FUEL CYCLE COST AND FABRICATION MODEL FOR FLUORIDE-SALT HIGH-TEMPERATURE REACTOR (FHR) "PLANK" FUEL DESIGN OPTIMIZATION

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FUEL CYCLE COST AND FABRICATION MODEL FOR FLUORIDE-SALT HIGH-TEMPERATURE REACTOR (FHR) "PLANK" FUEL DESIGN OPTIMIZATION

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LIST OF SYMBOLS AND ABBREVIATIONS

LSCR……………………………………………………………Liquid Salt Cooled Reactor

FHR……………………………….……Fluoride-Salt-Cooled High-Temperature Reactor

AHTR…………………………………………………Advanced High Temperature Reactor

AGR…………………………………………………………..Advanced Gas Reactor

ORNL…………………………………………………..Oak Ridge National Laboratory

INL………………………………………………………..…Idaho National Laboratory

B&W…………………………………………………………………...Babcock & Wilcox

FLiBe…………………………………Lithium Fluoride and Beryllium Fluoride, Li_2BeF_4

FCC……………………………………………………………………..Fuel Cycle Cost

TRISO……………………………………………………………Tristructural Isotropic

UCO……………………………………………………………Uranium OxyCarbide

HTGR…………………………………………………...High Temperature Gas Reactor

SmAHTR…………………………..Small Modular Advanced High Temperature Reactor

MSRE……………………………………………………Molten Salt Reactor Experiment

LRM…………………………………………………………Linear Reactivity Model

LWR……………………………………………………………..Light Water Reactor

BOC…………………………………………………………………...Beginning Of Cycle

EOC……………………………………………………………………..End Of Cycle

SWU…………………………………………………………………Separative Work Unit

QA……………………………………………………………………Quality Assurance

ROI……………………………………………………………….Return On Investment

PF……………………………………………………………………....Packing Fraction

HEXA………………………………………………………………Hexamethylenetetramine

O[I]PyC……………………………………………….…Outer [Inner] PyroCarbon Layer

SiC……………………………………………………………………….Silicon Carbide

CE…………………………………………………………………...Continuous Energy

MG……………………………………………………………………………Multi-Group

RPT………………...…………………………Reactivity-Equivalent Physical Transforms

BU……………………………………………………………………………..Burnup

EFPD……………………….....………………………………Effective Full Power Days

SUMMARY

The fluoride-salt-cooled high-temperature reactor (FHR) is a novel reactor design benefitting from passive safety features, high operating temperatures with corresponding high conversion efficiency, to name a few key features. The fuel is a layered graphite plank configuration containing enriched uranium oxycarbide (UCO) tri-structural isotropic (TRISO) fuel particles. Fuel cycle cost (FCC) models have been used to analyze and optimize fuel plate thicknesses, enrichment, and packing fraction as well as to gauge the economic competitiveness of this reactor design.

Since the development of the initial FCC model, many corrections and modifications have been identified that will make the model more accurate. These modifications relate to corrections made to the neutronic simulations and the need for a more accurate fabrication costs estimate. The former pertains to a MC Dancoff factor that corrects for fuel particle neutron shadowing that occurs for double-heterogeneous fuels in multi-group calculations. The latter involves a detailed look at the fuel fabrication process to properly account for material, manufacturing, and quality assurance cost components and how they relate to the heavy metal loading in a FHR fuel plank.

It was found that the fabrication cost may be a more significant portion of the total FCC than was initially attributed. TRISO manufacturing cost and heavy metal loading via packing fraction were key factors in total fabrication cost. This study evaluated how much neutronic and fabrication cost corrections can change the FCC model, optimum fuel element parameters, and the economic feasibility of the reactor design.

CHAPTER 1: INTRODUCTION

The Liquid Salt Cooled Reactor (LSCR), or Fluoride-salt-cooled High-temperature Reactor (FHR), is a type of Advanced High Temperature Reactor (AHTR), a generation IV reactor, currently under development by Oak Ridge National Laboratory (ORNL) for the U. S. Department of Energy, Office of Nuclear Energy's Advanced Reactor Concept Program [1]. The research has been underway since 2000 with preliminary research covering initial designs of a full power and modular scale reactor supported by various economic feasibility studies and specific work on depletion methods and core configurations.

