ANALYSIS OF SEPCTRUM CHOICES FOR SMALL MODULAR REACTORS-PERFORMANCE AND DEVELOPMENT

A Senior Scholars Thesis

by

NISCHAL KAFLE

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2011

Major: Nuclear Engineering

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Research Advisor: Pavel V. Tsvetkov
Director for Honors and Undergraduate Research: Sumana Datta

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ABSTRACT

Analysis of Spectrum Choices for Small Modular Reactors-Performance and Development. (April 2011)

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The process of comprehensive study about the small nuclear reactors on developing analysis metrics and its method of evaluation was conducted. General methods of analysis of nuclear reactors and techniques and tools required were discussed. The research primarily followed survey of advanced small reactor concepts and compilation of their design parameters and targeted deployment scenarios, simulations for identified designs, concepts and deployment scenarios, and technology gap matrix. The research mainly focused on producing a small modular reactor (Pebble Bed Modular Reactor) design to analyze the fuel depletion and plutonium and minor actinide accumulation with varying power densities. The reactors running at low power densities were found to have used less fuel during the three years running time set within the simulation code. The plutonium-239 accumulation at the low power densities of 20 was found to be about half compared to the high power density of 125. Low power densities are therefore preferred for the operation of nuclear power plants, especially in locations with difficult accessibility and minimal security for longer operation.

ACKNOWLEDGMENTS

I would like to thank Dr. Pavel V. Tsvetkov for being my research advisor and contributing his advice to this project. He has provided me a lot of guidance without which I would not have succeeded in doing any of this.

I would also like to thank the UGR program for providing me the opportunity to conduct this research and Megan Pritchard for helping me with SCALE analysis.

Finally, I would like to thank my family for encouraging me throughout this work and for keeping me motivated.

NOMENCLATURE

BWR	Boiling Water Reactor
FP	Fission Products
LWR	Light Water Reactor
IRIS	International Reactor Innovative and Secure
MA	Minor actinides
MHR	Modular High Temperature Reactor
MWe	Megawatt Electric
^{239}Pu	Plutonium-239 Isotope
^{235}U	Uranium-235 Isotope
PBMR	Pebble Bed Modular Reactor
PWR	Pressurized Water Reactor
SCALE	Standardized Computer Analyses for Licensing Evaluation
SMART	System-integrated Modular Advanced Reactor
SMR	Small Modular Reactor
$\frac{W}{m^3}$	Watts per Cubic Meter, also known as Power Density

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CHAPTER I

INTRODUCTION

Small modular reactors (SMRs) have a recognized technology niche. These systems are targeting remote or developing regions with limited or no infrastructure, regions with limited energy needs, and technology applications where not only electricity but also heat sources are needed for various industrial applications. The nuclear energy community has invested in several small modular reactor designs already that can be considered near-term deployable – Super Safe, Small and Simple Reactor (4S), International Reactor Innovative and Secure (IRIS) series, KLT series, System-integrated Modular Advanced Reactor (SMART), TPS, Hyperion, etc.; longer term reactors may include ENHS, SSTAR, and other. Some of these systems are thermal reactors while others are fast reactors. Ranges of operational times, enrichments, operational characteristics also vary broadly addressing needs of targeted deployment domains. The proposed effort is focused on performing consistent evaluations for emerging near-term deployable small modular reactors. SMR designs are mainly modeled to take advantage of its small design, faster construction time and various deployment approaches (Kuznetsov and Barkatullah, 2009).

This thesis follows the style of Journal of the Progress in Nuclear Energy.

Different types of small modular reactors

According to Innovative Nuclear Power Reactors and Fuel Cycle (INPRO) program, there could be 43 to 96 small modular reactors in operation by the year 2030 (World Nuclear Association, 2010). Different types of small modular reactors are being studied by companies around the world; CAREM in Argentina, HTR-PM in China, FUJI in Japan, BREST, KLT series, SVBR-100, and VK-300 in Russia, PBMR (Pebble Bed Modular Reactor) in South Africa, SMART in South Korea, mPower, NuScale, GT-MHR in United States of America, and many others. Most of the above mentioned reactors are pressurized water reactor (PWR), while some of them are high temperature reactor (HTR), others are liquid metal-cooled fast reactor (LMR) and molten salt reactor (MSR) (World Nuclear Association, 2010). Many of these reactors are not used for a sole purpose of generating electricity, but also used for desalination and as heat source for industries. Descriptions of some the small reactor designs are as follows:

BREST

BREST is a prototype for a liquid metal-cooled fast reactor design. This Russian designed reactor would be of 300MWe with lead (Pb) as the primary coolant. BREST does not produce any weapon grade plutonium and the used fuel can be recycled indefinitely (World Nuclear Association, 2011).

CAREM

CAREM is a pressurized water reactor being studied in Argentina by INVAP (World Nuclear Association, 2010). This reactor uses 3.4% enriched uranium, and can produce 27 MWe which can be extendable to more than 300MWe. CAREM is near to its developed stage and can be expected to be deployed in the near future.

IRIS

International Reactor Innovative and Secure (IRIS) is designed by Westinghouse electric company. This reactor has integral primary system reactor (IPSR), which means the reactor core, steam generators and pressurizer are put together into a one pressure vessel. This reactor uses advanced LWR technology, which has been studied by more than 20 organizations from 10 different countries. IRIS shares many design features from currently studied reactors such as CAREM and SMART. IRIS uses 4.95% enriched uranium and refueling frequency is of about 3.5 years. Its power level can be scaled between 100MWe and 300MWe. The core of the reactor consists of 89 traditional 17×17 pins (Ingersoll, 2009). In Fig 1, the containment of the primary side of an IRIS reactor is shown, which also shows the control drive rod mechanisms inside the reactor unlike conventional PWRs.

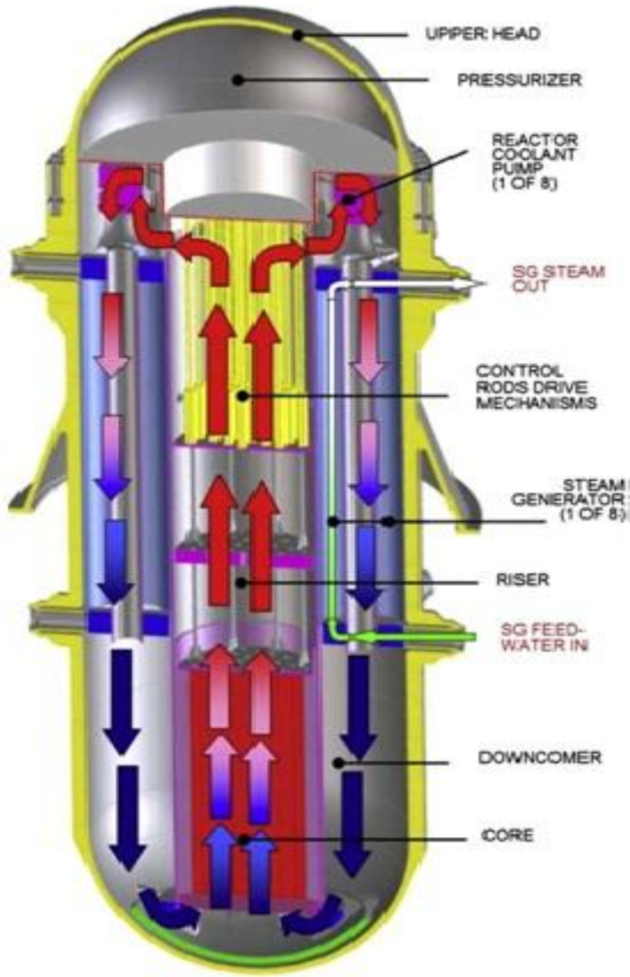

Fig 1. The reactor schematic of International Reactor Innovative and Secure (IRIS) (Ingersoll, 2009)

KLT series

KLT series, built in Russia, has two reactor variants; KLT-40 and KLT-40S. Both of these reactors are pressurized water reactor (PWR). These reactors can produce up to 35MWe of electricity for remote area power supply and desalination. KLT-40S is categorized as a floating nuclear power reactor; such floating reactors are built in ship building facilities and taken to the water near a city. Separate preparation of power generation and desalination equipment can be helpful in designing floating reactors. The two components can be manufactured in different facilities, and can be combined to one floating structure (Humphries and Davies, 1995).

