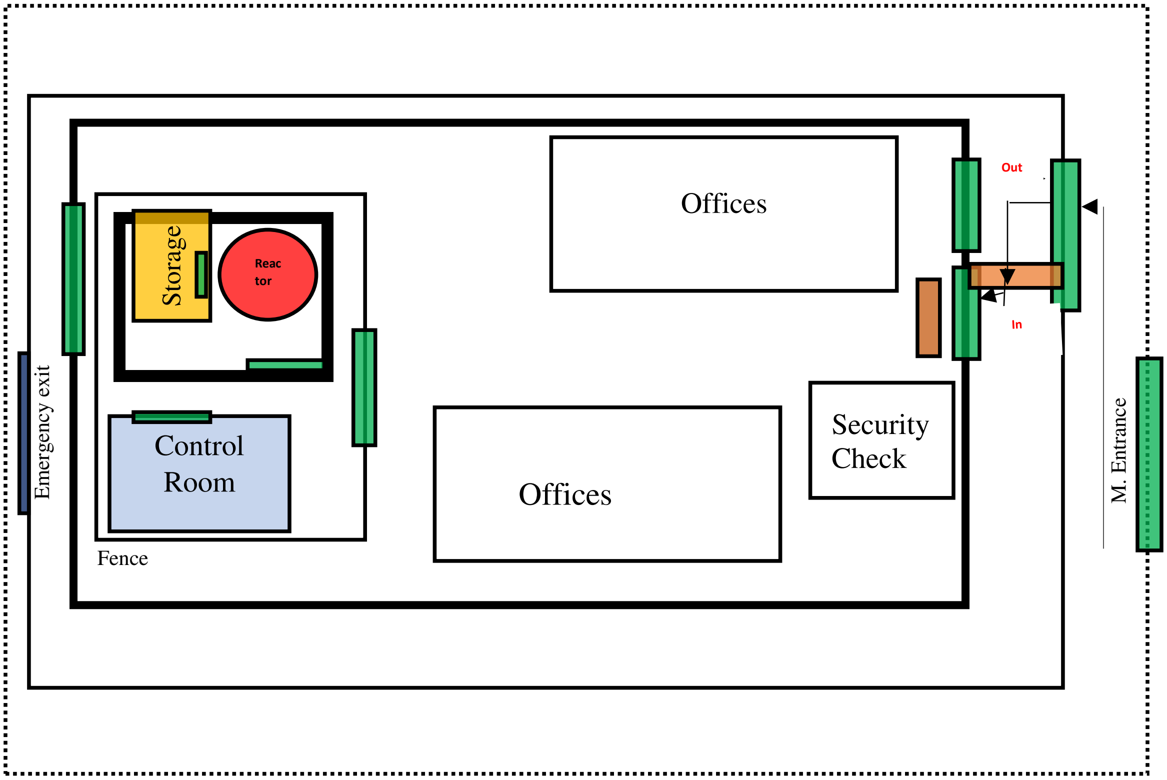


Figure 5.4. Hypothetical reactor layout design

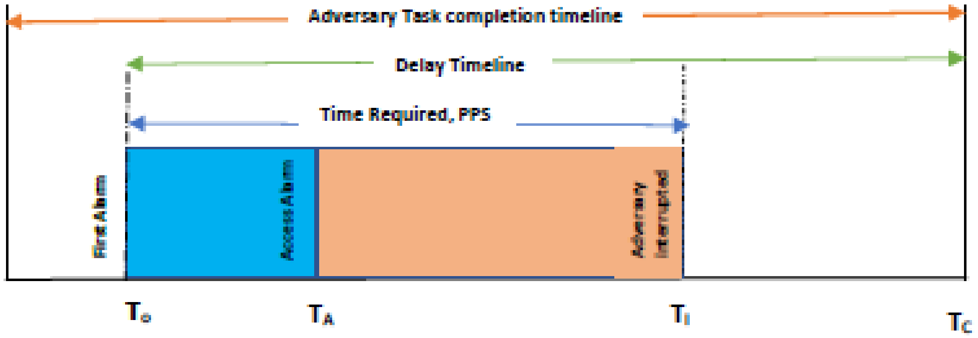


Figure 5.5. Adversary Task completion timeline

Source: [95]

$$\beta_D^j = 1 - P_D^j \qquad \textit{equation 5.4}$$

where,

β_D^j = Non-detection probability of each detection element

Equally, there is the probability that an adversary will not be detected all the numerus independent elements before the timeline, T_c either by a system breakdown or evasion. The probabilities or product of this non-detection for those elements

$$\beta_D = \prod_{j=1}^{J} \beta_D^j \qquad \textit{equation 5.6}$$

For a well-designed PPS, the probability of interruption (P_I) is represented by:

$$P_I = 1 - \beta_D \qquad \textit{equation 5.7}$$

From equation 5.7, the risk to the facility can be derived from applying equation 5.8 when

$$R = P_A\ (1 - P_I\ P_N\ )C \qquad \textit{equation 5.8}$$

where

- P_A is the probability that an adversary will attack a facility along a path,
- P_I is the probability of interruption of the adversary along that path,
- P_N is the probability of neutralization given that we have interrupted the adversary in a timely manner, and
- C is the consequence of adversary success

Adequate level of security systems must be placed on all critical infrastructure using a multilayered combination of human and material resources [96] to protect assets. Such design may employ the use of modeling and simulation tools in a way that brings together various elements of security system to achieve desired result [97]. Several organizations including the US DOE has employed the use of simulation tools like the Estimate of Adversary Sequence Interruption (EASI) and other software to develop as well as evaluate attack scenarios as a means of assessment of facility PPS [98]

According to the IAEA [99], physical protection system must be designed to protect all nuclear facilities, radioactive materials, and services as well as any critical infrastructures from consequences of unwarranted acts of sabotage. But the design must consider very clearly and succinctly the understanding of all threat, vulnerabilities, likely adversary both within (insider) or from outside of the facility. As well, the design must convey the ability to detect, delay and response including the requisite emergency plans to mitigate the challenges that may arise from such malicious actions.

This research exploited the quantitative method of analyzing the combination of probability of delay, detection and response designed with 95% statistical degree of confidence to evaluate the effectiveness of the PPS for the hypothetical facility in (Figure 5.4) using the EASI software was designed by the Sandia National Laboratory to evaluate PPS design by proving scenarios of path and conditions of vulnerability as well as threat within a facility [95]. In view of the heat map of terrorist attacks shown in (Figure 5.2) as well as the threat and capability table of non-state actors in (Table 5.4), a sequence of nine adversary layered event was developed using the hypothetical facility in (Figure 5.4) as shown in (Figure 5.6).

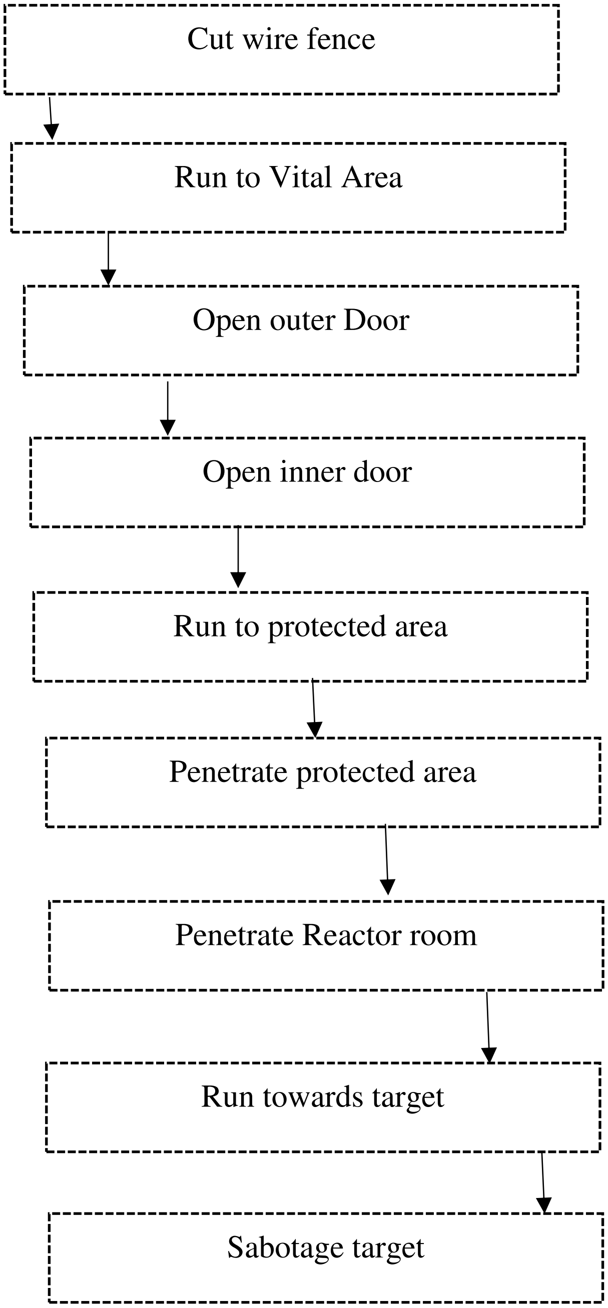
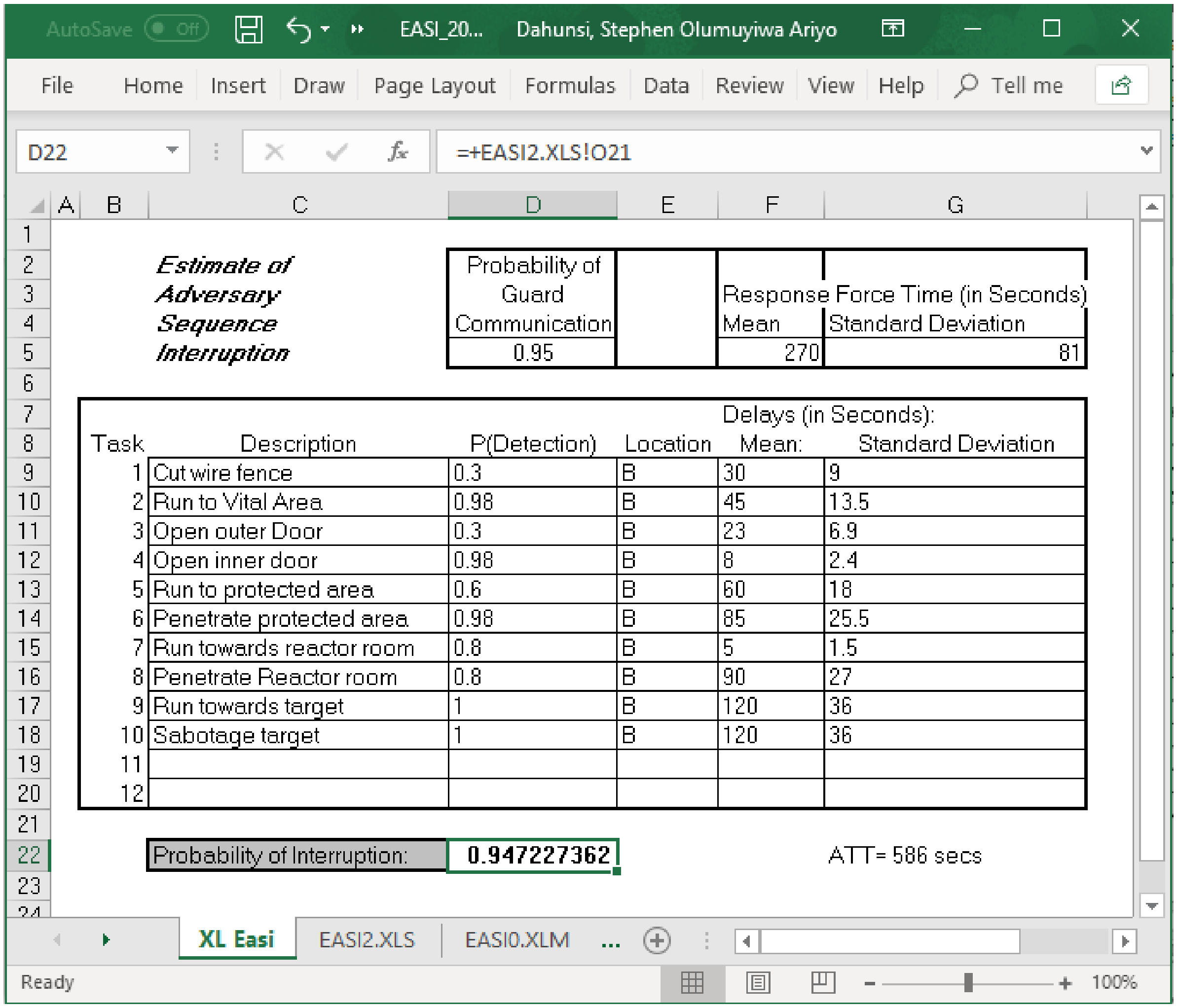


Figure 5.6. Sequence and adversary path layer of event for hypothetical facility

The evaluation of the facility PPS sequence of nine adversary layered event was carried out in two scenarios; (i) an adversary working without any assistance from an insider and (ii) an adversary assisted by an insider. The model was designed to achieve a 95% statistical degree of confidence of effectiveness of guard's communication after the first alarm is received, equally the response force time (RFT) was set at 270 seconds limit to intercept adversary actions. In addition, the EASI design uses an estimated ± 30% standard deviation for each mean value. (Figure 5.7) describes the scenario without any insider collusion and from the result obtained using the EASI model, the probability of interruption (P_I) obtained was 0.9472. From the design, the total response force time used in the design was 270 seconds, while the adversary total time was 586 seconds. Based on this PPS, the adversary will be interrupted and neutralized on the 7th path which is the critical detection point (CDP), this is referred to as the point within the system design along the adversary path where the projected delay exceeds the response force time. From this PPS, the time remaining after interruption is the difference between the adversary task time ATT (586) and the response force time (270) is 316 seconds.