The current design is based on a 3400 MW_t plant with a 2-year cycle. It uses fluoride lithium beryllium (FLiBe) coolant operating at an average temperature of around 700 °C [1]. It has many favorable features, namely passive safety systems relying on natural circulation and low operating pressure, negating the cost and design limitations of a pressure vessel. The fuel is a novel type of graphite compact with tri-structural isotropic (TRISO) uranium oxycarbide (UCO) particles dispersed throughout. The compact is in the shape of a rectangular 'plank', disparate from the cylindrical and spherical compacts commonly used for graphite based fuels.

In developing a new reactor design economic feasibility is equally significant as its physical operation. A fuel cycle cost (FCC) model develops a metric to gauge the economic feasibility of a reactor design by coupling associated physical cost (capital, fuel enrichment, fuel fabrication, waste disposal, etc.) with the in core utilization of fuel (production of energy) usually given as a discharge burnup (energy/mass) [2]. A competitive FCC value ($/electric energy produced) has low associated costs with maximal energy production. When modeling, accuracy in cost estimation and neutronic simulation needs to be adequate to correctly yield FCC value as this value is a key component influencing core and fuel design optimization where a compromise between fuel utilization and associated cost must be considered.

Previous FCC analyses have been simplified in regards to fuel fabrication estimates and simulation fidelity [3]. Previous neutronic simulations approximated operating temperatures for the various regions of the reactor based on simplified thermal hydraulic models and were ran without any correction for errors from possible fuel shadowing effects that are prone to occur when fuel kernels are packed closely together within a moderating medium. Recent research has developed updated representations of temperatures throughout the core via RELAP5 models [4] and correction values in the form of Monte Carlo (MC) Dancoff factors that account for double heterogeneity in multigroup neutronic simulations. When compared against an uncorrected model the effects of temperature and self-shielding can be analyzed to show how important such corrections are towards forming a more accurate neutronic model. However slight or significant the changes will be both corrections contribute to a more thorough neutronic analysis.

In regards to fuel fabrication, cost estimates were previously based on a generic range of costs on a per kilogram uranium basis not specific to any particular design of fuel, i.e., independent of the packing fraction and other fuel design parameters. However, this FHR plank design variable significantly impacts the amount of uranium (or heavy metal) in fuel planks; with increasing packing fraction increases the amount of uranium in a single fuel element. Therefore, fuel elements with varying packing fraction cannot have the same fabrication costs on a per kilogram uranium basis. A change in packing fraction also includes a change in the amount of graphite displaced by TRISO fuel and this in turn will affect the material costs. These are just examples of why FHR fuel fabrication needs to be analyzed with some level of detail and specificity.

For typical LWR fuel the fabrication cost is as low as 12% of the total FCC cost [5] but it is speculated that this percentage may be much higher for FHR fuel due to heterogeneity of the fuel elements requiring more structural material, more complex fuel fabrication, and precise manufacturing control. A more accurate fabrication cost estimate looks to scrutinize the material, manufacturing, and quality assurance (QA) components of FHR fuel fabrication. The manufacturing component in particular consolidates capital cost of a fabrication facility, facility operation and maintenance cost, and expected yearly capacity, which has the potential to become quite costly.

Many values associated with material and manufacturing costs are hard to ascertain with low uncertainty but informed approximations can be made based on the available literature. More mature graphite fuel designs such as pebble fuel and cylindrical compacts used in high temperature gas reactors (HTGR) have a level of operating experience that can be translated to FHR fuel fabrication. Even some elements of LWR fuel fabrication are translatable. As long as a reasonable justification is made for the similarities that exist, parallel technologies can help to develop cost estimates with improved accuracy and yielding a more refined fabrication cost. Indeed this sort of logic will be used many times in developing the FHR fuel fabrication cost but it is the motivation of this research to develop a FCC analysis model and methodology that accounts for fuel design characteristics and main cost components and apply it to a range of design and refueling scenarios.

Ideally a competitive FCC cost will be the result of this analysis but even if this does not prove to be the case, high cost components of the entire fabrication cost can be discerned. Once identified, these components can be developed further, if at all possible, to drive the price down. Other components might be perceived to be fixed costs therefore requiring increased efficiency in other associated costs. In any case generic fabrication costs are inadequate for progressing the FHR design optimization and this research looks to cast some light on the influence of fuel fabrication costs on the overall FHR design.