PBMR

PBMR is an example of graphite moderated high temperature reactor (HTR). Developed by Eskom utility of South Africa and with German fuel design, it has been expected to be safe, secure and economical. This reactor initially was planned to work at higher electrical output of 165MWe, but later was decreased to 85MWe. PBMR uses helium as coolant and is fueled by 360,000 fuel pebbles of silicon carbide coated uranium dioxide, which is enriched to 9.6% (World Nuclear Association, 2010). The plant design and licensing is expected to be completed around 2014 and commercial deployment by 2021 (Ingersoll, 2009). This reactor has continuous refueling frequency. The efficiency of this reactor could be up to 50%, which is about 17% more efficient than the commercial reactors currently in use. The electricity cost of PBMR will be as reasonable as the existing light water reactors or coal fire plants, and the transmission cost can be reduced as reactors can be constructed in close proximity to the desired city with added safety features (Tsuchie, 2000). Fig 2 shows a schematic of Pebble Bed Modular Reactor.

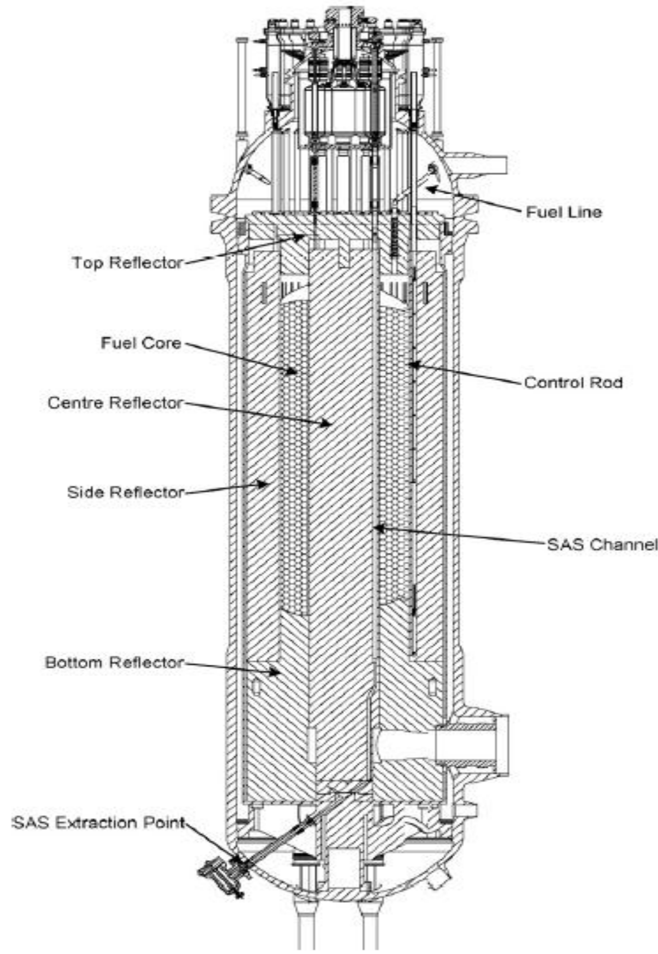

Fig 2. The reactor schematic of Pebble Bed Modular Reactor (PBMR) (Venter, 2006)

MHR

As the name itself defines, Modular High-Temperature Reactor (MHR) project was initially started by the Russian Ministry and the General Atomics Company in the USA (Kuznetsov, 2009). With 47% efficiency this reactor has 285MWe of capacity (World Nuclear Association, 2010). This reactor has annular core and is made up of 102 hexagonal graphite blocks as fuel elements. The fuel is enriched up to 20% and refueling is done every one and half years (Ingersoll, 2009). There are two types of

MHR designs; Gas Turbine Modular Helium Reactor (GT-MHR), Remote-Site Modular Helium Reactor (RS-MHR). RS-MHR is a smaller version of GT-MHR. Below in Fig 3, both the primary and secondary system of the Gas-Turbine Modular High Temperature Reactor is presented.

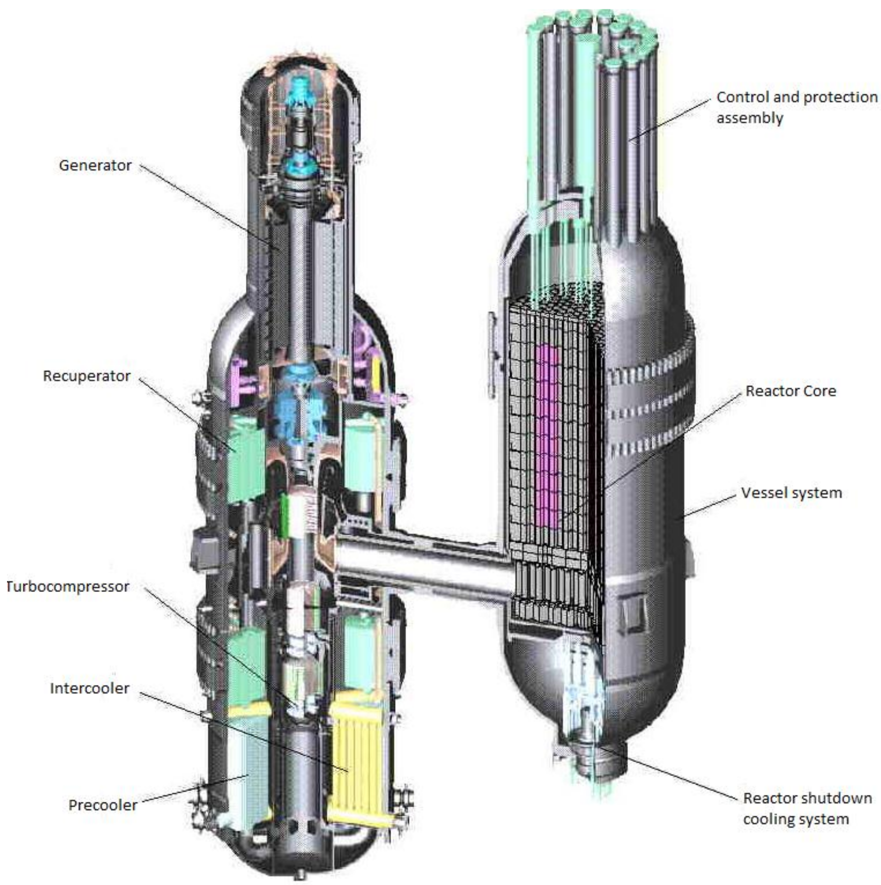

Fig 3. Reactor core for Gas-Turbine Modular High-Temperature Reactor (GT-MHR) (Internaltional Atomic Energy Agency, 2009)

There are many other reactors under study for near future deployment. The reactors like PRISM, 4S, SSTAR, Hyperion fall under fast reactors, which like high temperature reactor, are also a part of advance reactor technology. The Table I below gives parameters for some of the reactors introduced above.