D22 =+EASI2.XLS!O21

Estimate of Adversary Sequence Interruption

Probability of Guard Communication		Response Force Time (in Seconds) Mean	Standard Deviation
0.95		270	81

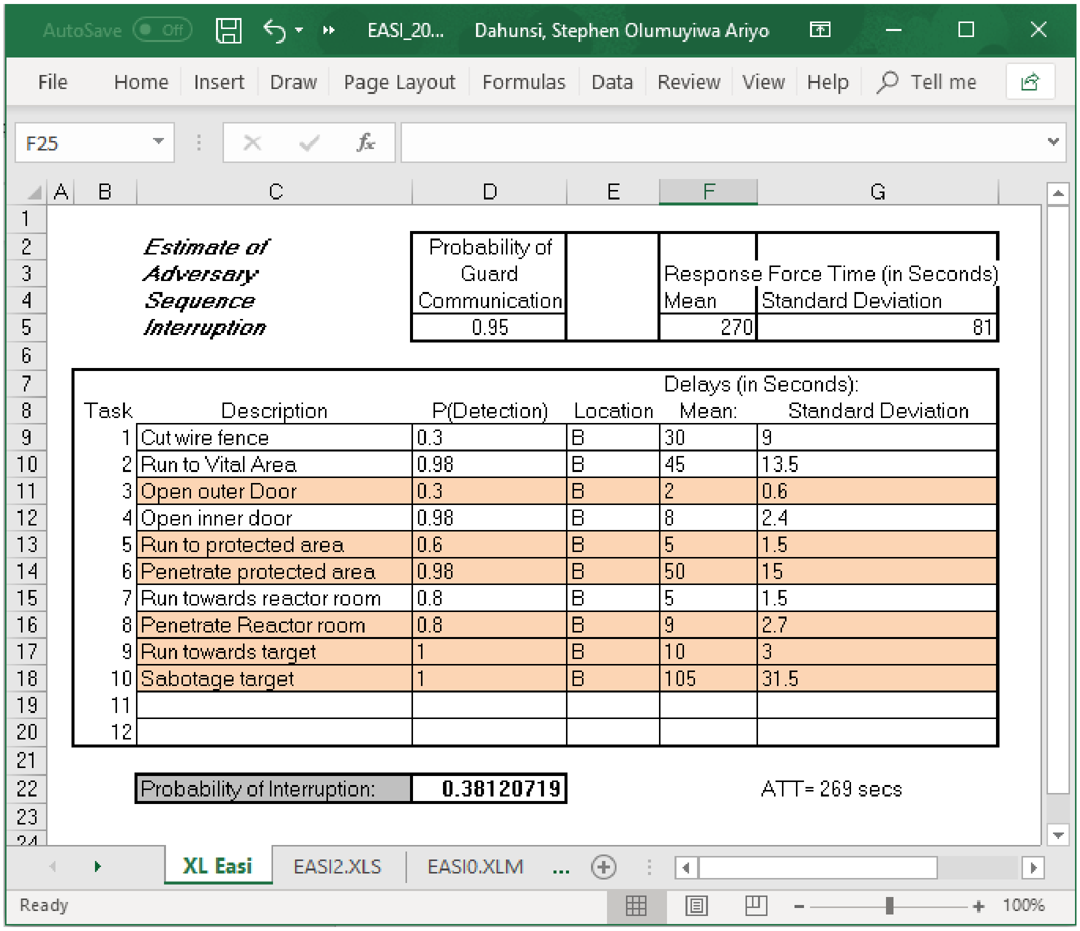
Task	Description	P(Detection)	Location	Delays (in Seconds): Mean:	Standard Deviation
1	Cut wire fence	0.3	B	30	9
2	Run to Vital Area	0.98	B	45	13.5
3	Open outer Door	0.3	B	23	6.9
4	Open inner door	0.98	B	8	2.4
5	Run to protected area	0.6	B	60	18
6	Penetrate protected area	0.98	B	85	25.5
7	Run towards reactor room	0.8	B	5	1.5
8	Penetrate Reactor room	0.8	B	90	27
9	Run towards target	1	B	120	36
10	Sabotage target	1	B	120	36
11					
12					

Probability of Interruption: **0.947227362**

ATT= 586 secs

Figure 5.7. Facility EASI estimate of Probability of Interruption without insider collusion

Consequently, (Figure 5.8) was developed to describe another scenario with insider collusion, it was assumed that the insider collusion adversely affected the effectiveness of the security detection system within the facility. As seen from (Figure 5.8), most delay elements were greatly reduced due to the insider assistance, which gave the adversary an advantage of shorter time to beat the delay systems in place as well as lesser time to reach the target. The adversary total time for Table 5.5 was 269 seconds while the response force time was 270 seconds. Accordingly, since the adversary task time is lesser than the response force time, the probability of interruption (P_I) obtained from the EASI model was 0.3812 which is an indication of an ineffective PPS, hence the response force will not be able to neutralize the adversary.



Estimate of Adversary Sequence Interruption

Probability of Guard Communication	Response Force Time (in Seconds) Mean	Response Force Time (in Seconds) Standard Deviation
0.95	270	81

				Delays (in Seconds):	
Task	Description	P(Detection)	Location	Mean:	Standard Deviation
1	Cut wire fence	0.3	B	30	9
2	Run to Vital Area	0.98	B	45	13.5
3	Open outer Door	0.3	B	2	0.6
4	Open inner door	0.98	B	8	2.4
5	Run to protected area	0.6	B	5	1.5
6	Penetrate protected area	0.98	B	50	15
7	Run towards reactor room	0.8	B	5	1.5
8	Penetrate Reactor room	0.8	B	9	2.7
9	Run towards target	1	B	10	3
10	Sabotage target	1	B	105	31.5
11					
12					

Probability of Interruption: **0.38120719**

ATT= 269 secs

Figure 5.8. Facility EASI estimate of Probability of Interruption with insider collusion

Chapter 6

RESULTS OF ANALYSIS AND HOW IT AFFECTS CONVENTIONAL WISDOM PLANNING, APPROACH, AND OPERATION

The ORIGEN suit of SCALE code was used to generate a wide-ranging radionuclide composition for the plutonium and uranium isotopic composition as well as their corresponding radioactivity. Inventories for three material groups; fission products, actinides including their daughter isotopes. The mass in gram and activities in curies were tracked and documented. From the result as well, a 3-D image for the core of the reactor was generated.

As a first step in this study, SCALE code was developed from an existing MCNP input for the study and evaluation of the HEU core performance as well as the corresponding LEU replacement fuel. The plutonium balance in both the HEU and LEU simulated core were analyzed to predict the extent of weapon-usable materials that will be left in the spent fuel after some predetermined Effective Full Power Day (EFPD). The rated power obtained from the safety analysis report (SAR) were used in the simulation for both the HEU and the LEU core 30 KW and 34 KW respectfully. Equally obtained from the SAR was the choice of UO_2 Zircaloy fuel replacement at 12.5% enrichment. However, the input to the SCALE has a flexibility of modification depending on the enrichment level of choice for further simulation. From the result obtained from the simulation which is further discussed later in this chapter, the quantity of plutonium produced at lower enrichment in the global evaluation of the non-proliferation in research and test reactors should be revisited if the for all purpose and intent, the conversion program is set to achieve the objectives set forward.

A characteristic assessment to evaluate the technical and safety risk was developed using neutronic model derived from the unit cell/rod design shown in (Figure 6.1 and 6.2). The reactor burnup was carried out the TRITON depletion model to determine and estimate the fission products and the actinides, above all the materials classified as special nuclear materials (SNM) that are important to production of weapon-usable material of any type and form

The results obtained for seven days TRITON RUN from a unit rod showed that the quantity of plutonium was more at higher nominal power. From the result, it can be observed that; for all intent and purpose, risk evaluation restricted to reduced enrichment in all test and research reactor is not complete not minding the additional vulnerabilities assessment in the type, location and size of facility as well as capabilities of terrorist groups operating near the facility or state that may be seeking nuclear materials.

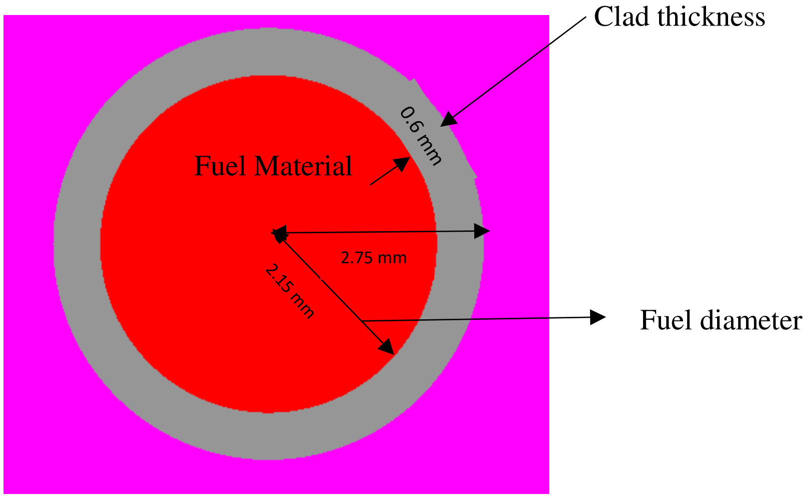


Figure 6.1. Top view of material arrangements in NIRR-1-unit cell

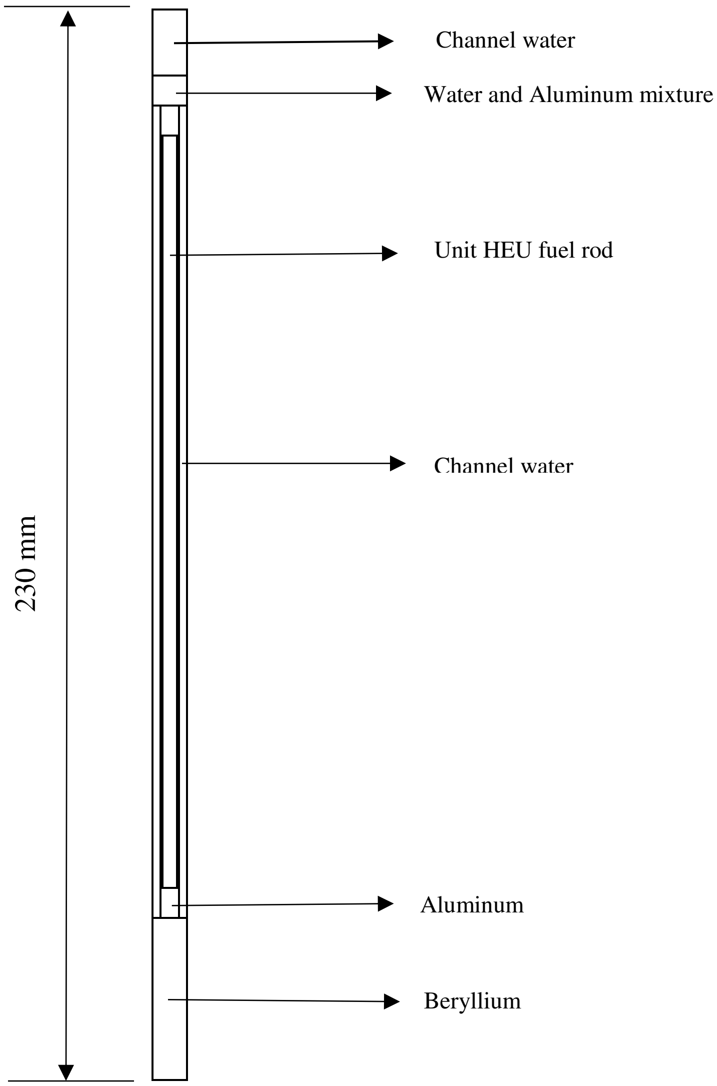


Figure 6.2. Lateral view of simulated NIRR-1unit rod design

Equally, the 3-D model of the NIRR-1 developed with the GeeWiz is shown in (Figure 6.3) while (Figure 6.4) is the 3-D model of the core surrounded by the beryllium reflector as well as the upper beryllium shim plate and the lower or bottom beryllium reflector slab.

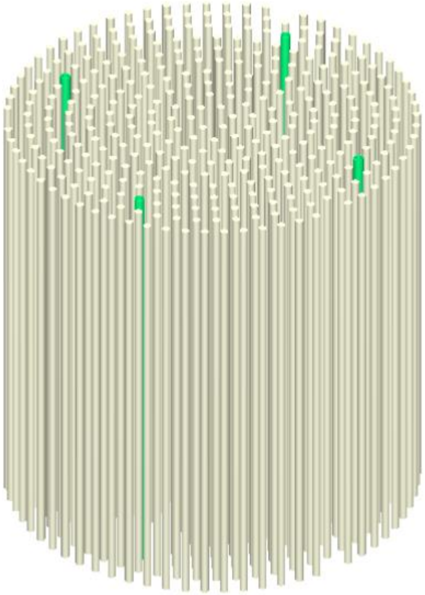


Figure 6.3. 3-D model of NIRR core with SCALE/GeeWiz

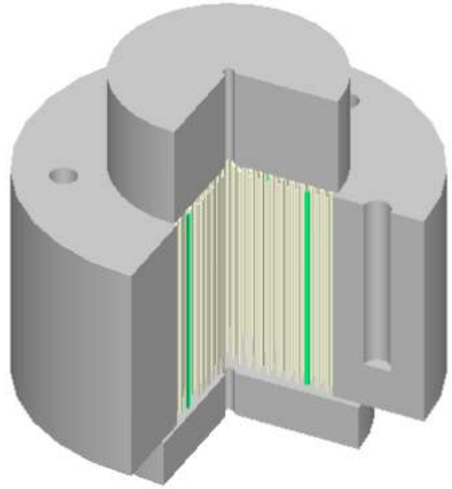


Figure 6.4. 3-D model of NIRR-1 with SCALE/GeeWiz

6.1.1 NIRR-1 burnup and activity related to risk

The initial result from the unit rod burnup was used to investigate the amount and specific activity of selected nuclides of uranium and plutonium isotopes at the end of variable predetermined years of burnup. According to Mark et al [100], critical mass of any reactor grade plutonium metal after discharge is more reactive than any weapon grade uranium. For every weapon grade material, it is expected that a certain amount of isotope composition of plutonium is present as highlighted in (Table 6.1) [100]. Subsequently, for safeguards, it is expected that any measured level above the facility or levels should draw the attention of the state regulators or the IAEA.