This thesis is organized as follows. Chapter 2 will discuss the background of this novel reactor design and previous work that has been accomplished in developing a FCC model as well as description of fabrication techniques used by similar fuel technologies. Chapter 3 covers in a high level of detail the geometry of the plant including fuel, the type of neutronic analysis that will be conducted, and a thorough breakdown of the component costs (material, manufacture, and QA) associated with FHR fuel fabrication and finally how it all relates to a FCC model. All results will be presented in Chapter 4 and a detailed discussion will be conducted in Chapter 5 with a conclusion summary of the significant insights this research provides.

CHAPTER 2: BACKGROUND

2.1 Fluoride-Salt-Cooled High-Temperature Reactor Development History

The use of liquid salt as a coolant started in 1954 with the Aircraft Reactor Experiments [1]. Oak Ridge National Lab (ORNL) continued the research from 1965 to 1969 with the Molten Salt Reactor Experiment, which used fuel dispersed homogenously in the coolant with graphite moderation. Limited experiments and design research were carried out throughout the 70's with Russia and China developing their own designs. Prototype plants were built and operated at the Fermi and Hanford sites. A divergence in design occurred around 2004 with focus either on molten salt fuels or solid fuel with salt coolant. University of California, Berkley in conjunction with ORNL and Massachusetts Institute of Technology (MIT) led the effort for the initial designs of an AHTR using solid fuels similar to HTGRs with molten salt coolant [6].

More recently research and development has drastically increased in pursuing an operational design of a Generation IV+ reactor with the Generation IV International Forum framework. China is pursuing a dual program at the Shanghai Institute of Applied Physics for their thorium molten salt reactor using both solid and liquid fuel [6]. Operation of the first prototype reactor is slated for 2020 with various prototypes being built up to 2032, the projected commercial deployment date. Russia is looking at molten salts for actinide recycling and transmuting of transuranic fluorides, uranium, and light water reactor (LWR) mixed oxide (MOX) fuels. Japan is pursuing a 100-200 MW_e 'near-breeder' reactor. Various commercial designs are being pursued by a few Canadian, British, and US companies such as Moltex Energy LLP, Terrestrial Energy Inc., Transatomic Power Corp., and Thorcon all toting different fuels, enrichments, and fuel cycles with no projected licensing or construction schedules.

Work at ORNL and other research organizations over the past decade have significantly advanced FHR technology. An AHTR design was chosen using the FLiBe salt as a coolant to supply roughly 1500 MWe [1]. The higher temperature and choice of salt coolant allow for near atmospheric operating pressure. The safety margin for fuel melting scenarios is much higher than that for traditional LWR oxide fuels through the use of TRISO fuel particles that use uranium oxycarbide surrounded by pyrolytic graphite and silicon carbide. These features allow for the reactor to be 'walk away' safe, a primary motivator in pursuing this type of reactor system.

Early designs relied on geometry similar to high temperature gas reactors with hexagonal assemblies containing embedded cylindrical fuel compacts [3]. ORNL also looked at pebble-bed and plank fuel configurations [7], with UC Berkeley continuing to pursue the former. The plank fuel was initially designed for use in a small modular AHTR (SmAHTR) designed for 125 MW_t, and proved to be functionally preferable to other fuel configurations as packing fraction and plank dimensions are powerful design variables [8]. The full power 3400 MW_t design currently uses plank fuel, either for a straight burn 2-year cycle with 19.75% enriched fuel [1], or for 2-batch 6-month cycle with 9% enriched fuel.

As this is mostly new technology and infrastructure, which does not currently exist for commercial scale fabrication of fuel assemblies and other reactor components, it is difficult to gauge the economic feasibility of this design. However, with the inherent safety features, long cycle length, potential for on-line refueling, higher conversion rates, and the chemical and mechanical differences from an LWR that would most likely lower capital costs, the design has great economic potential.