Table I.
Parameters of different small modular reactors

	Pressurized Water Reactors		High Temperature Reactors		Fast Reactors	
	IRIS	**NuScale**	**PBMR**	**MHR**	**4S**	**Hyperion**
Primary Coolant	Light Water	Light Water	Helium	Helium	Sodium	Potassium
Coolant Circulation	Forced	Natural	Forced	Forced	Forced	Natural
Primary Configuration	Integral	Integral	Pebble Bed	Prismatic	Pool	Heat Pipe
Electrical Output (MW)	335	45	250	280	10	27
Outlet Temperature (°C)	330	300	950	950	485	550
Secondary Configuration	Indirect	Indirect	Indirect	Direct	Indirect	Indirect
Power Conversion Cycle	Steam Rankine	Steam Rankine	Steam Rankine	He Brayton	Steam Rankine	TBD
Vessel Diameter (m)	6.2	2.7	6.8	8.2	3.5	1.5
Vessel Height (m)	22.2	14	30	31	24	2
Fuel Type	UO_2	UO_2	TRISO	UCO TRISO	U-Zr	UH_3
Fuel Enrichment (%)	<5	<5	10	19.8	18	<5
Refueling Frequency (yr)	3.5	2.5	10	1.5	30	
Deployment Schedule	2015	2015	2021	2021	2013	TBD

Previous study was done in this area to study the fuel demand cycle for small modular reactors. Now the study is done towards development of the analysis matrices.

Technology gaps will be assessed focusing on safety, proliferation resistance, and performance characteristics. Varieties of reactor designs seem prominent but the most effective reactor should be mass produced in general case. Study and research become vital for this aspect to choose the best from these various reactors for on a certain geographical location and depending on the technology demand. The thermal hydraulics, neutronics, and accident analysis of reactors for generic small modular nuclear reactor design should be done to identify the expected perform characteristics considering their near term deployment possibilities. Various computer coding using SCALE 6.0 and RELAP5 simulation program can be used to fulfill the above mentioned purpose.

CHAPTER II

METHODS

Optimization is the continuous process through of the life of a reactor design. Even the reactors, such as PWR and BWR, which are running for several years have been consistently studied for better output. As a result varieties of nuclear reactor designs have been developed for both commercial and noncommercial usage. IRIS is one such variance of PWR design from Westinghouse which is considered for safe use with optimal performance, while PBMR and MHR are examples of Very High Temperature Reactor (VHTR). Within a nuclear reactor, areas such as neutronics, thermal hydraulics, and thermal dynamics are major areas of concern for safe, secure and enhanced result. During the course of the research, studies were focused on optimization of above mentioned areas for near term deployable nuclear reactors; however a generic small modular reactor design has been studied primarily. Neutronics analysis was mainly used in this research to generate the solution for the duration of this research. The following software and tools are essential for present and future analysis. However, just SCALE analysis was conducted for the given duration.

Software used for the study

As mentioned in the previous chapter, primarily two computer programs, RELAP5 and SCALE 6.0, can be used for computer simulation and analysis for different reactor design and with analytical solutions. The neutronics analysis can be used using SCALE

6.0, and most of the thermal hydraulics analysis for light water reactors uses RELAP5. Brief description of the each software is provided below.

Relap5

RELAP5 codes, developed at the Idaho National Laboratory, are widely used for the study of the transient mainly in light water reactor systems during postulated accidents. The developed code can be widely used for nuclear and nonnuclear systems. The modeling can also be conducted for control systems and secondary system components such as plant control, turbines, condensers, secondary feed water systems. The newest version of RELAP5 is RELAP5-3D, which has enhanced capabilities such as fully integrated performance, such as multi-dimensional thermal-hydraulic and kinetic modeling. This model is not just limited reactor pressure vessel, but can also analyze 1D, 2D, and 3D array of volumes and internal junctions (The RELAP5-3D Code Development Team, 2005).

RELAP5 contains three major level structures as shown in Fig 4; first is the input block (INPUTD), which processes inputs, checks and prepares data blocks, second is the transient/steady-state block (TRNCTL), which is used for transient and steady-state options for conditions which are changing rapidly or stagnant at a given time, and the third is the strip block, which helps to interpret data as plots in other programs (The RELAP5-3D Code Development Team, 2005).

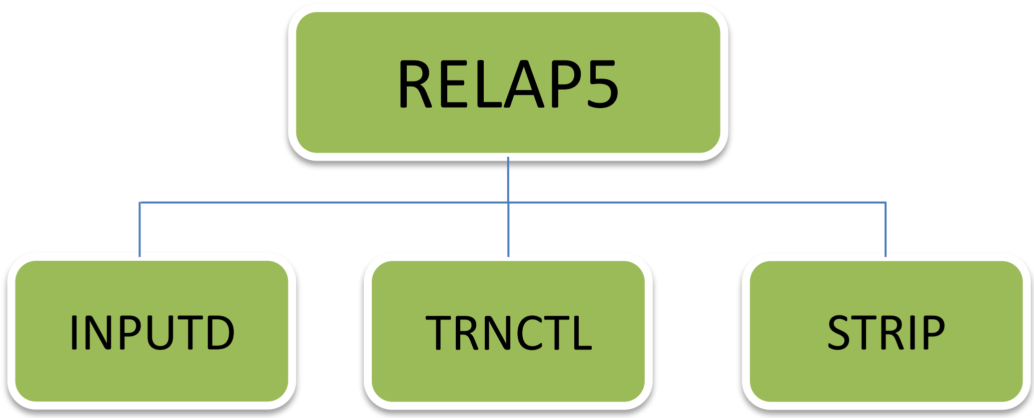

Fig 4. RELAP5-3D Level Structure (The RELAP5-3D Code Development Team, 2005)

Despite enhanced capabilities, various assumptions are still established in RELAP5 in the hydrodynamic model. Assumptions such as heat transfer to and from fluids from walls of pipes and tube, form losses at junctions, wall friction. RELAP5 is primarily used to solve fundamental equations such as conversation of mass momentum and energy and other field equations for pressure, velocity, specific internal energy, void fraction.

RELAP5 code is one of the software for extensive thermal hydraulics and accident analysis. The brief description introduces RELAP5, which was provided just to familiarize with such a tools that will be incorporated for rigorous calculations in the future.

Scale

SCALE (Standardized Computer Analyses for Licensing Evaluation) is developed by Oak Ridge National Laboratory. The necessity of SCALE was seen to perform nuclear reactor physics, criticality safety, radiation shielding, and spent fuel characterization for nuclear facilities (Oak Ridge National Laboratory). Various libraries have been included in SCALE for different purposes; resonance self-shielding of cross-section data is one of many examples. Tools within SCALE are KENO, which uses Monte Carlo codes for criticality safety calculation, likewise ORIGEN is another tool used for spent fuel characterization, depletion, decay heat, and radiation source terms, and TSUNAMI is used for sensitivity and uncertainty for criticality safely analyses (Bowman, 2007). In the research KENO was used for generating 3D model of reactor pressure vessel, and ORIGEN was used for depletion calculation.