Table 6.1. Estimated plutonium isotopic composition in weapon grade materials

Grade	Isotope				
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Super-grade		0.98	0.02	-	-
Weapon-grade	0.00012	0.938	0.058	0.0035	0.00022
Reactor-grade	0.013	0.603	0.243	0.091	0.050
MOX-grade	0.019	0.404	0.321	0.178	0.078
FBR blanket	-	0.96	0.04	-	-

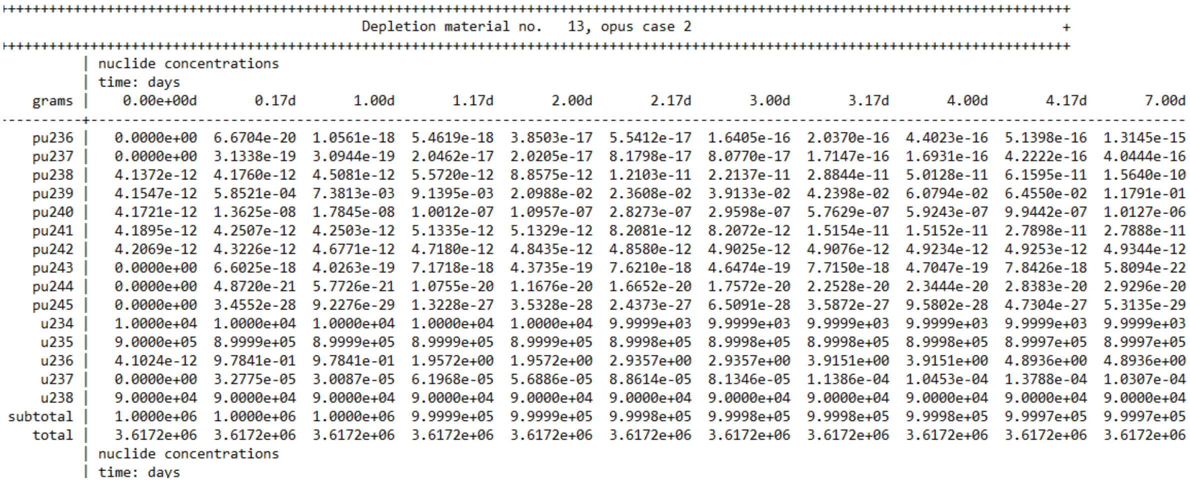
Source: [100]

The manufacture of a nuclear weapon may be quite expensive [101], production of nuclear explosives takes about 35 pounds of ^{235}U or 9 pounds of ^{239}Pu [102]. It takes more effort to produce, but not as much to invade by terrorist or disperse radioactive materials. Besides, ^{239}Pu is widely considered by the public to be the worst of all transmutation products with half-life of up to 24,100 years. The element emits an alpha radiation which is very highly ionizing. It is produced in nuclear reactor by neutron capture of ^{238}U [100] continuously irrespective of the level of enrichment.

Risk from the radiotoxic elements were quantified by simulating the quantities in grams and curies of the nuclides of uranium and plutonium isotopes from the decay and production of nuclides for seven days to identify the most weapon-usable materials that can be produced per operational time of the NIRR-1 research reactor. As part of the IAEA requirements for peaceful application of nuclear technologies, it is required that states prevent the malicious use of nuclear materials under the "prudent management practices" as well as encourages the classification of materials with respect to element, isotope, quantity and irradiation [68].

This will be a valuable information required by the IAEA as part of declaration and safeguards verification. In addition, it will be valuable for evaluation of risk considering all identified vulnerabilities, security and safeguards. As well, (Figure 6.5 and 6.8) results were obtained for quantity in grams (g) as well as the specific activity in curies (ci) respectfully, the activity obtained in (Figure 6.8) is important for planning emergency and the inherent in the accidental or deliberate dispersal of such material.

The nuclide concentration of both the HEU and the LEU were simulated for a week worth operation of approximately 2.5 hours of operation per day. The average burnup from the simulated result was 0.021 GW/MTIHM for the HEU while that obtained for LEU was 0.014.



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+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                                                              Depletion material no.   13, opus case 2                                                             +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
          | nuclide concentrations
          | time: days
    grams |   0.00e+00d       0.17d       1.00d       1.17d       2.00d       2.17d       3.00d       3.17d       4.00d       4.17d       7.00d
----------+-----------------------------------------------------------------------------------------------------------------------------------
    pu236 |  0.0000e+00  6.6704e-20  1.0561e-18  5.4619e-18  3.8503e-17  5.5412e-17  1.6405e-16  2.0370e-16  4.4023e-16  5.1398e-16  1.3145e-15
    pu237 |  0.0000e+00  3.1338e-19  3.0944e-19  2.0462e-17  2.0205e-17  8.1798e-17  8.0770e-17  1.7147e-16  1.6931e-16  4.2222e-16  4.0444e-16
    pu238 |  4.1372e-12  4.1760e-12  4.5081e-12  5.5720e-12  8.8575e-12  1.2103e-11  2.2137e-11  2.8844e-11  5.0128e-11  6.1595e-11  1.5640e-10
    pu239 |  4.1547e-12  5.8521e-04  7.3813e-03  9.1395e-03  2.0988e-02  2.3608e-02  3.9133e-02  4.2398e-02  6.0794e-02  6.4550e-02  1.1791e-01
    pu240 |  4.1721e-12  1.3625e-08  1.7845e-08  1.0012e-07  1.0957e-07  2.8273e-07  2.9598e-07  5.7629e-07  5.9243e-07  9.9442e-07  1.0127e-06
    pu241 |  4.1895e-12  4.2507e-12  4.2503e-12  5.1335e-12  5.1329e-12  8.2081e-12  8.2072e-12  1.5154e-11  1.5152e-11  2.7898e-11  2.7888e-11
    pu242 |  4.2069e-12  4.3226e-12  4.6771e-12  4.7180e-12  4.8435e-12  4.8580e-12  4.9025e-12  4.9076e-12  4.9234e-12  4.9253e-12  4.9344e-12
    pu243 |  0.0000e+00  6.6025e-18  4.0263e-19  7.1718e-18  4.3735e-19  7.6210e-18  4.6474e-19  7.7150e-18  4.7047e-19  7.8426e-18  5.8094e-22
    pu244 |  0.0000e+00  4.8720e-21  5.7726e-21  1.0755e-20  1.1676e-20  1.6652e-20  1.7572e-20  2.2528e-20  2.3444e-20  2.8383e-20  2.9296e-20
    pu245 |  0.0000e+00  3.4552e-28  9.2276e-29  1.3228e-27  3.5328e-28  2.4373e-27  6.5091e-28  3.5872e-27  9.5802e-28  4.7304e-27  5.3135e-29
     u234 |  1.0000e+04  1.0000e+04  1.0000e+04  1.0000e+04  1.0000e+04  9.9999e+03  9.9999e+03  9.9999e+03  9.9999e+03  9.9999e+03  9.9999e+03
     u235 |  9.0000e+05  8.9999e+05  8.9999e+05  8.9999e+05  8.9999e+05  8.9998e+05  8.9998e+05  8.9998e+05  8.9998e+05  8.9997e+05  8.9997e+05
     u236 |  4.1024e-12  9.7841e-01  9.7841e-01  1.9572e+00  1.9572e+00  2.9357e+00  2.9357e+00  3.9151e+00  3.9151e+00  4.8936e+00  4.8936e+00
     u237 |  0.0000e+00  3.2775e-05  3.0087e-05  6.1968e-05  5.6886e-05  8.8614e-05  8.1346e-05  1.1386e-04  1.0453e-04  1.3788e-04  1.0307e-04
     u238 |  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04  9.0000e+04
 subtotal |  1.0000e+06  1.0000e+06  1.0000e+06  9.9999e+05  9.9999e+05  9.9998e+05  9.9998e+05  9.9998e+05  9.9998e+05  9.9997e+05  9.9997e+05
    total |  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06  3.6172e+06
          | nuclide concentrations
          | time: days
```

Figure 6.5. List of selected nuclides volumetric concentration (g) (unit rod HEU)

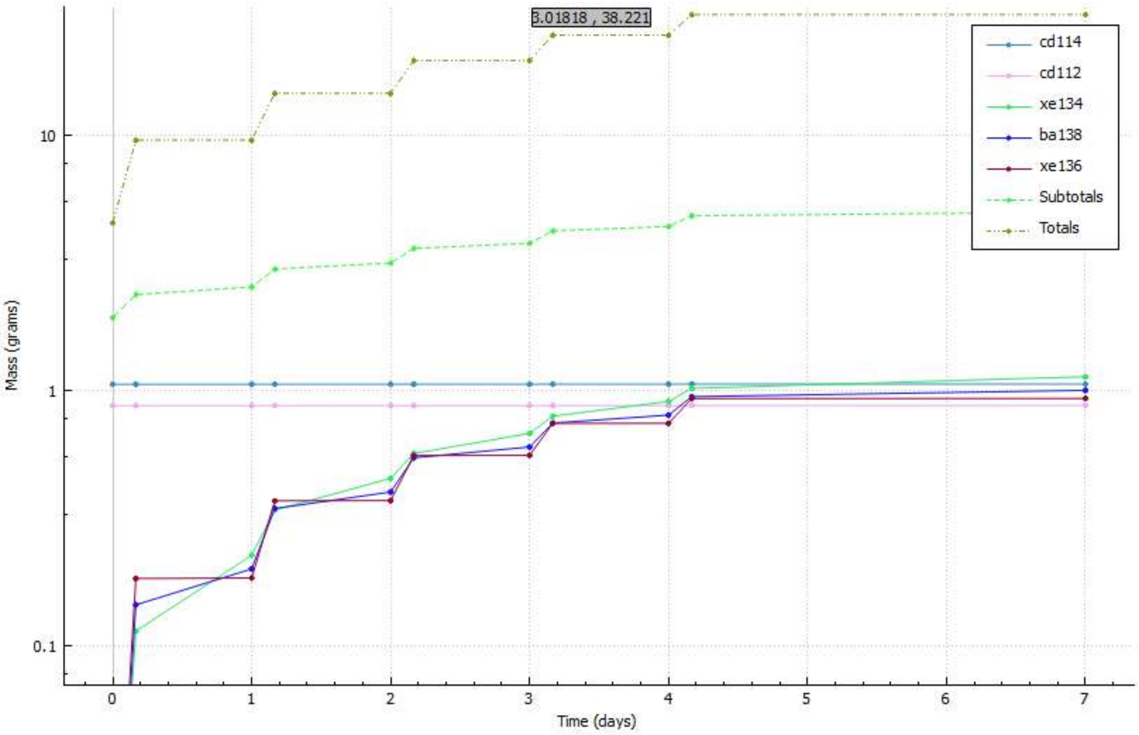


Figure 6.6. Fission products after seven day (g) (unit rod HEU)

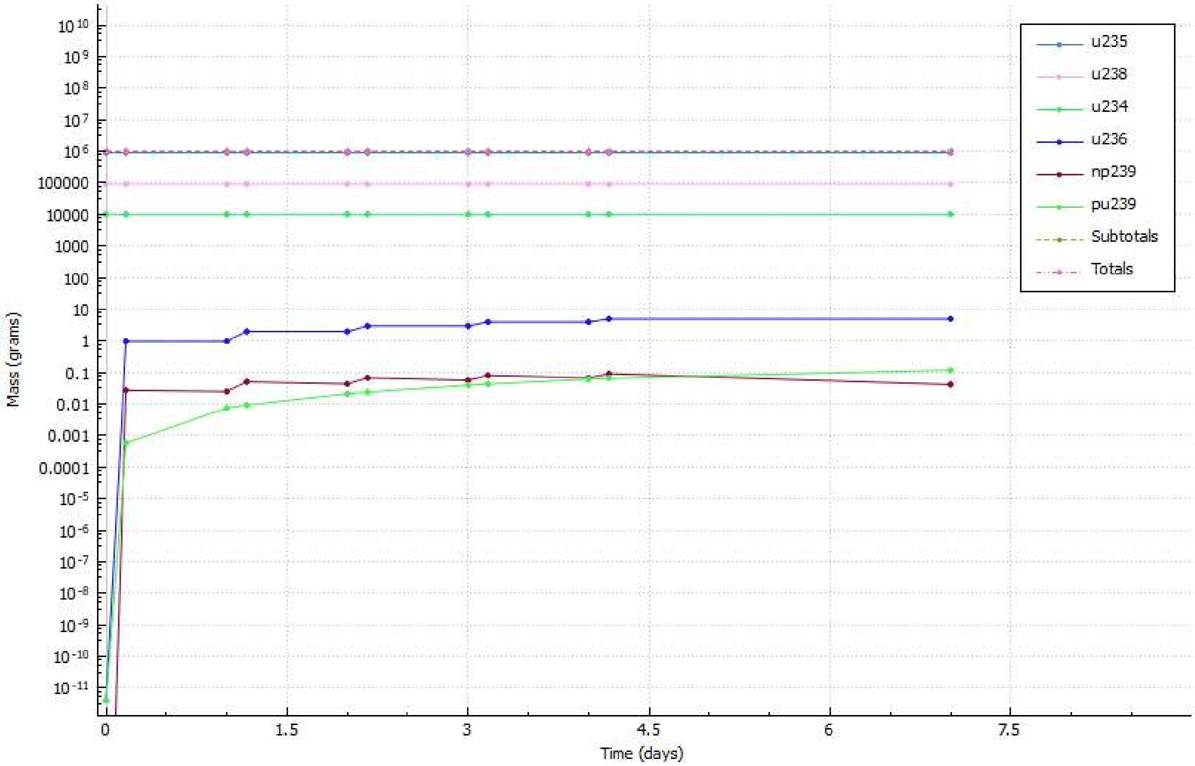
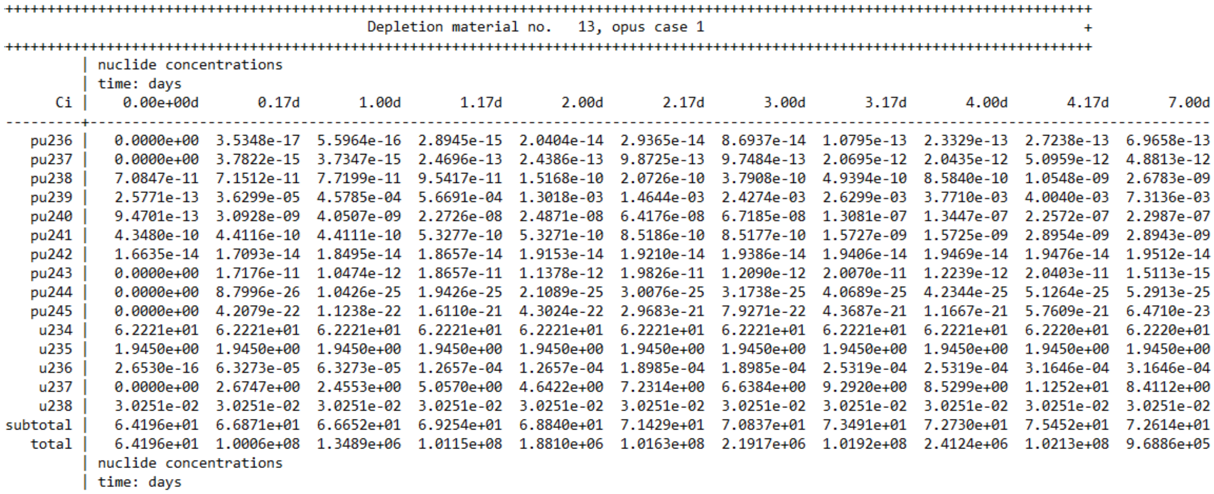


Figure 6.7. Actinides elements after seven day (g) (unit rod HEU)