2.2 Fuel Fabrication

With particular regards to FHR plank fuel fabrication, much research is yet to be accomplished though the fabrication technology for other graphite compacts is fairly well developed on the lab scale. The U.S. and Germany accomplished extensive research on TRISO fabrication in the 60s and 70s. The more mature HTGR design developed the means of fabricating cylindrical and spherical (pebble) graphite fuel compacts [9]. Industrial scale manufacturing of pebble fuel is currently being pursued by Chinese Nuclear Fuel Element Co at the Baotou facility [10]. This facility will have a 300,000 pebble/year capacity starting in 2020 to support the Shidaowan HTR-PM coming online in 2017 [11].

With certain unique considerations, these technologies translate well to the fabrication of plank fuel in which TRISO compact regions can be formed and embedded in non-fuel containing graphite compact regions. The plank geometry is the real challenge in adapting fabrication techniques for HTGR cylindrical compacts and pebble bed spherical compacts. Current research by Babcock and Wilcox (B&W) on the Advanced Gas Reactor (AGR) graphite fuel compacts provides vital manufacturing knowledge for 'green' (pre-carbonized) compacts in regards to achieving desired TRISO fuel packing fractions and matrix densities [12]. Therefore, it can be seen that the fabrication techniques are indeed developed on a certain scale and can most likely be adapted readily to the FHR plank design.

It is insightful to become well acquainted with the manufacturing processes of other nuclear fuels so that parallels can be identified and information pertaining to cost may be translated over to FHR fuel. AGR and HTR-PM fuel can offer expertise on using TRISO embedded into graphite fuel compacts. Even a look at LWR uranium oxide fuel is warranted as similar fabrication stages are present (prepressing, machining/lathing, annealing, etc.) therefore fabrication facilities may contain many of the same equipment. In the following sections various fabrication techniques will be discussed.

2.2.1 Spherical Pebble and Cylindrical Compact Fabrication

The first step in both spherical and cylindrical compact fabrication (assuming that TRISO particles with fuel have already been fabricated) is to make the resinated graphite matrix powder, which involves taking the components for graphite and mixing them in sequence. Graphite compact material is typically 64% natural graphite, 16% synthetic graphite, and 20% phenolic thermosetting resins (by weight) to get the best adhesion between the matrix and the TRISO particles as well as overall compact strength [9]. The synthetic and natural graphite is first mixed in a conical mixer, with the phenolic resin dissolved in alcohol added last in a kneading machine. The now paste like material is extruded, cut into small pieces, let to dry at around 80-100°C, and finally ground and sifted to acquire powder grains of the desired size.

The next step involves coating the TRISO particles with the resinated graphite powder to a coating thickness needed to acquire the desired packing fraction once compacted (Figure 2.1). The powder and particles are mixed at a certain ratio in a rotating drum that is spinning sufficiently fast to fix the mixture to the drum walls. An agitator arm is then inserted to separate the mixture from the wall such that it falls through a methanol mist provided by a jet nozzle. The methanol ensures proper adherence of the graphite powder to the particles as well as sufficient lubricant during compacting to allow movement of particles into open spaces. Details about how long this process takes, how many particles can be coated at once, how much methanol is needed, and so forth is said to depend on the desired packing fraction and manufacturing equipment available.