Analytical Method

In the study of the thermal hydraulics, the centerline temperature of each sub channel in the reactor core is given by the following equation,

$$T_{CL} = T_{in} + \frac{q''' r_{fs}^2 H_e}{\dot{m}_{ch} \cdot c_p} \cdot \left(\sin\left(\frac{\pi z}{H_e}\right) + \sin\left(\frac{\pi H}{2H_e}\right) \right) + \frac{q''' r_{fs}^2}{h_{D-B} \cdot 2r_{co}} \cos\left(\frac{\pi z}{H_e}\right)$$
$$+ \frac{q''' r_{fs}^2}{2K_c} \ln\left(\frac{r_{fs} + (r_{co} - r_{ci})}{r_{fs}}\right) \cdot \cos\left(\frac{\pi z}{H_e}\right) + \frac{q''' r_{fs}}{2 \cdot h_{gap}} \cos\left(\frac{\pi z}{H_e}\right) \quad (1)$$
$$+ \frac{q''' r_{fs}^2}{4 \cdot K_f} \cos(\pi z).$$

In equation (1), T_{CL} represents centerline temperature, T_{in} represents bulk coolant temperature at the core inlet, q''' represents the volumetric heat generation, r_{fs} represents the radius of the fuel surface, H_e represents the extrapolated height of the core, $\dot{m}_{ch}$ represents the mass flow rate in the fuel channel, c_p represents the specific heat capacity of the fluid, H represents the actual height of the core, h_{D-B} represents the Dittus-Boelter equation for coefficient of convection of heat, r_{co} represents the radius of the outer surface of the clad, K_c represents the coefficient of conduction of the clad, r_{ci} represents the radius of the inner surface of the clad, h_{gap} represents the coefficient of heat transfer from the gap, K_f represents the coefficient of conduction of the fuel.

Most of the variables equations (1) are bounded by the limitation of the material used. Therefore, the analysis can be done based on the few remaining variables such as mass flow rate in the channel, radius of the fuel surface, the conductivity of the fuel.

In the study of neutronics, the transport theory is primarily used. In the transport theory the conservation law is applied in a finite nuclear reactor to the sub populations of neutrons, in the sub-volume of the reactor, energy interval, and in a cone direction as given by the angular flux, ψ. However, less detailed version of equation known as diffusion theory equation, which is an alternative to transport theory also given good estimates of reactor criticality, flux shapes.

Different tools can therefore be used to analyze different area of the nuclear reactor design. Combination of above mentioned tools can be used to obtain the real life experiment results based on different conditions and assumptions. Fig 5 is a chart visualizing the above mentioned techniques. All the mentioned aspects of nuclear engineering will be under consideration in the future study as a continuation to this research.

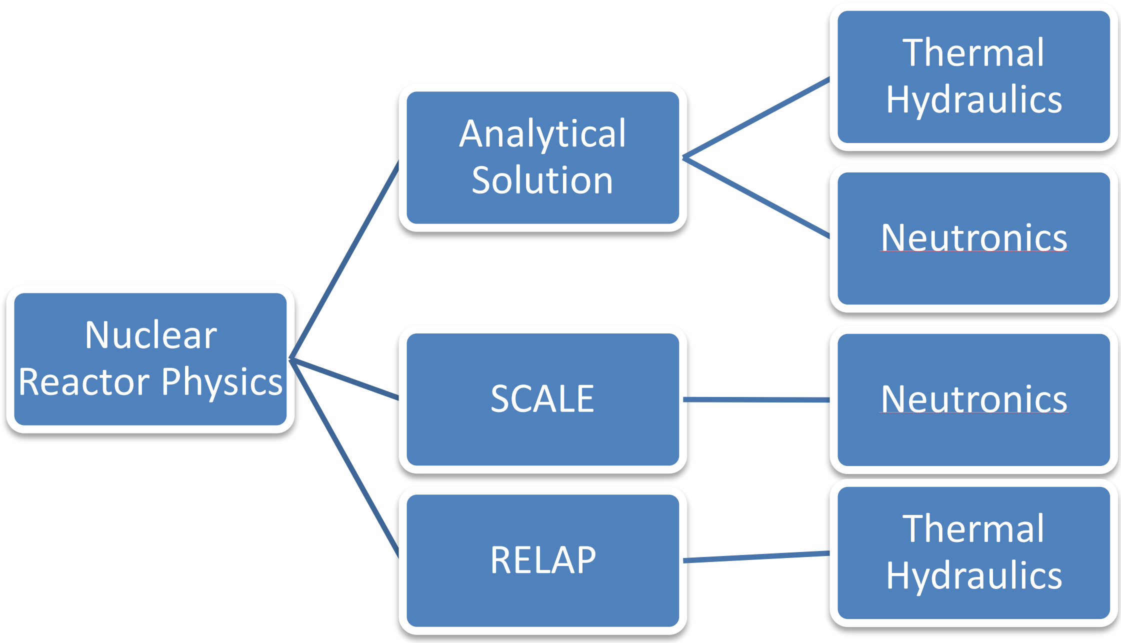

Fig 5. Tools used for the analysis of nuclear reactor.

In this research, the change in concentration of the fuel and fission products and minor actinides were primarily studied for different power densities. Power density is defined to be the power per unit volume, and it has units of watts per cubic meter $\left(\frac{\mathrm{W}}{\mathrm{m}^3}\right)$. Power density is also one of the figure of merits in a nuclear reactor. A SCALE 5.1 code was written to model a small modular reactor design, in this case a Pebble Bed Modular reactor (PBMR).

CHAPTER III

RESULTS AND ANALYSIS

For the purposes of our calculation, a generic form of a small modular reactor had been chosen. Fig 6 shows the top view of the nuclear reactor vessel where the uranium dioxide (UO_2) fuel mixed with graphite moderator is in the middle. The control rod materials are placed in between the fuel and moderator material. Helium (He) coolant flow channels are as shown in the figure to cool down the reactor.

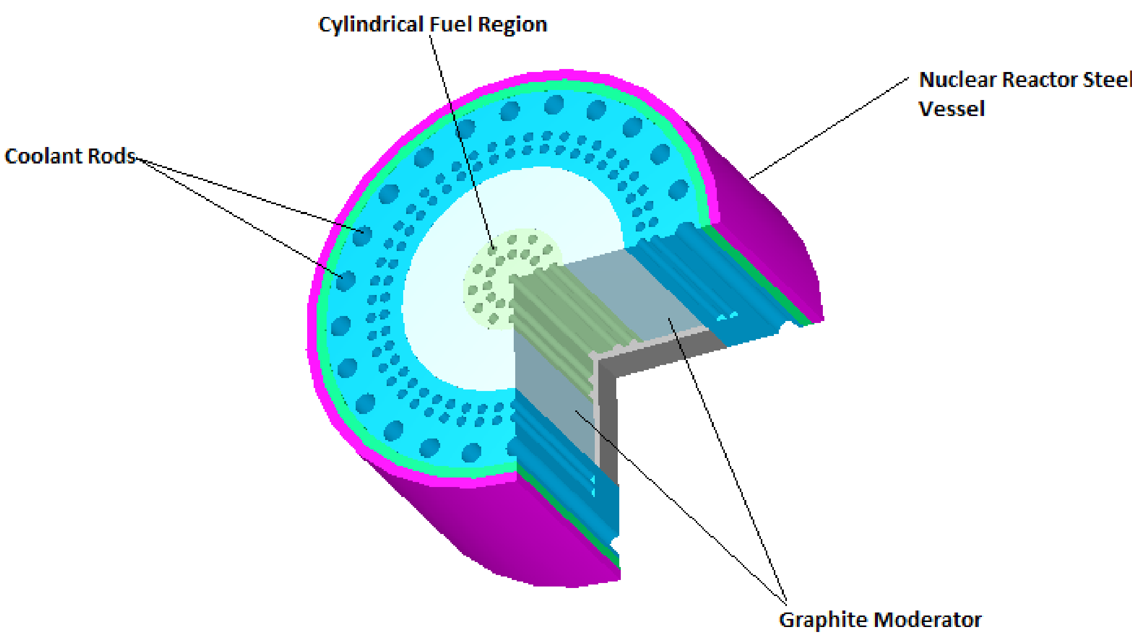

Fig 6. Top view of the KENO 3d model of Pebble Bed Modular Reactor

Fig 7 presented below is the front right corner view of the generated model. The reactor actually has graphite reflector on the top and the bottom of the model which was not shown in the above diagram. The presented model was generated using KENO- Va. software of SCALE 5.1.