```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                                           Depletion material no.   13, opus case 1                                             +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
         | nuclide concentrations
         | time: days
      Ci |    0.00e+00d        0.17d        1.00d        1.17d        2.00d        2.17d        3.00d        3.17d        4.00d        4.17d        7.00d
---------+-----------------------------------------------------------------------------------------------------------------------------------------
   pu236 |   0.0000e+00  3.5348e-17  5.5964e-16  2.8945e-15  2.0404e-14  2.9365e-14  8.6937e-14  1.0795e-13  2.3329e-13  2.7238e-13  6.9658e-13
   pu237 |   0.0000e+00  3.7822e-15  3.7347e-15  2.4696e-13  2.4386e-13  9.8725e-13  9.7484e-13  2.0695e-12  2.0435e-12  5.0959e-12  4.8813e-12
   pu238 |   7.0847e-11  7.1512e-11  7.7199e-11  9.5417e-11  1.5168e-10  2.0726e-10  3.7908e-10  4.9394e-10  8.5840e-10  1.0548e-09  2.6783e-09
   pu239 |   2.5771e-13  3.6299e-05  4.5785e-04  5.6691e-04  1.3018e-03  1.4644e-03  2.4274e-03  2.6299e-03  3.7710e-03  4.0040e-03  7.3136e-03
   pu240 |   9.4701e-13  3.0928e-09  4.0507e-09  2.2726e-08  2.4871e-08  6.4176e-08  6.7185e-08  1.3081e-07  1.3447e-07  2.2572e-07  2.2987e-07
   pu241 |   4.3480e-10  4.4116e-10  4.4111e-10  5.3277e-10  5.3271e-10  8.5186e-10  8.5177e-10  1.5727e-09  1.5725e-09  2.8954e-09  2.8943e-09
   pu242 |   1.6635e-14  1.7093e-14  1.8495e-14  1.8657e-14  1.9153e-14  1.9210e-14  1.9386e-14  1.9406e-14  1.9469e-14  1.9476e-14  1.9512e-14
   pu243 |   0.0000e+00  1.7176e-11  1.0474e-12  1.8657e-11  1.1378e-12  1.9826e-11  1.2090e-12  2.0070e-11  1.2239e-12  2.0403e-11  1.5113e-15
   pu244 |   0.0000e+00  8.7996e-26  1.0426e-25  1.9426e-25  2.1089e-25  3.0076e-25  3.1738e-25  4.0689e-25  4.2344e-25  5.1264e-25  5.2913e-25
   pu245 |   0.0000e+00  4.2079e-22  1.1238e-22  1.6110e-21  4.3024e-22  2.9683e-21  7.9271e-22  4.3687e-21  1.1667e-21  5.7609e-21  6.4710e-23
    u234 |   6.2221e+01  6.2221e+01  6.2221e+01  6.2221e+01  6.2221e+01  6.2221e+01  6.2221e+01  6.2221e+01  6.2221e+01  6.2220e+01  6.2220e+01
    u235 |   1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00  1.9450e+00
    u236 |   2.6530e-16  6.3273e-05  6.3273e-05  1.2657e-04  1.2657e-04  1.8985e-04  1.8985e-04  2.5319e-04  2.5319e-04  3.1646e-04  3.1646e-04
    u237 |   0.0000e+00  2.6747e+00  2.4553e+00  5.0570e+00  4.6422e+00  7.2314e+00  6.6384e+00  9.2920e+00  8.5299e+00  1.1252e+01  8.4112e+00
    u238 |   3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02  3.0251e-02
subtotal |   6.4196e+01  6.6871e+01  6.6652e+01  6.9254e+01  6.8840e+01  7.1429e+01  7.0837e+01  7.3491e+01  7.2730e+01  7.5452e+01  7.2614e+01
   total |   6.4196e+01  1.0006e+08  1.3489e+06  1.0115e+08  1.8810e+06  1.0163e+08  2.1917e+06  1.0192e+08  2.4124e+06  1.0213e+08  9.6886e+05
         | nuclide concentrations
         | time: days
```

Figure 6.8. List of selected nuclides concentration (Ci) (unit rod HEU)

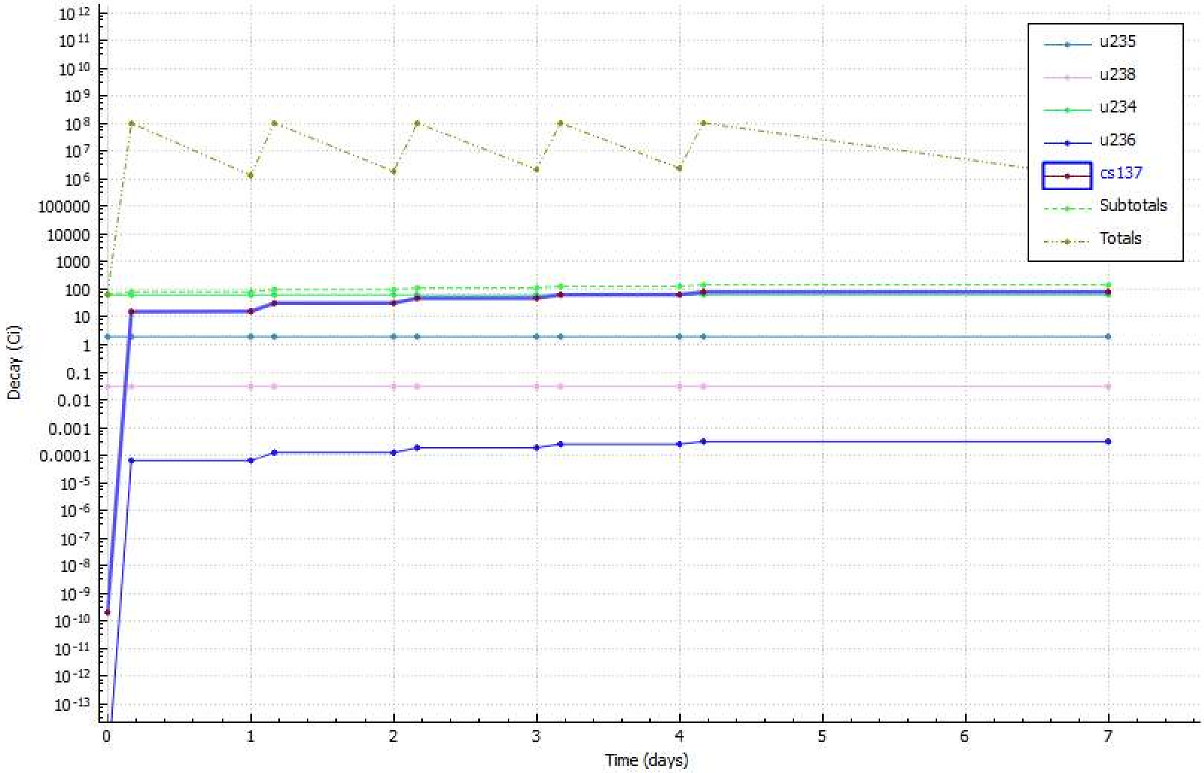
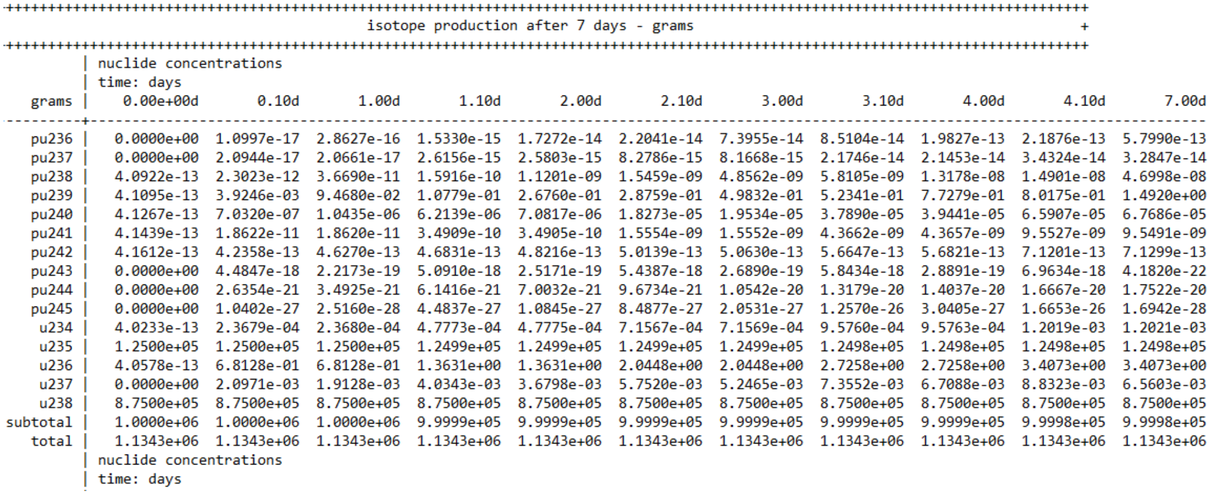


Figure 6.9. Seven days operational decay (unit rod, HEU)