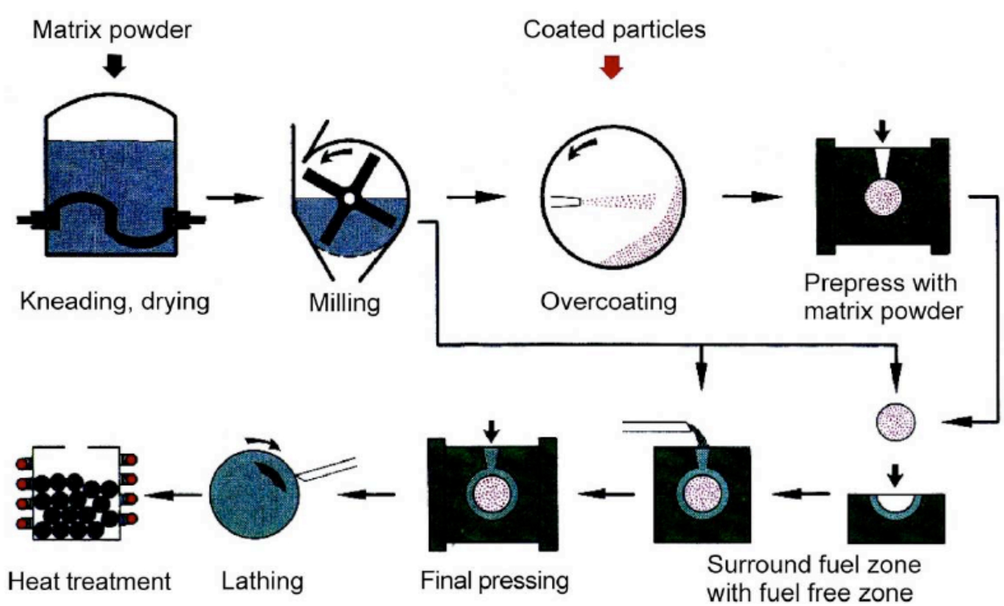

Figure 2.1 Manufacturing steps for spherical fuel compacts [10]

The first compression step (prepress) involves hot-pressing the graphite powder/TRISO particle mixture under 5-15 MPa (depending on desired density) for about 70 seconds at around 175-190 °C for packing fractions around 40-50%. For optimal compression at other packing fractions different pressures, compression times, and temperatures may be used. Desired packing fractions can be acquired with proper over-coating thickness of the TRISO particles with graphite.

The next step incorporates the prepressed fuel sphere with a fuel free zone. Spherical compacts have a central fuel region that is pre-formed and then incorporated with a layer of non-TRISO containing graphite that surrounds it. The lower half of the layer is first put into the compression chamber, the fuel region placed on top and the rest of the graphite powder fed into the top of the chamber to fill the rest of the mold. The filled mold is then pressed at 300 MPa with little concern that TRISO particles will be damaged since the fuel region is pre-formed. The spherical shape requires quasi-isostatic compression. The formation of cylindrical compacts is homogenous (no fuel free regions) and is formed with a die press as shown in Figure 2.2.

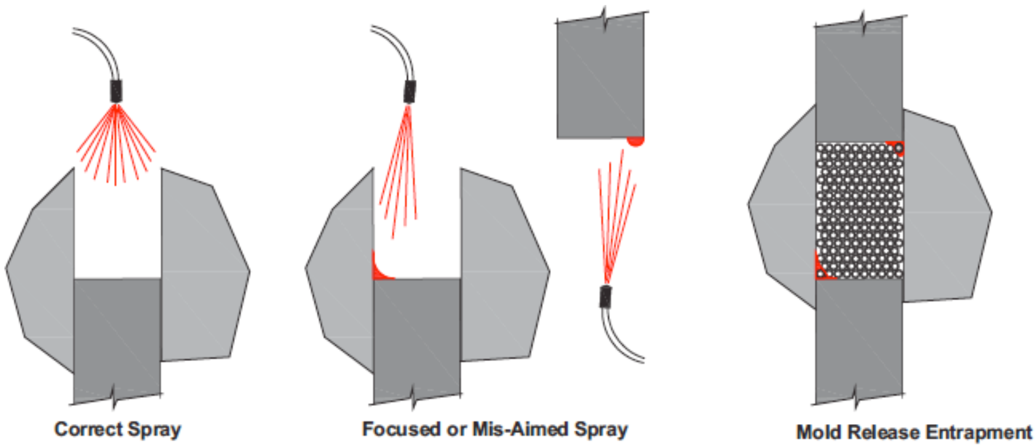

Figure 2.2: Correct and incorrect application of removal spray in a die press used in the formation of cylindrical compacts [12]

The next two stages involve furnaces for carbonizing and impurity removal. The green compacts must first be lathed and machined to specifications prior to being placed in the furnaces. Carbonization bakes the compacts in an inert helium, nitrogen, or argon environment at 800-950 °C for one hour, carbonizing the thermosetting resin binder for strength and de-gassing any organic products. Next the compacts are baked in a vacuum furnace at 1800-1950 °C for an hour to ensure removal of impurities and to increase hardness. The final products for spherical and cylindrical compacts are shown in Figure 2.3 and Figure 2.4, respectively.