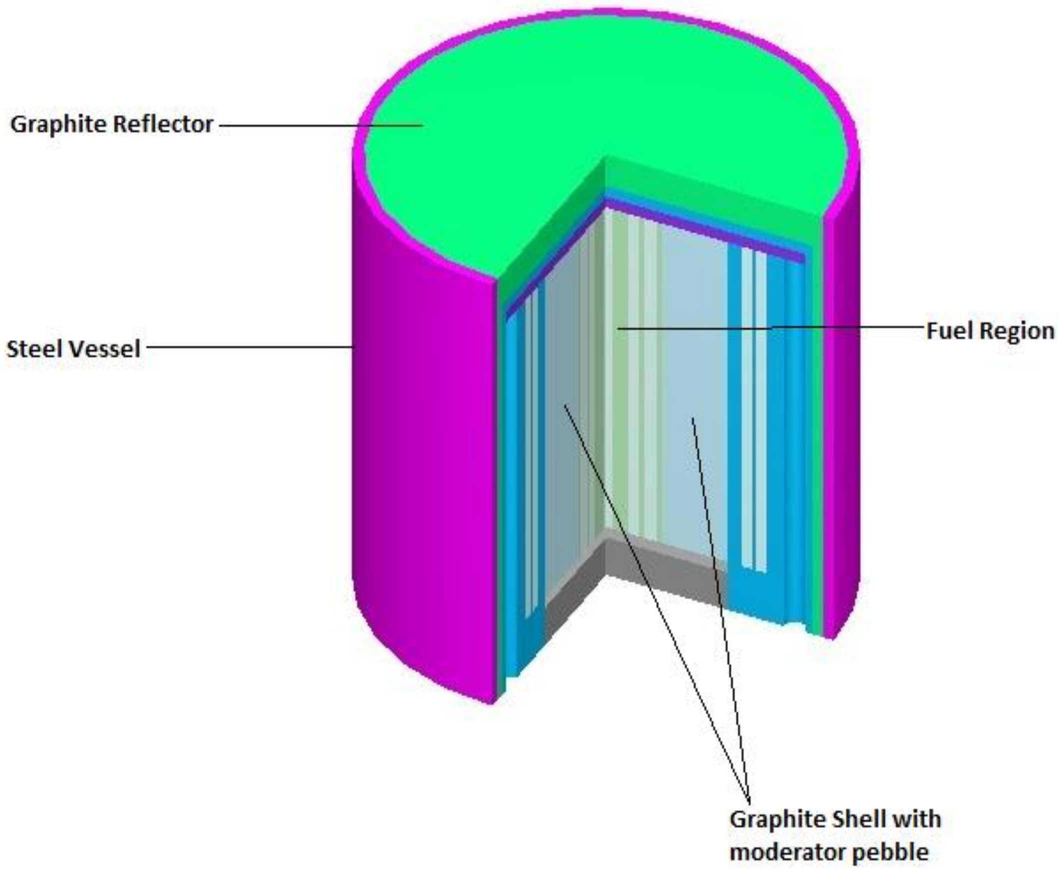

Fig 7. Front right corner view of KENO 3d model of Pebble Bed Modular Reactor

As mentioned earlier in Chapter II, the analysis of the above model was done in SCALE. The power densities were varied from 20 to 125, and the reactor running time was 1095 days (equivalent to 3 years) for all of them. From the simulation, two graphs in Fig 8 and Fig 9 were generated for changing fuel concentration, i.e. ^{235}U and ^{238}U with various power densities versus the running time of the reactor.