```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                                              isotope production after 7 days - grams                                             +
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
         | nuclide concentrations
         | time: days
   grams |   0.00e+00d       0.10d       1.00d       1.10d       2.00d       2.10d       3.00d       3.10d       4.00d       4.10d       7.00d
---------+-----------------------------------------------------------------------------------------------------------------------------------
   pu236 |  0.0000e+00  1.0997e-17  2.8627e-16  1.5330e-15  1.7272e-14  2.2041e-14  7.3955e-14  8.5104e-14  1.9827e-13  2.1876e-13  5.7990e-13
   pu237 |  0.0000e+00  2.0944e-17  2.0661e-17  2.6156e-15  2.5803e-15  8.2786e-15  8.1668e-15  2.1746e-14  2.1453e-14  3.4324e-14  3.2847e-14
   pu238 |  4.0922e-13  2.3023e-12  3.6690e-11  1.5916e-10  1.1201e-09  1.5459e-09  4.8562e-09  5.8105e-09  1.3178e-08  1.4901e-08  4.6998e-08
   pu239 |  4.1095e-13  3.9246e-03  9.4680e-02  1.0779e-01  2.6760e-01  2.8759e-01  4.9832e-01  5.2341e-01  7.7279e-01  8.0175e-01  1.4920e+00
   pu240 |  4.1267e-13  7.0320e-07  1.0435e-06  6.2139e-06  7.0817e-06  1.8273e-05  1.9534e-05  3.7890e-05  3.9441e-05  6.5907e-05  6.7686e-05
   pu241 |  4.1439e-13  1.8622e-11  1.8620e-11  3.4909e-10  3.4905e-10  1.5554e-09  1.5552e-09  4.3662e-09  4.3657e-09  9.5527e-09  9.5491e-09
   pu242 |  4.1612e-13  4.2358e-13  4.6270e-13  4.6831e-13  4.8216e-13  5.0139e-13  5.0630e-13  5.6647e-13  5.6821e-13  7.1201e-13  7.1299e-13
   pu243 |  0.0000e+00  4.4847e-18  2.2173e-19  5.0910e-18  2.5171e-19  5.4387e-18  2.6890e-19  5.8434e-18  2.8891e-19  6.9634e-18  4.1820e-22
   pu244 |  0.0000e+00  2.6354e-21  3.4925e-21  6.1416e-21  7.0032e-21  9.6734e-21  1.0542e-20  1.3179e-20  1.4037e-20  1.6667e-20  1.7522e-20
   pu245 |  0.0000e+00  1.0402e-27  2.5160e-28  4.4837e-27  1.0845e-27  8.4877e-27  2.0531e-27  1.2570e-26  3.0405e-27  1.6653e-26  1.6942e-28
    u234 |  4.0233e-13  2.3679e-04  2.3680e-04  4.7773e-04  4.7775e-04  7.1567e-04  7.1569e-04  9.5760e-04  9.5763e-04  1.2019e-03  1.2021e-03
    u235 |  1.2500e+05  1.2500e+05  1.2500e+05  1.2499e+05  1.2499e+05  1.2499e+05  1.2499e+05  1.2498e+05  1.2498e+05  1.2498e+05  1.2498e+05
    u236 |  4.0578e-13  6.8128e-01  6.8128e-01  1.3631e+00  1.3631e+00  2.0448e+00  2.0448e+00  2.7258e+00  2.7258e+00  3.4073e+00  3.4073e+00
    u237 |  0.0000e+00  2.0971e-03  1.9128e-03  4.0343e-03  3.6798e-03  5.7520e-03  5.2465e-03  7.3552e-03  6.7088e-03  8.8323e-03  6.5603e-03
    u238 |  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05  8.7500e+05
subtotal |  1.0000e+06  1.0000e+06  1.0000e+06  9.9999e+05  9.9999e+05  9.9999e+05  9.9999e+05  9.9999e+05  9.9999e+05  9.9998e+05  9.9998e+05
   total |  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06  1.1343e+06
         | nuclide concentrations
         | time: days
```

Figure 6.10. List of selected nuclides volumetric concentration (g) (unit rod LEU)

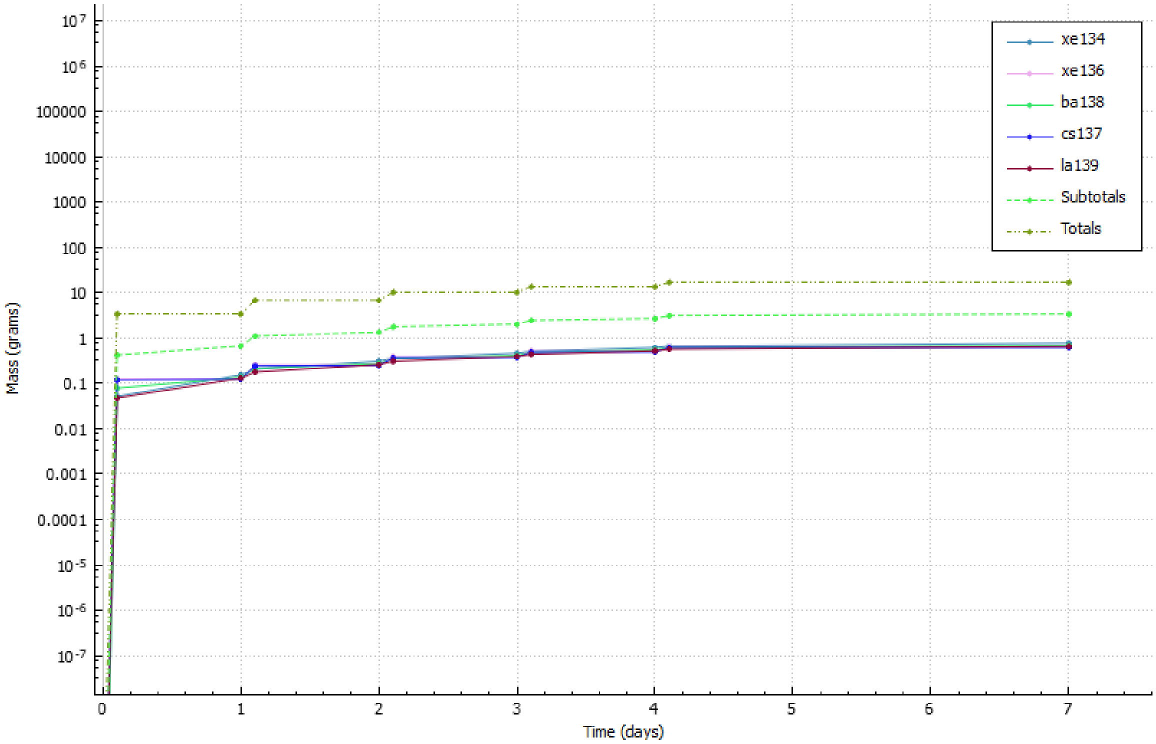


Figure 6.11. *Fission products after seven day (g) (unit rod LEU)*

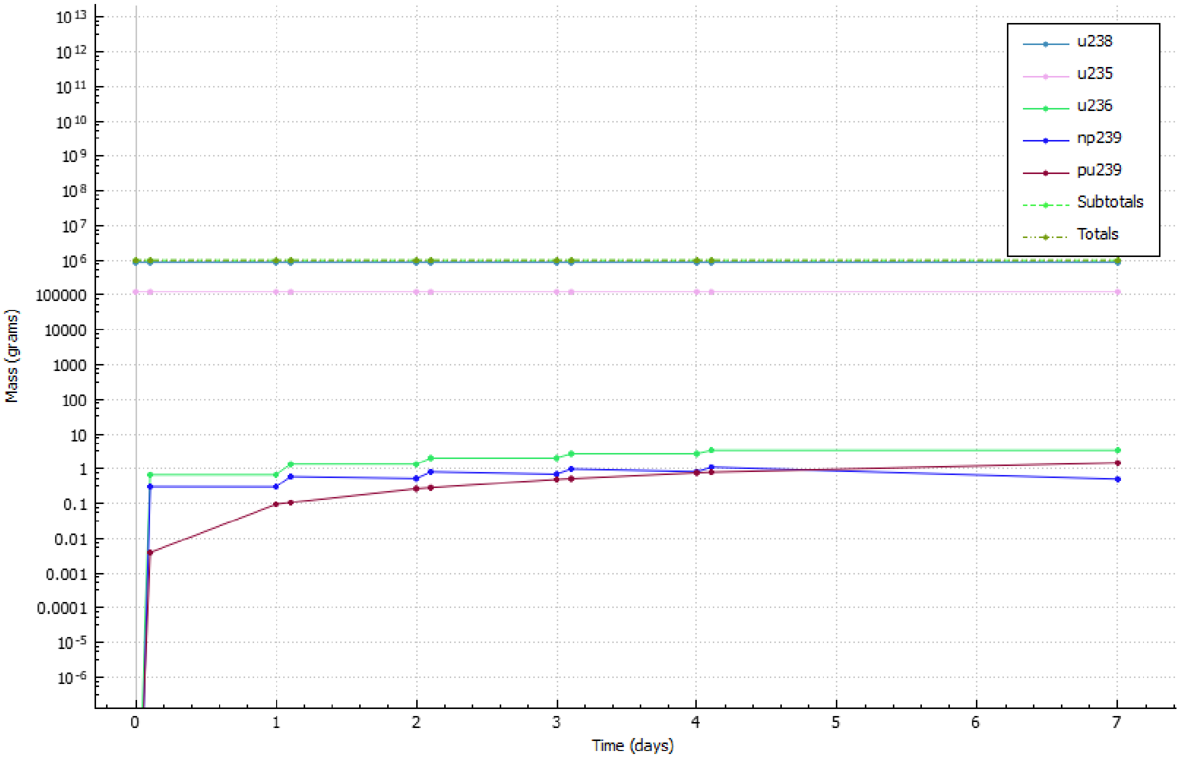


Figure 6.12. Actinides elements after seven day (g) (unit rod LEU)

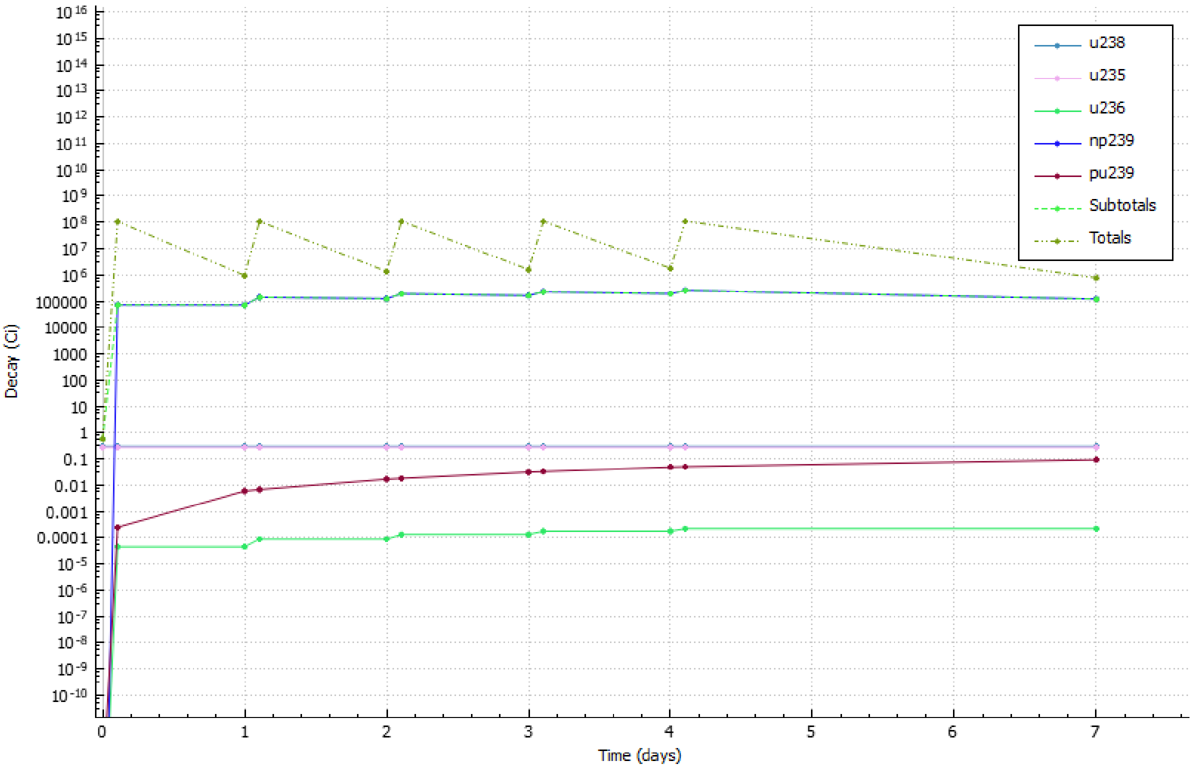
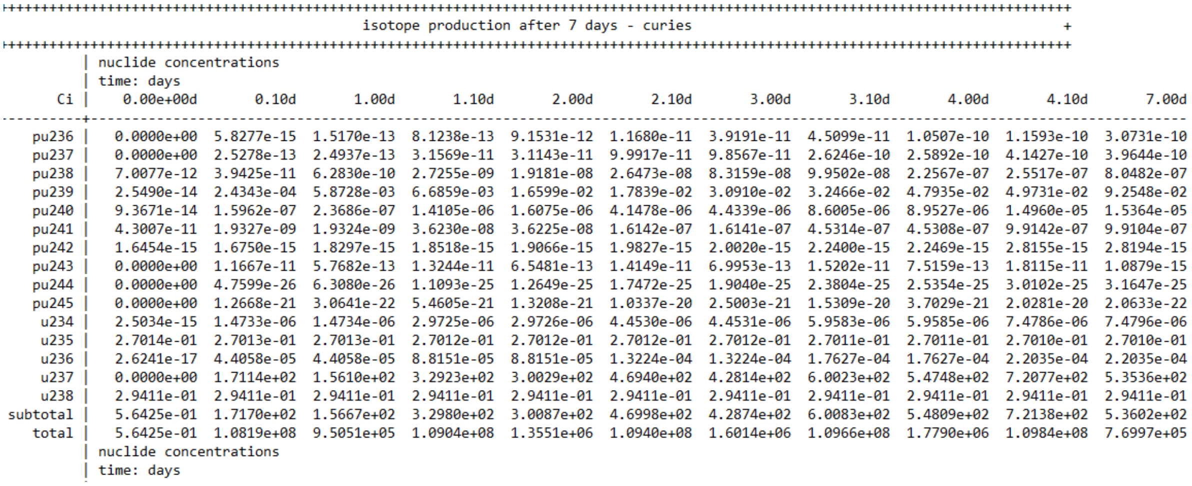


Figure 6.13. Seven days operational radioactive nuclide activity decay (unit rod, LEU)