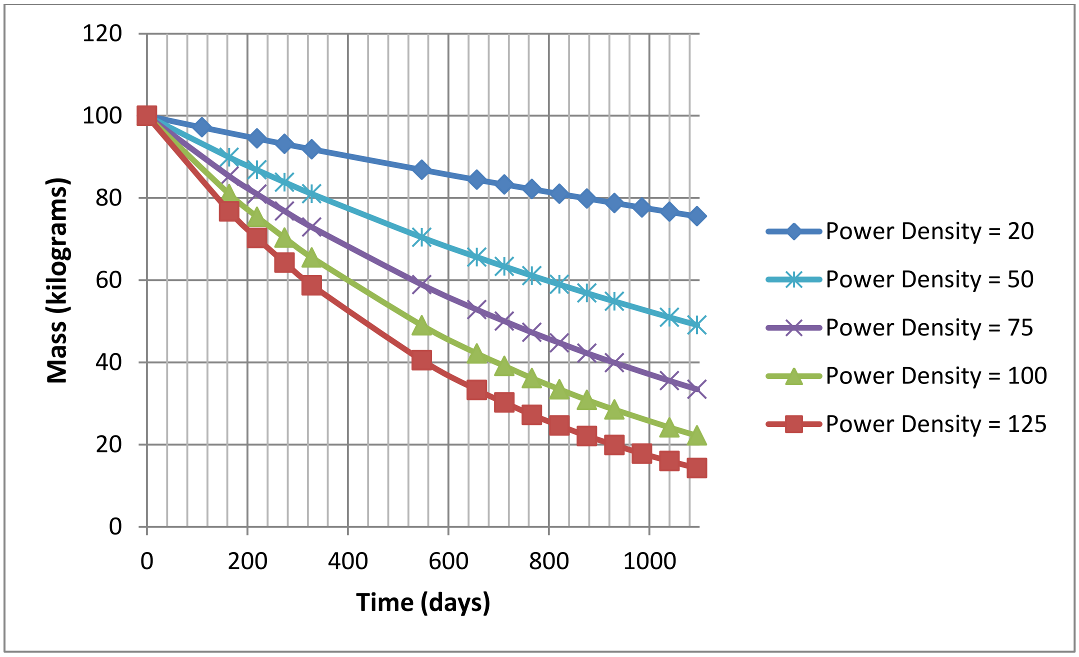

Fig 8. Depletion in ^{235}U concentration with changing power densities

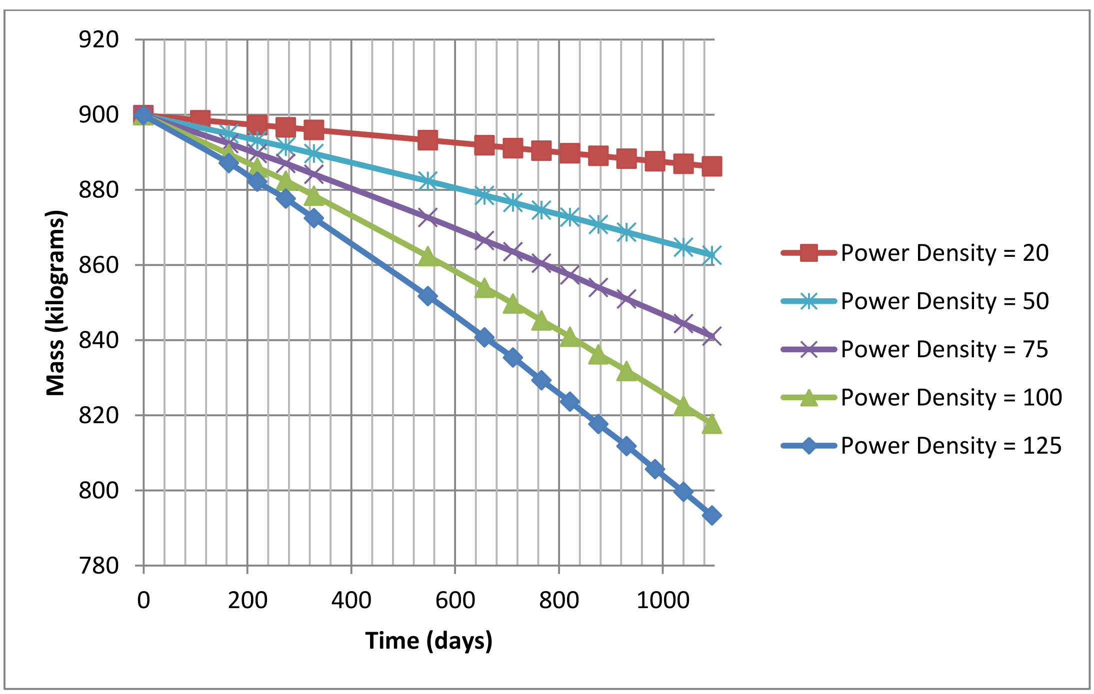

Fig 9. Depletion in ^{238}U concentration with changing power densities

The analysis of the change in ^{235}U and ^{238}U concentration is essential because they are the fuel material in the reactor core. The decrease in concentration ^{235}U is highly dependent the power density a reactor is running at. The reactor has been initially fueled with one ton of fuel (900 kilograms of ^{238}U and 100 kilograms of ^{235}U). For a nuclear reactor running at low power density the decrease in concentration is little compared to a reactor running at high power density.

The next five graphs were generated for plutonium, fission product and minor actinide concentration versus the running time of the reactor.

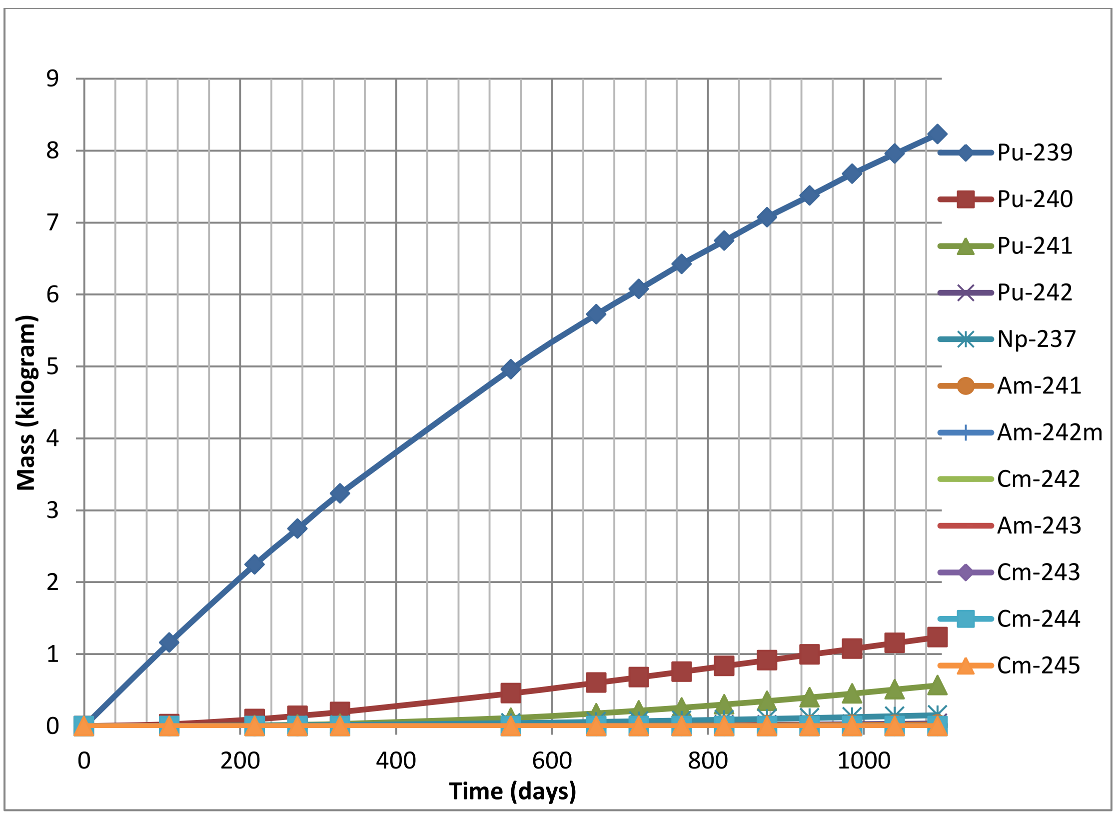

Fig 10. Pu and MA concentration as a function of time at power density of 20

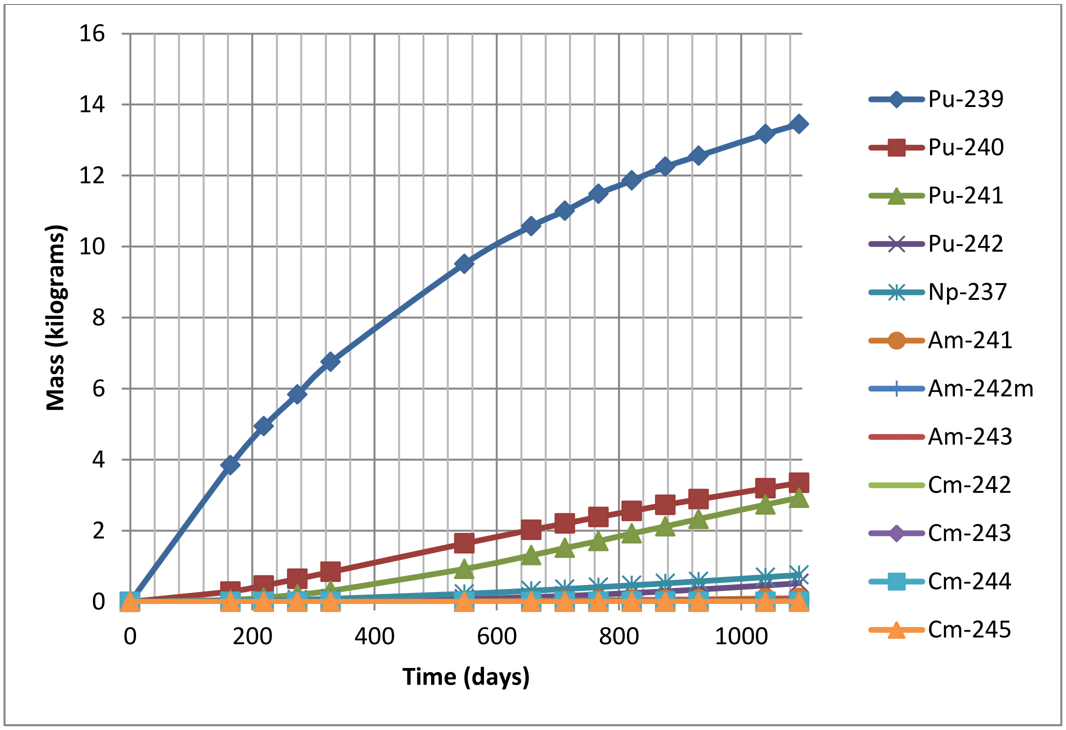

Fig 11. Pu and MA concentration as a function of time at power density of 50

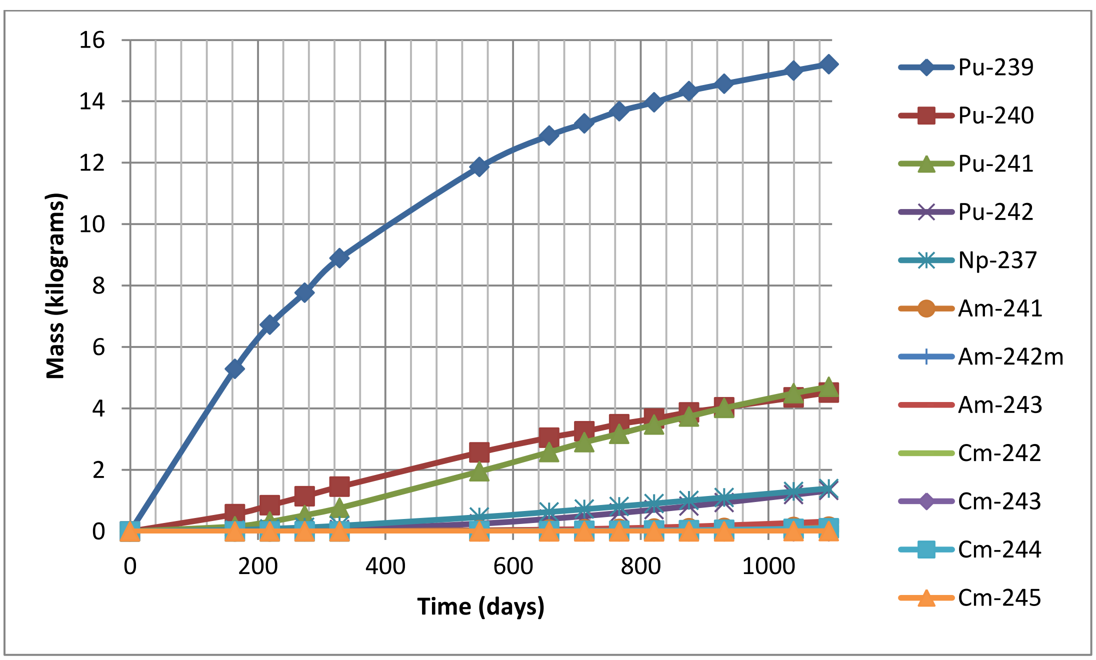

Fig 12. Pu and MA concentration as a function of time at power density of 75

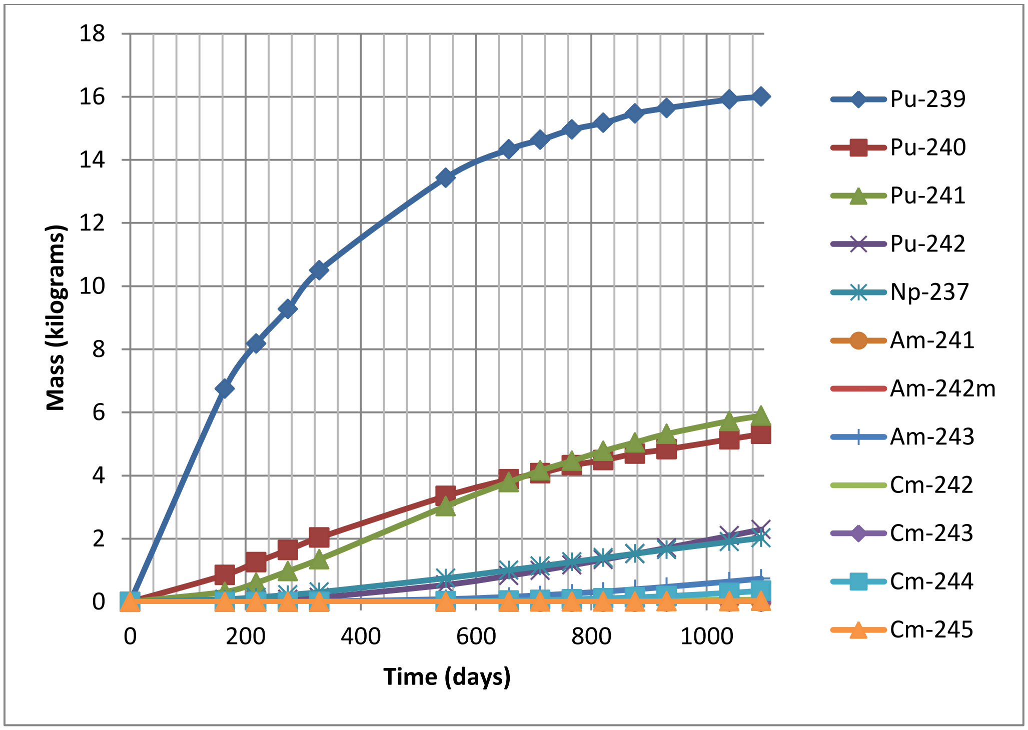

Fig 13. Pu and MA concentration as a function of time at power density of 100

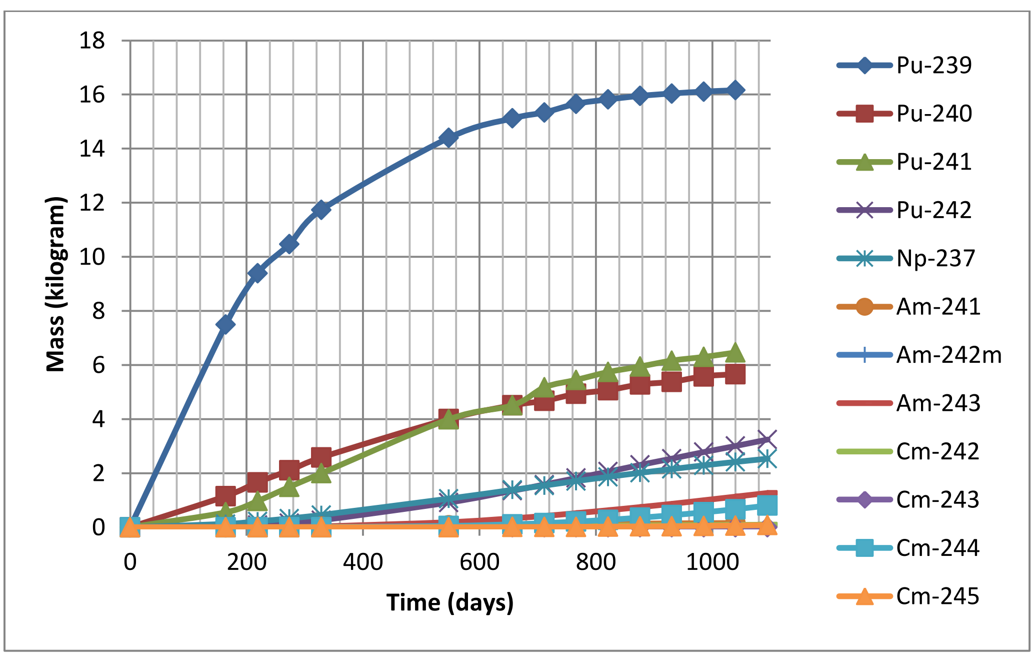

Fig 14. Pu and MA concentration as a function of time at power density of 125

A general trend can be seen in all the plots presented from Fig 10 to Fig 14. The ^{239}Pu are deposited with highest concentration in the fuel, followed by ^{240}Pu and ^{241}Pu. Plutonium isotopes concentration is quite important to keep track of because of their weapons graded quality. With an increase in power density increasing trend on plutonium and minor actinides can be observed. Comparing the power density of 20 and 125 it can be seen that ^{239}Pu concentration has almost doubled in the higher power density. The only major difference that can be seen is that at a low power density the trend seem to be linear increases, whereas at a high power density the trend seem to increase rapidly and settles nearly to a steady state, depicting the strong depletion of fissile material and later are primarily surrounded by neutron poisons.