```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                                        isotope production after 7 days - curies                                     +
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
         | nuclide concentrations
         | time: days
      Ci |   0.00e+00d       0.10d       1.00d       1.10d       2.00d       2.10d       3.00d       3.10d       4.00d       4.10d       7.00d
---------+--------------------------------------------------------------------------------------------------------------------------------------
   pu236 |  0.0000e+00  5.8277e-15  1.5170e-13  8.1238e-13  9.1531e-12  1.1680e-11  3.9191e-11  4.5099e-11  1.0507e-10  1.1593e-10  3.0731e-10
   pu237 |  0.0000e+00  2.5278e-13  2.4937e-13  3.1569e-11  3.1143e-11  9.9917e-11  9.8567e-11  2.6246e-10  2.5892e-10  4.1427e-10  3.9644e-10
   pu238 |  7.0077e-12  3.9425e-11  6.2830e-10  2.7255e-09  1.9181e-08  2.6473e-08  8.3159e-08  9.9502e-08  2.2567e-07  2.5517e-07  8.0482e-07
   pu239 |  2.5490e-14  2.4343e-04  5.8728e-03  6.6859e-03  1.6599e-02  1.7839e-02  3.0910e-02  3.2466e-02  4.7935e-02  4.9731e-02  9.2548e-02
   pu240 |  9.3671e-14  1.5962e-07  2.3686e-07  1.4105e-06  1.6075e-06  4.1478e-06  4.4339e-06  8.6005e-06  8.9527e-06  1.4960e-05  1.5364e-05
   pu241 |  4.3007e-11  1.9327e-09  1.9324e-09  3.6230e-08  3.6225e-08  1.6142e-07  1.6141e-07  4.5314e-07  4.5308e-07  9.9142e-07  9.9104e-07
   pu242 |  1.6454e-15  1.6750e-15  1.8297e-15  1.8518e-15  1.9066e-15  1.9827e-15  2.0020e-15  2.2400e-15  2.2469e-15  2.8155e-15  2.8194e-15
   pu243 |  0.0000e+00  1.1667e-11  5.7682e-13  1.3244e-11  6.5481e-13  1.4149e-11  6.9953e-13  1.5202e-11  7.5159e-13  1.8115e-11  1.0879e-15
   pu244 |  0.0000e+00  4.7599e-26  6.3080e-26  1.1093e-25  1.2649e-25  1.7472e-25  1.9040e-25  2.3804e-25  2.5354e-25  3.0102e-25  3.1647e-25
   pu245 |  0.0000e+00  1.2668e-21  3.0641e-22  5.4605e-21  1.3208e-21  1.0337e-20  2.5003e-21  1.5309e-20  3.7029e-21  2.0281e-20  2.0633e-22
    u234 |  2.5034e-15  1.4733e-06  1.4734e-06  2.9725e-06  2.9726e-06  4.4530e-06  4.4531e-06  5.9583e-06  5.9585e-06  7.4786e-06  7.4796e-06
    u235 |  2.7014e-01  2.7013e-01  2.7013e-01  2.7012e-01  2.7012e-01  2.7012e-01  2.7012e-01  2.7011e-01  2.7011e-01  2.7010e-01  2.7010e-01
    u236 |  2.6241e-17  4.4058e-05  4.4058e-05  8.8151e-05  8.8151e-05  1.3224e-04  1.3224e-04  1.7627e-04  1.7627e-04  2.2035e-04  2.2035e-04
    u237 |  0.0000e+00  1.7114e+02  1.5610e+02  3.2923e+02  3.0029e+02  4.6940e+02  4.2814e+02  6.0023e+02  5.4748e+02  7.2077e+02  5.3536e+02
    u238 |  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01  2.9411e-01
subtotal |  5.6425e-01  1.7170e+02  1.5667e+02  3.2980e+02  3.0087e+02  4.6998e+02  4.2874e+02  6.0083e+02  5.4809e+02  7.2138e+02  5.3602e+02
   total |  5.6425e-01  1.0819e+08  9.5051e+05  1.0904e+08  1.3551e+06  1.0940e+08  1.6014e+06  1.0966e+08  1.7790e+06  1.0984e+08  7.6997e+05
         | nuclide concentrations
         | time: days
```

Figure 6.14. List of selected nuclides concentration (Ci) (unit rod LEU)

The production of isotopes of plutonium in large quantity will be the most significant attributes of any proliferating state. In the simulated output, the quantity of ^{239}Pu balance after 7 days of operation was recorded in both HEU and LEU output. (Figure 6.15) shows the quantity of ^{239}Pu in both HEU and the LEU fuels simulated. Evidently, from the values obtained from the plot, ^{239}Pu balance for LEU fuel was 1.49g while HEU was 0.118g.

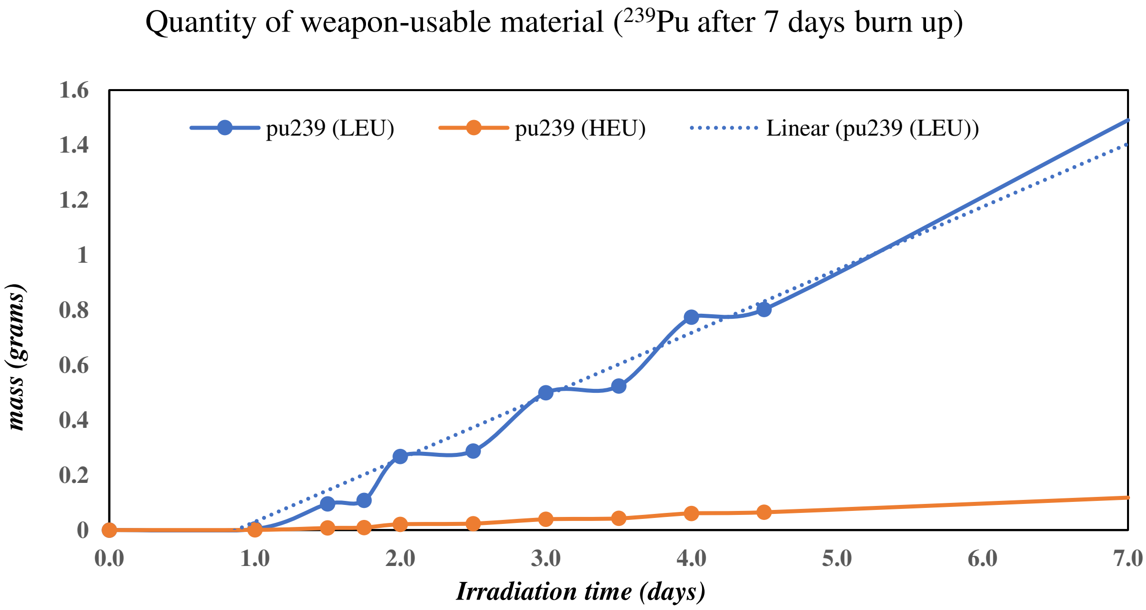


Figure 6.15. Plutonium (^{239}Pu) balance after 7 days burn up HEU versus LEU

Equally, the isotopic quantity of selected uranium and plutonium isotopes for both HEU and the LEU were simulated for 1-year worth operation of approximately 2.5 hours of operation per day for 5 days a week for the three-material groups; fission, actinides and the light elements are highlighted in (Figure 6.22).

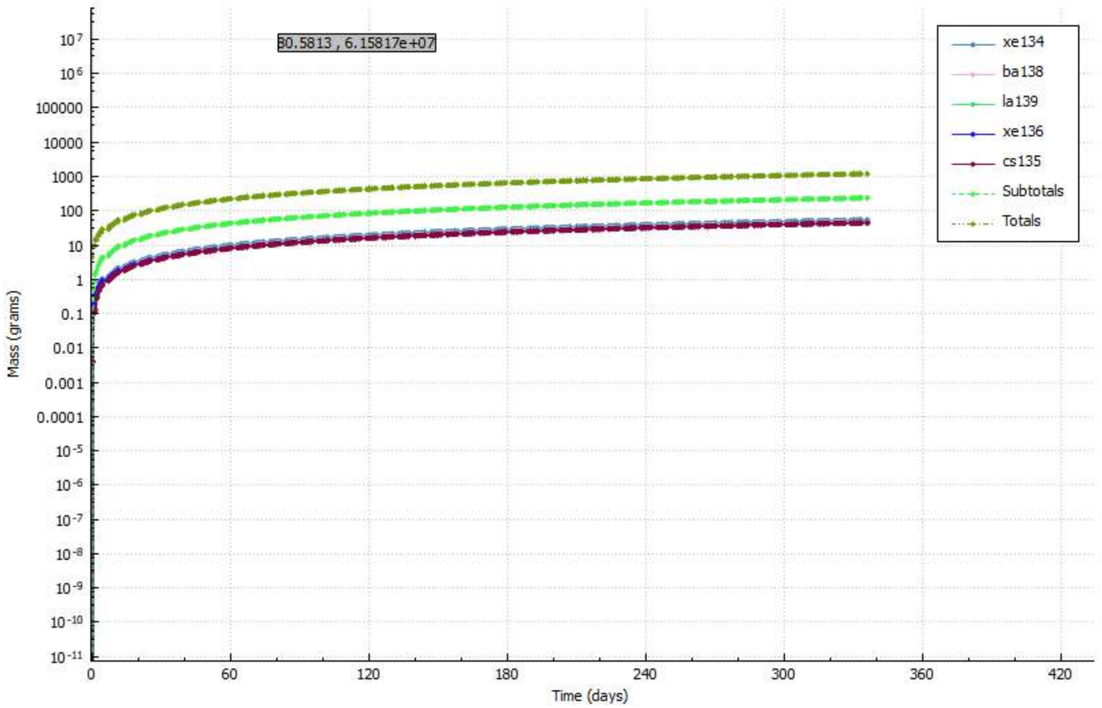


Figure 6.16. Fission products after 1-year operating time for unit rod (HEU)

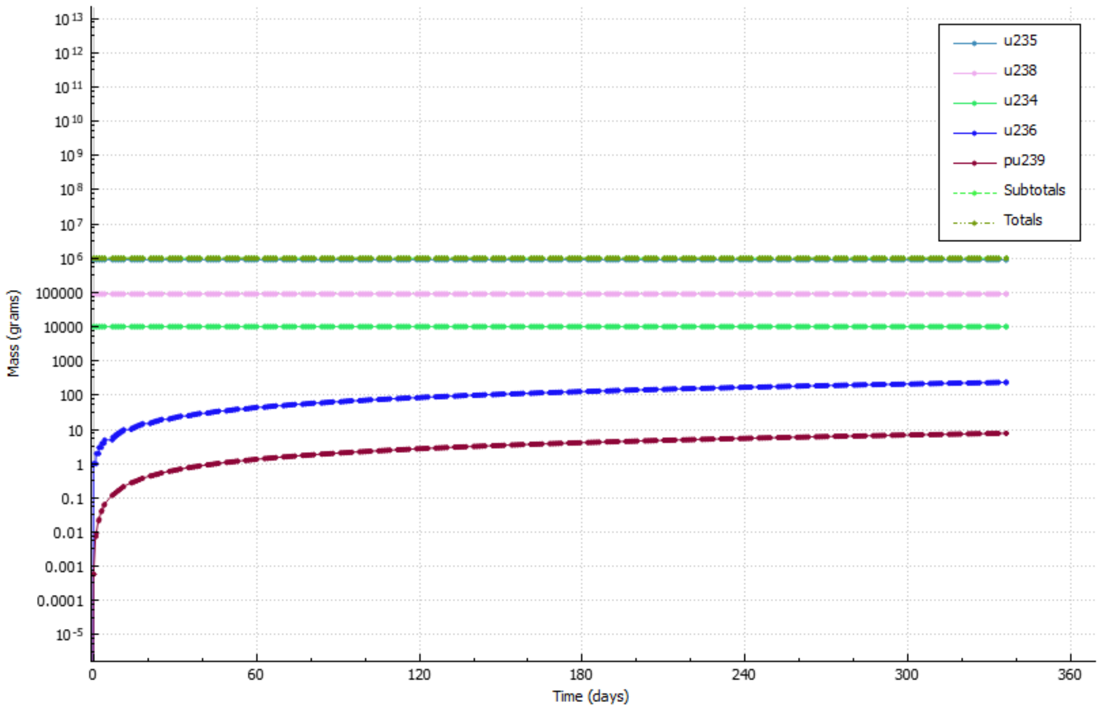


Figure 6.17. Actinides after 1-year operating time for unit rod (HEU)

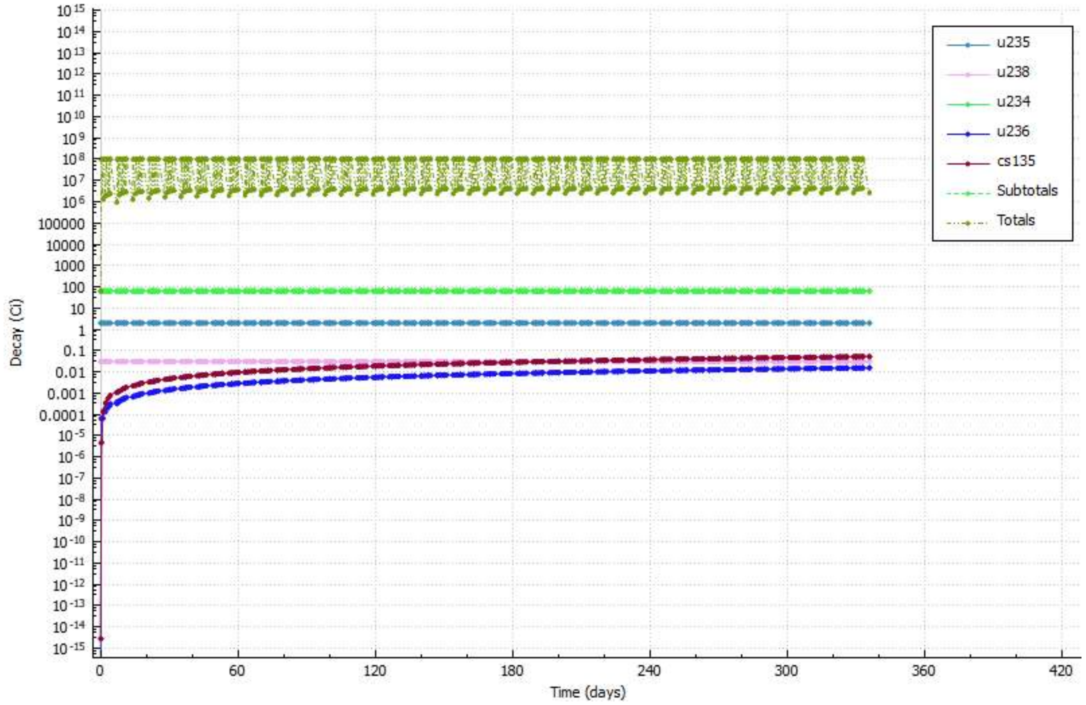


Figure 6.18. 1- year operational radioactive nuclide activity decay (unit rod, HEU)

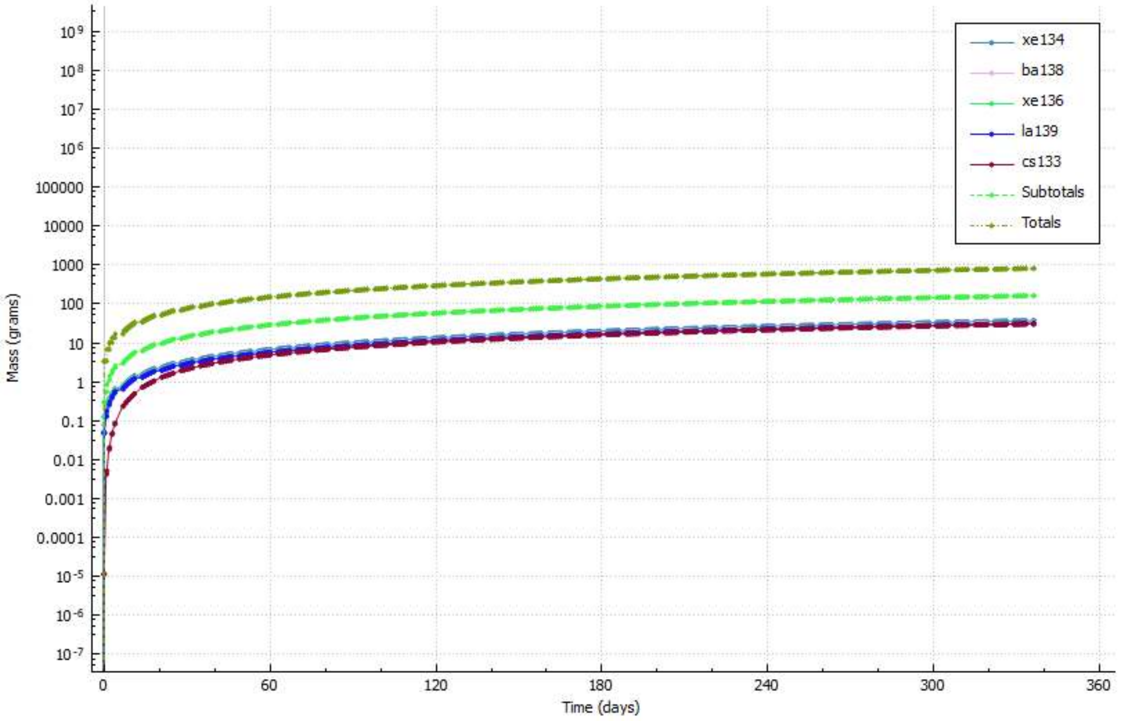


Figure 6.19. Fission products after 1-year operating time for unit rod (LEU)

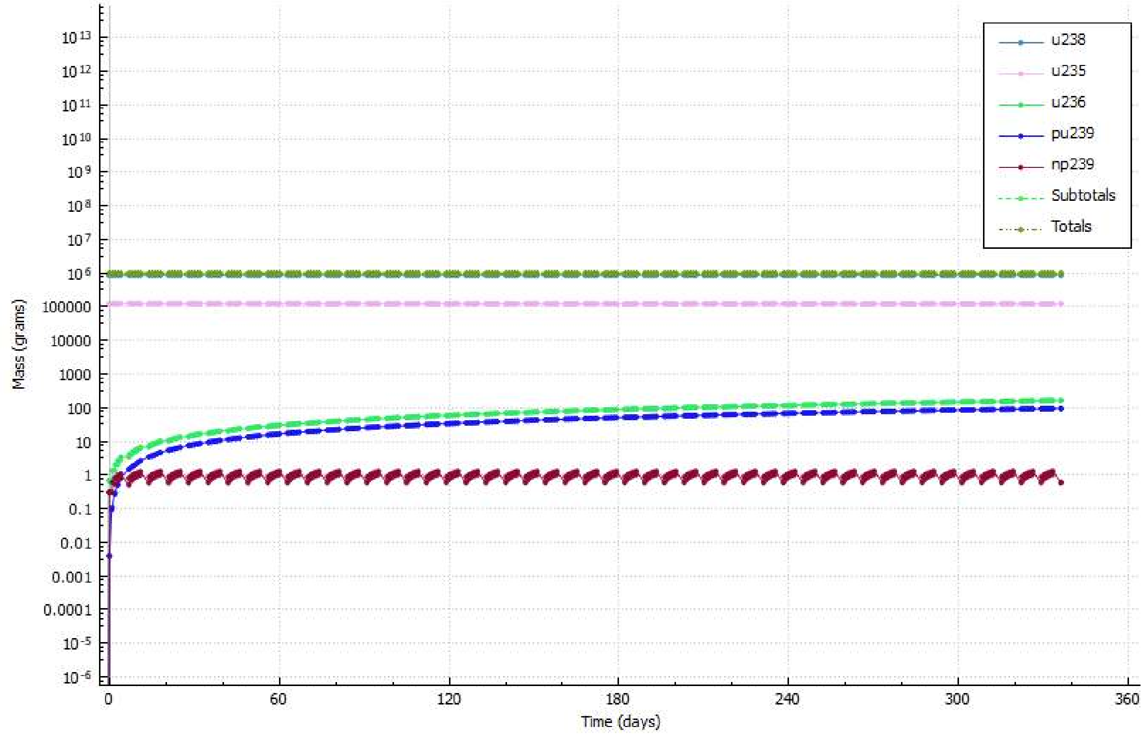


Figure 6.20. Actinides after 1-year operating time for unit rod (LEU)

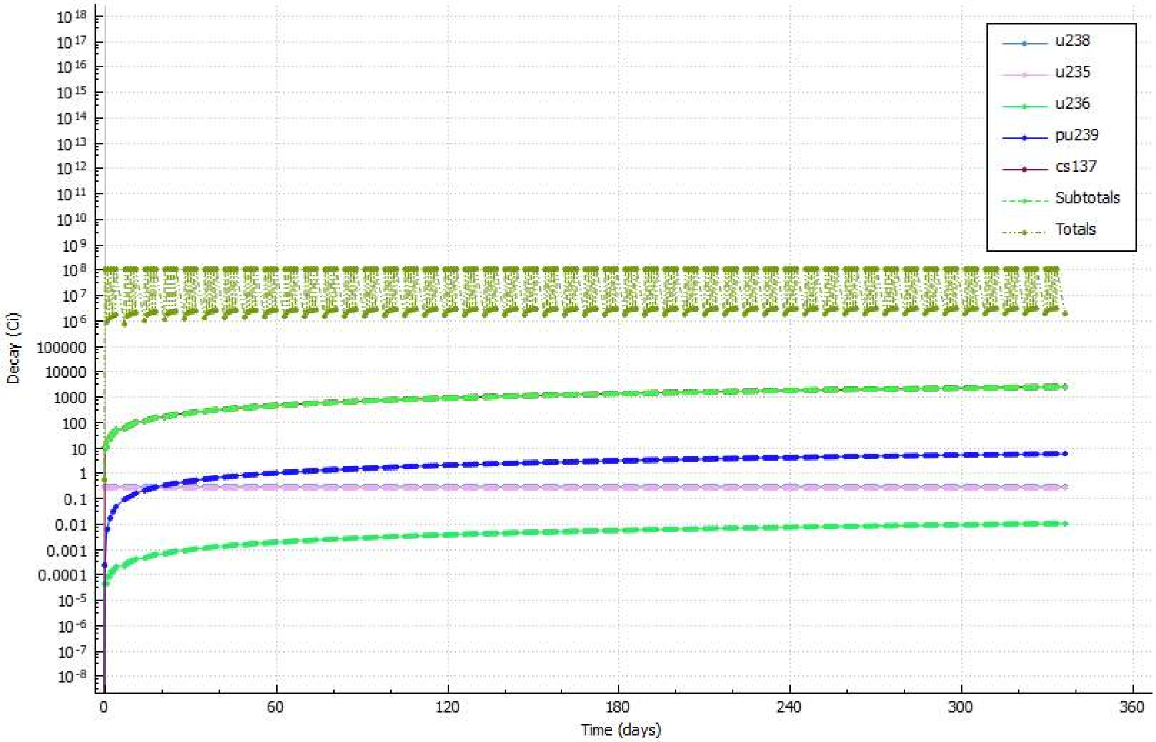


Figure 6.21. 1-year operational radioactive nuclide activity (Unit rod, LEU)

Furthermore, the characteristic assessment was carried out using same neutronic model derived from the unit cell/rod design shown in (Figure 6.1 and 6.2) to determine and estimate of the materials classified as special nuclear materials (SNM) that are important to production of weapon-usable material or dispersal agent. The result obtained as well showed that the quantity of plutonium was more when the LEU was simulated, apparently as mentioned in chapter 1 that the increase in ^{238}U isotopic content in HEU from 9.0 wt% to 87.05 wt% in LEU will produce more weapon-usable ^{239}Pu in spent fuel of the LEU, equally from the values obtained from the plot, ^{239}Pu balance for LEU fuel was 95.089g while HEU was 7.652g shown in (Figure 6.22). Consequently, the fact that this noticeable increase will give rise to weapon-usable ^{239}Pu in spent fuel of the LEU should be a big source of concern for the enrichment reduction program as well as international safeguards and accounting for nuclear materials. Based on the quantity of weapon-usable ^{239}Pu obtained from both simulations, it is suggested that risk evaluation restricted to reduced enrichment in all test and research reactor is not complete, not minding the additional vulnerabilities assessment in the type, location and size of facility as well as capabilities of terrorist groups operating near the facility or state that may be seeking nuclear materials.

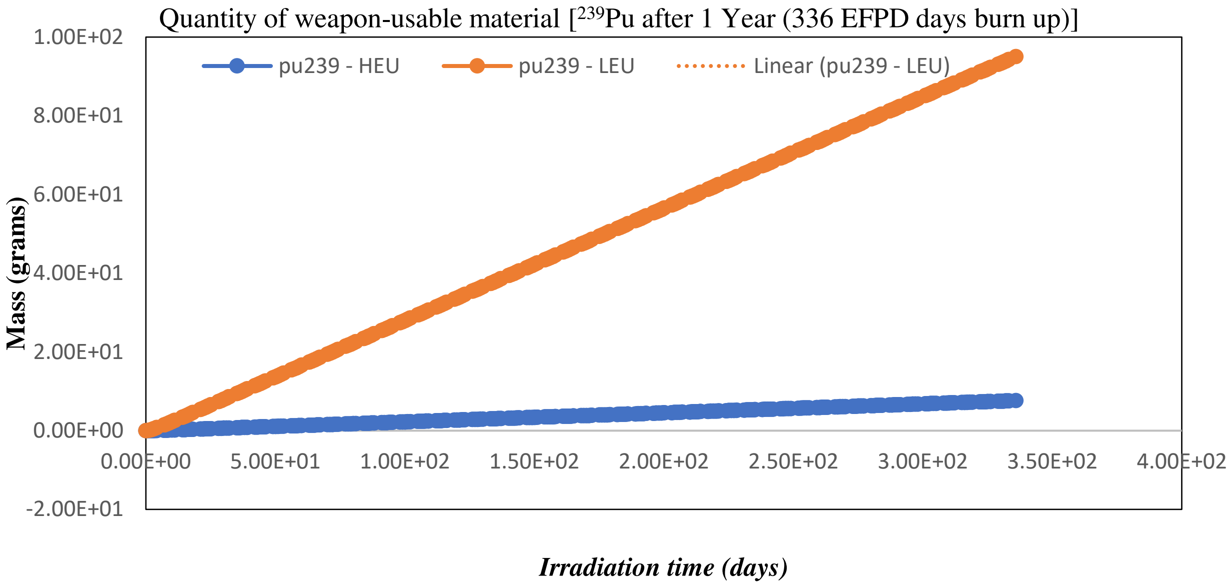


Figure 6.22. Plutonium (239Pu) balance after 7 days burn up HEU versus LEU

Table 6.2. Plutonium isotopes with their properties including Americium-241

Isotopes	Half-life (years)	Bare critical mass (Kg, α- phase)	Spontaneous fission neutrons (gm-s)$^{-1}$	Decay heat (watts Kg^{-1})
^{238}Pu	87.7	10	2.6 x 10^{3}	560
^{239}Pu	24,100	10	22 x 10-^{3}	1.9
^{240}Pu	6,560	40	0.91 x 10^{3}	6.8
^{241}Pu	14.4	10	49 x 10-^{3}	4.2
^{242}Pu	376,000	100	1.7 x 10^{3}	0.1
^{241}Am	430	100	1.2	114

Source: [100]

6.1.2 Safeguards of nuclear material in Nigeria

The NIRR-1 facility is regulated by the Nigeria Nuclear Regulatory Authority (NNRA) established by an Act of parliament (Act 19 of 1995) to ensure the protection of life, health, property and the environment as well as ensuring that Nigeria's national and international security, safety and safeguards obligations are met. The NNRA is also charged with the powers to categorize and license facilities and services involving ionizing radiation. Under the IAEA safeguards, Nigeria has ratified and domesticated most of the existing Legally Binding International Instruments as well as Legally Non-binding International Instruments such as the; the Convention on Physical Protection of Nuclear Material (CPPNM) as well as the Amendment to the Convention on Physical Protection of Nuclear Material; and International Convention for the Suppression of Acts of Nuclear Terrorism, Comprehensive Safeguards Agreement (CSA) as well as the Protocol Additional to the CSA, UN Security Council Resolutions 1540, the Pelindaba Treaty on the African Nuclear-Weapon-Free zone, the IAEA Code of Conduct on the Safety and Security of Radioactive Sources and the Supplementary Guidance to the Code on Import and Export of Radioactive Material.

Accordingly, the objectives of safeguards application to the NIRR-1 facility and general nuclear and radiological practice in Nigeria is directed towards the regulating and mitigation of accidental harmful exposure as well as preventing amongst others the malicious use of radioactive sources; unauthorized access, damage, loss, theft and unauthorized transfer of nuclear materials, services and technology [103].

Safeguards for the NIRR-1 must continue to evolve in the protection of personnel, public and the environment. (Figure 6.23.) highlights list of selected nuclides and their corresponding activity after 10-years of the unit core operation. During regulatory or IAEA verification, any change in background that is different from reported measurement would then be classified as an indication of malicious or clandestine operation either by the facility or the state by extension. The list could as well serve a measure of emergency preparedness and planning for the facility.

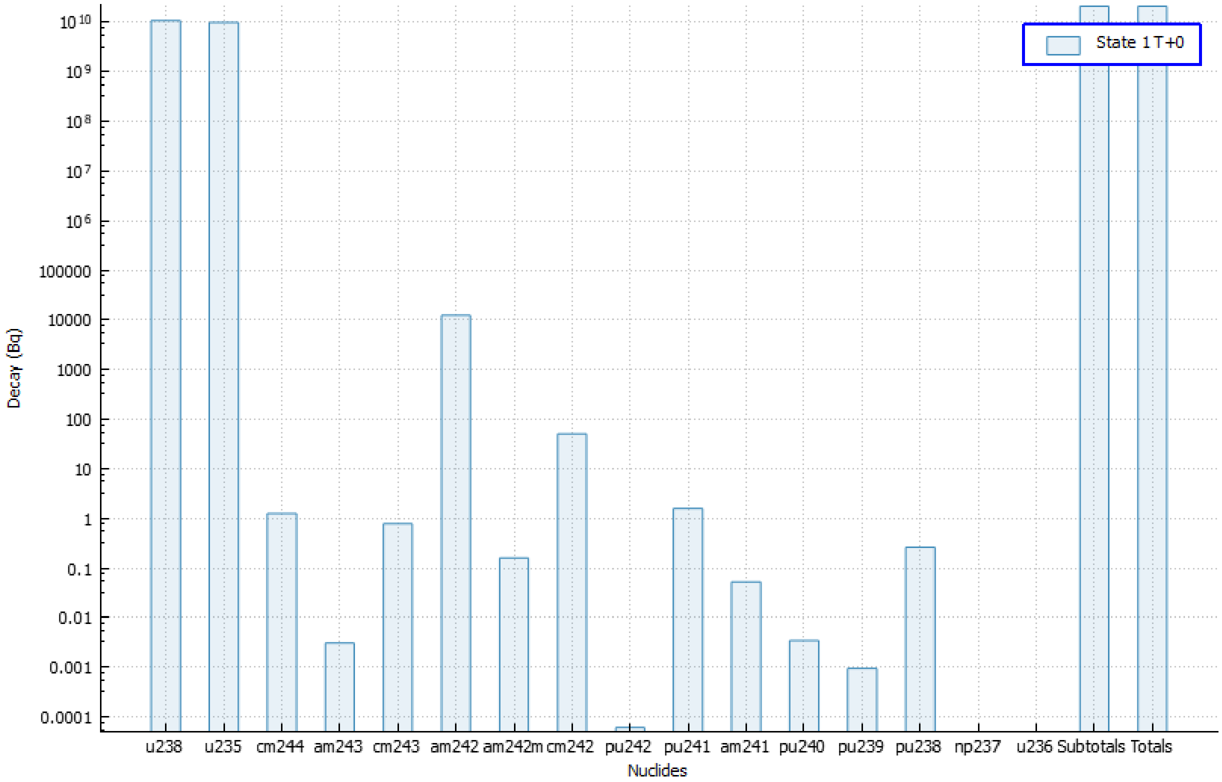


Figure 6.23. Initial activity of selected radioisotopes and their corresponding initial activities in Bq

Chapter 7

CONCLUSION AND RECOMMENDATION

The security risk and safeguards of the reactor under conversion and the facility were evaluated, gaps were identified by comparing this research with other methods adopted in the evaluation of security risk. Results obtained from the SCALE and ORIGEN simulation showed at higher thermal power of the candidate LEU at 12.5% enrichment produces more amount of weapon-usable materials from the reactor at varying time intervals of operation.

The weapon-usable ^{239}Pu balance for LEU fuel compared to the HEU was measured for 4 EFPD (one week) and the value obtained in both cases were highlighted in (Figure 6.15.) as 1.49g and 0.118g respectively. Equally, the ^{239}Pu balance for LEU fuel compared to the HEU measured for 336 EFPD (one year) and the value obtained in both cases were highlighted in (Figure 6.22.) as 95.089g and 7.652g respectively due to the increase in ^{238}U isotopic content in HEU from 9.0 wt% to 87.05 wt% in LEU. Consequently, this noticeable increase will continue to increase linearly with each day of operations and subsequently increasing the production of weapon-usable ^{239}Pu in spent fuel of the LEU. This should be a big source of concern for the enrichment reduction program as well as international safeguards and accounting for nuclear materials. Similarly, this research showed that methodologies for risk evaluation should not be based on the technical background of a would-be adversary as the only measure of risk metric because the amount of weapon-usable material may not be adequate to manufacture any weapon but may cause consequential environmental challenges if dispersed.

Based on this, results from this research established a criteria and requirements for risk evaluation, security, safeguards that is expected to be of tremendous benefit for a global perspective security, safeguards and general physical protection system to support the ongoing enrichment reduction program as well as supporting safeguards for transport security when importing the LEU core as well as returning the present HEU core.

The simulation carried out in this research was targeted towards helping to improve the safety performance, inventory, identification of actinides and fission products as well as to support the regulatory changes that comes with any conversion process while in addition to the advancement of a new legal framework for safeguards and security of nuclear materials, verification, including material control and accountancy for the HEU and new LEU in Nigeria.

Assessments of proliferation risk, to security and safeguards of storage and transportation of unirradiated and irradiated HEU and LEU fuel will be improved with the knowledge of quantity of materials generated by the simulation for the facility.

Under this assessment, technical risk, insider risk, outsider collusion, terrorist attack or invasion, the vulnerability assessment and above all perceived acquisition pathways for the hypothetical facility representative of the NIRR-1 facility were carried out using unique Nigeria country circumstances based on existing location of the NIRR-1. Also, the proposed 10MW research reactor will be a beneficiation of the security and adversary path analysis developed in this research, because of the proposed location in the north central region of Nigeria.

The result generated from the SCALE and ORIGEN will provide some generic analyses in support of the ongoing core conversion of HEU to LEU in Nigeria. It was established that the NIRR-1 enrichment reduction will attract additional verification challenges based on the HEU core removal and the new LEU core replacement because the operating history will change for the new LEU fuel as well as the requirements for the security and safeguard from the view of the quantity of weapon-usable plutonium that will be left after the conversion.

Above all, the cost of the enrichment reduction in each facility must be economically justified based on facility assessment.

7.1 Recommendations

Continuous review of risk assessment is encouraged and should reflect security culture, level of education and access to education, government bureaucracy, perceived corruption index that will be reflected in the facility services as well as personnel engagement.

Based on the ongoing enrichment reduction, there must be adequate improvement in the regulatory oversight in a way that reflects the present status of the nuclear program in Nigeria. Equally, safeguards verification and inspectors' skills that matches the present operating conditions of nuclear services and facilities in Nigeria must be put in place.