Table II provides the all the accumulated concentration of nuclide masses at the end of their life for different power densities. Some of the minor actinides (such as ^{242}Am and all Cm isotopes) concentrations are not presented in the table because of their very low concentration.

Table II.

Accumulated concentration of nuclides at the end of the three year reactor life with varying power density

Accumulated Nuclide (kg) / Power Density	U-238	U-235	Pu-239	Pu-240	Pu-241	Pu-242	Np-237	Am-241	Am-243
20	886.2	75.52	8.229	1.235	0.5653	0.03717	0.1517	0.02116	0.00208
50	862.6	49.08	13.45	3.348	2.929	0.525	0.7557	0.1042	0.08303
75	841	33.44	15.21	4.523	4.706	1.328	1.398	0.1514	0.3245
100	817.7	22.16	16	5.315	5.894	2.289	2.021	0.1666	0.7362
125	793.3	14.23	16.13	5.805	6.564	3.242	2.535	0.1553	1.266

The last plot generated from the simulation is of multiplication factor versus reactor running time at different power densities. For a nuclear reactor to sustain a controlled chain reaction the multiplication factor must remain at a value of one, which is also known as being at critical state (the net number of neutrons remain same throughout operation time). If the number becomes more or less than one, the number of neutrons production changes and a nuclear reactor becomes supercritical (the net number of neutrons increases) or subcritical (the net number of neutrons decreases) respectively.

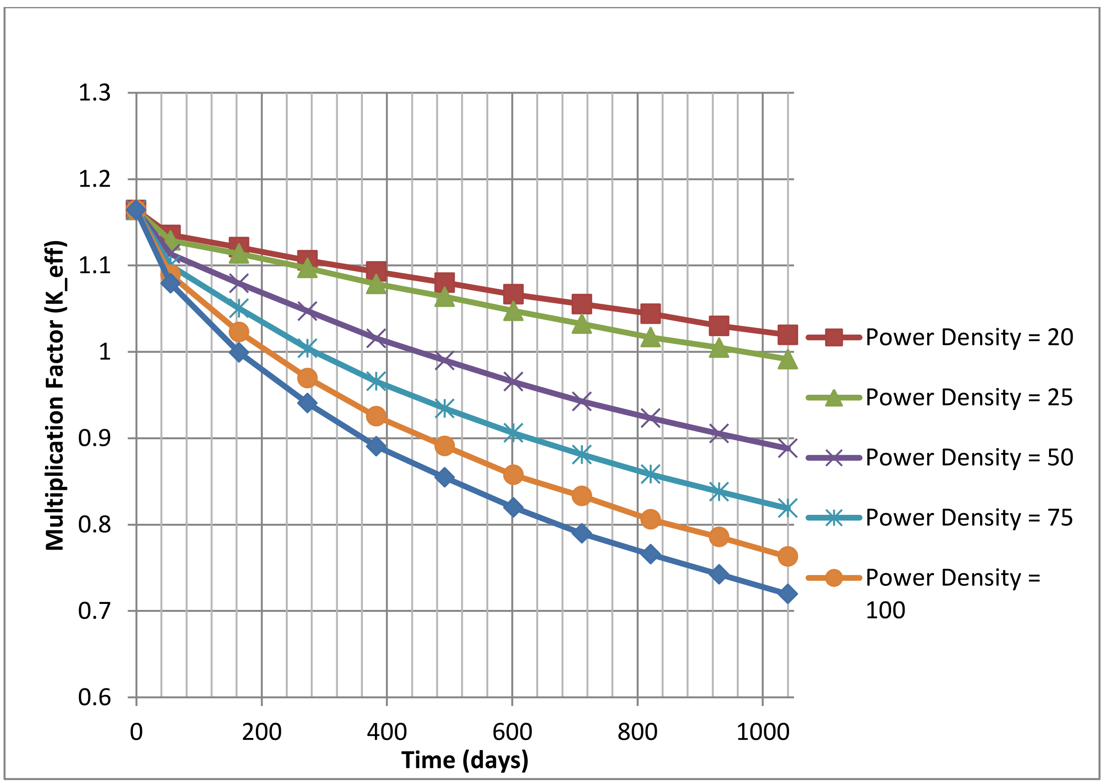

Fig 15. Multiplication factor as a function of time at different power densities

From Fig 15, it can be seen that the there is rapid change in reactivity with the change in the power density. However, depending on the power level of the reactor the decrease in multiplication factor can then be interpreted to be either linear (in lower power densities) or logarithmic (in high power densities). From the figure it can be seen that at lower power densities (25 or less) the multiplication factor remains around one. While for higher power density the multiplication factor decreases significantly and the nuclear reactor becomes subcritical within a few hundred days of operation, which means the nuclear reactor running at higher power densities must be fueled frequently because of the buildup of excessive non fissionable materials.

As this design is a Pebble Bed Modular Gas Cooled Reactor, they are designed to run at low power densities compared to light water reactors with longer core length; therefore, increasing the cost of the reactor core (Kadak et al., 1998). Increase in reactor core length increases the dimensions of a reactor pressure vessel which can increase the cost of the reactor significantly.

CHAPTER IV

SUMMARY AND CONCLUSION

The objective of this research was to introduce small reactor technology, understand their potential, methods involved in rigorous study of nuclear reactor systems, and analyze a generic form of a design based on varying power densities.

Nuclear power is the major source of clean energy for the near future, and small modular reactors are the driving mechanisms to harness this energy worldwide. Potential benefits from small modular reactors are countless; variety of features such as production of electricity, industrial heat, for being capable of land based or water based, inherently safer designs, and their shear size makes them economical. Small reactor technology can therefore be considered as highly efficient, cost effective source of generating considerable amount of energy, especially in developing countries.

Engineering is a process constantly working progress towards safer and sustainable designs. In depth analysis of nuclear reactor becomes important because it will help to understand physics engineering required to create an optimal design. Major classifications for the analysis are neutronics, thermal hydraulics and accident analysis. Each section can be studied either by analytical methods or using simulation software to obtain real life solutions.

A small modular reactor (Pebble Bed Modular Reactor) design was considered to understand the behavior of fuel and multiplication factor for this research. Varying the power density of this model generated in SCALE 5.1, analysis were made on change in multiplication factors, uranium fuel, plutonium, and minor actinides. The results obtained from the simulation were plotted against time to see the behavior of above mentioned these items. All the plots obtained were showing a substantial decrease in fuel and increase in plutonium and minor actinides concentration. Power densities of the nuclear reactor should be chosen according to the location. As high temperature reactor are designed to operate at low power density and the fuel can therefore be used for a long period of time without refueling. Especially high temperature Pebble Bed Modular Reactor has higher efficiency and longer fuel life (Kadak et al., 1998). At deployment this would help to keep reactors running in places with difficult accessibility or in places with less security for longer period.

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