Nigeria as well as other states implementing the enrichment reduction should endeavor to reach out to the international community to adapt and domesticate best practices, models and strategies that accommodate unique country circumstances, including but not limited to their present fuel cycle, plans for future nuclear power plants and research facilities, budget, education infrastructure, government bureaucracy, international agreements and information management systems for implementing their national safeguards inspection program.

When considering facility security and safeguards design, it is important to establish a threshold at a level that attracts a very high consequence as a means of dissuading a potential insider or an invader from accomplishing set ulterior motives at research reactor facilities. Nonetheless, the consequence must be such that emergency plan and intervention or arrangements by the facility or state can easily be neutralized when activated against the set threshold.

Domestic safeguards and verification protocols oversite in the application of safeguards and material accounting for the facility and country at large must be enhanced.

There must be a continuous review of the inventory management system, potential proliferation risk assessments, facility specific theft pathways analysis and vulnerability assessment for the improvement of detection and interdiction. Equally, there must be a continuous review of the inventory management system, potential proliferation risk assessments, facility specific theft pathways analysis and vulnerability assessment for the improvement of detection and interdiction and counterterrorism policy that considers peculiar facility situation, operation and infrastructure. Additionally, the present acquisition pathway analysis (APA) used in this research could be adopted to develop information for the State Level Approach (SLA) for the LEU fuel. The present safety analysis report is outdated and must be reviewed to reflect the new operating history, security and safeguards requirement at the facility

7.2 Future work

Develop an adequate data profile to mitigate insider and continuous review of the facility design basis threat.

Develop a model that will determine the fuel requirements and consumption rate of the reactor under the Material Control and Accounting.

Based on the challenges of running the SCALE code at full core for the 10-year period of the core life, there will be a genuine need for further neutronic analysis to reflect the reality of the life time of the fresh core when more accurate operational data from the is available.

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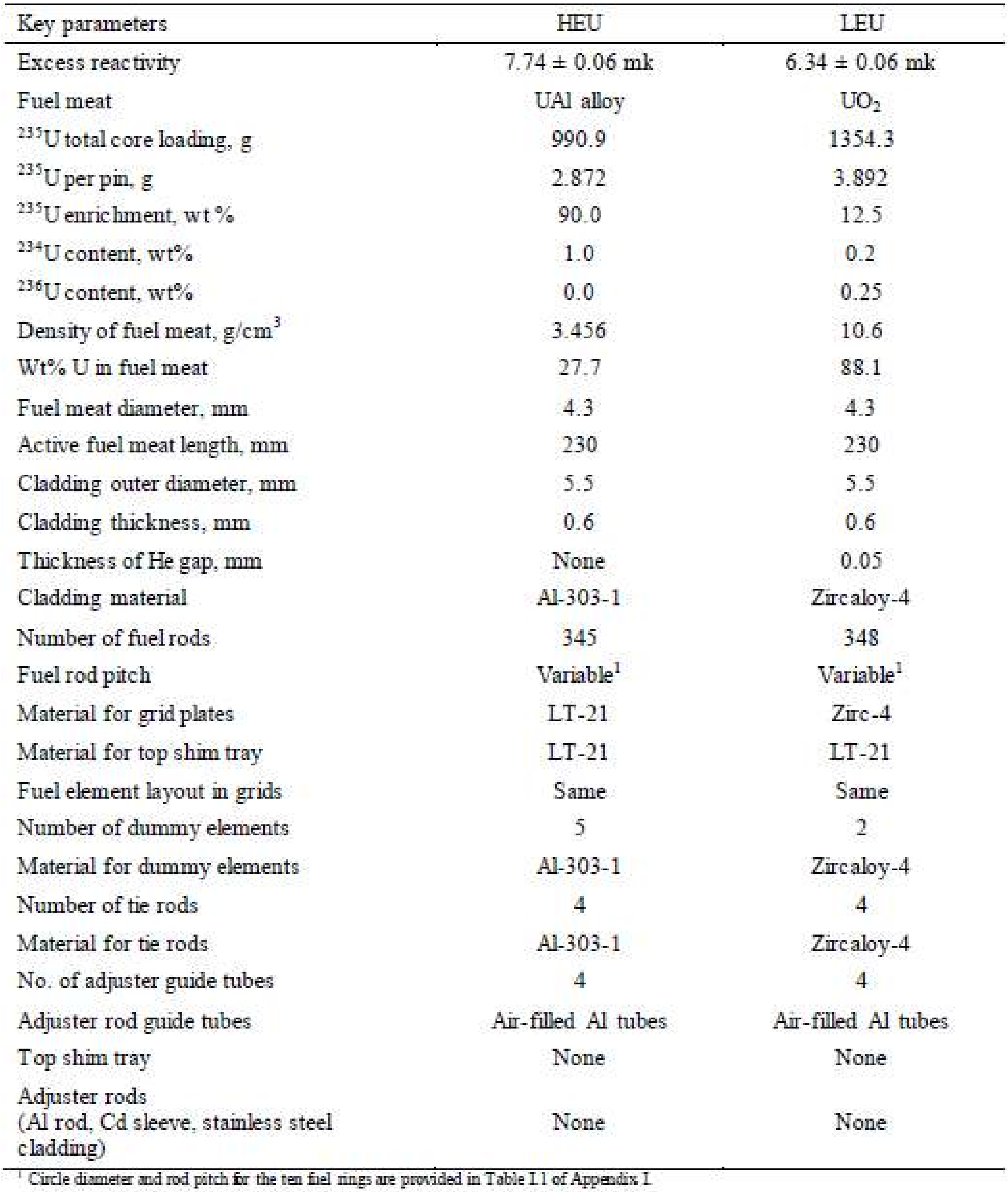
APPENDIX

Appendix 1

Generic Base parameters - HEU (UAl alloy) versus LEU (UO_2) candidate fuel. Source: [37]



Key parameters	HEU	LEU
Excess reactivity	7.74 ± 0.06 mk	6.34 ± 0.06 mk
Fuel meat	UAl alloy	UO_2
^{235}U total core loading, g	990.9	1354.3
^{235}U per pin, g	2.872	3.892
^{235}U enrichment, wt %	90.0	12.5
^{234}U content, wt%	1.0	0.2
^{236}U content, wt%	0.0	0.25
Density of fuel meat, g/cm^3	3.456	10.6
Wt% U in fuel meat	27.7	88.1
Fuel meat diameter, mm	4.3	4.3
Active fuel meat length, mm	230	230
Cladding outer diameter, mm	5.5	5.5
Cladding thickness, mm	0.6	0.6
Thickness of He gap, mm	None	0.05
Cladding material	Al-303-1	Zircaloy-4
Number of fuel rods	345	348
Fuel rod pitch	Variable[1]	Variable[1]
Material for grid plates	LT-21	Zirc-4
Material for top shim tray	LT-21	LT-21
Fuel element layout in grids	Same	Same
Number of dummy elements	5	2
Material for dummy elements	Al-303-1	Zircaloy-4
Number of tie rods	4	4
Material for tie rods	Al-303-1	Zircaloy-4
No. of adjuster guide tubes	4	4
Adjuster rod guide tubes	Air-filled Al tubes	Air-filled Al tubes
Top shim tray	None	None
Adjuster rods (Al rod, Cd sleeve, stainless steel cladding)	None	None

[1] Circle diameter and rod pitch for the ten fuel rings are provided in Table I.1 of Appendix I.

Appendix 2 Categorization of Nuclear Materials

Material	Form	Category I	Category II	Category III[c]
1. Plutonium [a]	Unirradiated [b]	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
2. Uranium-235 (235U)	Unirradiated [b] – Uranium enriched to 20% 235U or more 5 kg or more	5Kg or more	Less than 5 Kg but more than 1 kg	1Kg or less but more than 15 g
	– Uranium enriched to 10% 235U but less than 20% 235U		10Kg or more	Less than 10 Kg but more than 1 Kg
	– Uranium enriched above natural, but less than 10% 235U			10 Kg or more
3. Uranium-233 (233U)	Unirradiated b	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
4. Irradiated fuel (The categorization of irradiated fuel in the table is based on international *transport* considerations. The State may assign a different category for domestic use, storage and *transport* taking all relevant factors into account.)			Depleted or natural uranium, thorium or low enriched fuel (less than 10% fissile content) d, e	

a. All plutonium except that with isotopic concentration exceeding 80% in plutonium-238.

b. Material not irradiated in a reactor or material irradiated in a reactor but with a radiation level equal to or less than 1 Gy/h. (100 rad/h) at 1 m unshielded.

c. Quantities not falling in Category III and natural uranium, depleted uranium and thorium should be protected at least in accordance with prudent management practice.

d. Although this level of protection is recommended, it would be open to States, upon evaluation of the specific circumstances, to assign a different category of physical protection.

e. Other fuel which by virtue of its original fissile material content is classified as Category I or II before irradiation may be reduced one category level while the radiation level from the fuel exceeds 1 Gy/h (100 rad/h) at one meter unshielded.

VITA

Stephen Olumuyiwa Ariyo Dahunsi was born in Lagos, Nigeria. He attended Birch Freeman High School, Lagos. Stephen obtained his Senior Secondary Certificate of Education in 1994. He attended the Abubarkar Tafawa Balewa University, Bauchi Nigeria and graduated with a Bachelor of Engineering (B.Eng) degree in Electrical/Electronic Engineering in 2004. Upon graduating, he joined the SocketWorks limited, Lagos as a Project manager. He later joined the Nigeria Atomic Energy Commission in 2007 as a Scientific Officer. In 2012, Stephen was awarded the International Atomic Energy Agency's fellowship to the University of Ghana where he obtained a Post-Graduate diploma in Radiation protection. He was admitted to the University of Tennessee, Knoxville in 2014 in pursuit of his M.S. in Nuclear and Radiological Engineering. Stephen proceeded to pursue a doctoral degree in Energy Science and Engineering, specializing in Nuclear Engineering. The publication of this dissertation in December of 2018 is in partial fulfillment for the award of Doctor of Philosophy in Energy Science and Engineering.