Figure 2.3: A completed spherical compact and furnace mold [10]

Figure 2.4: A completed cylindrical compact. Can see TRISO particles on surface [12]

2.2.2 LWR Uranium Oxide Fuel Pellets

Light water reactor uranium oxide pellets are significantly smaller fuel elements than a FHR plank but the process has similar steps just on a different scale. Figure 2.5 shows the various manufacturing steps involved in pellet fuel fabrication. Parameters such as impurity concentration, oxide to metal ratio, and equivalent boron concentration will be carefully monitored throughout the manufacturing process particularly at the front end when recycled powder is used and at the back end after fabrication [13]. Additives such as binders and lubricants are incorporated to help with final pellet integrity and flowability. Milling and sieving then ensures consistincy in grain size, which will affect the final density (and nature of porosity) of the final product. The binders and lubricants mentioned before then promote granulation via advanced spray-drier systems for flowability into the press [14].

The presses can either be single action or double action, mechanical rotary (single cavity) or hydraulic (multi-cavity) presses or combinations there in, pressing the green compacts at roughly 150-300 MPa. Rotary systems are much faster but lack control over certain variables such as variable punch advance and press dwell time. The hydraulics systems that operate on the withdrawal system are more advanced but usually require larger machines for smaller throughput but tend to yield a more consistent product.

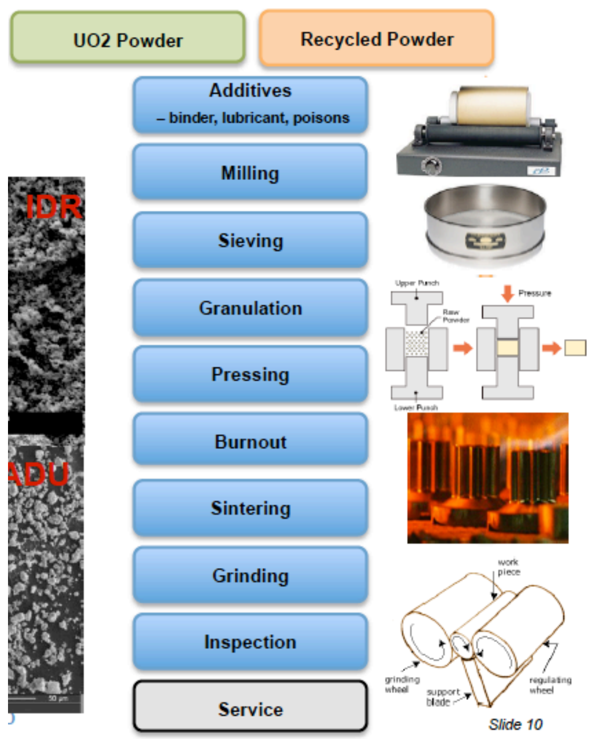

Figure 2.5: Portion of slide presentation describing the pellet manufacturing process in detail [13]

The sintering process is carried out in one stage in a hydrogen atmosphere at approximately 1600-1800 °C from anywhere between 1.5-9 hours [14]. The green pellets are loaded mechanically into furnace boats, usually made of molybdenum, and fed into mechanical or hydraulic stoker drawn furnaces or 'walking-beam' drawn furnaces. The sintered pellets are then chamfered and dished via machining and finally inspected for strength, size, and the various paramters discribed at the beginning. Any residual powder left over from any of the manufacturing steps are recycled back to the beginning of the pelleting process.

2.3 Neutronic Analysis

Simple neutronic models were developed for the SmAHTR plank fuel design to examine which CHM (carbon to heavy metal) ratio values would provide adequate moderation. Once ORNL decided on a scaled up reference design of 3400 MW_t with a 2-year cycle, mainly based on thermal-hydraulic and mechanical performance, a more thorough neutronic analysis was conducted. Most of the analyses used a number of modules from the SCALE code package, namely continuous energy (CE) KENO V (a Monte Carlo transport code) for BOC eigenvalue models and multi-group (MG) KENO V with TRITON for depletion. SERPENT and MCNP5 (via VESTA) have also been used for code-to-code comparisons and access to functionalities not available to SCALE [15]. Preliminary studies have shown that the reference core with a 2-year cycle and a ~80 GWd/MTU discharge BU could operate with high CHM ratios that translate to increased fuel utilization (better economics) while maintaining negative temperature and void reactivity coefficients (Figure 2.6 through Figure 2.8). These studies also showed fast energy neutron fluence as a limiting factor for the material integrity of components that have lengthy residence times within the core, as they would degrade fairly quickly in the harsh neutron environment [15].

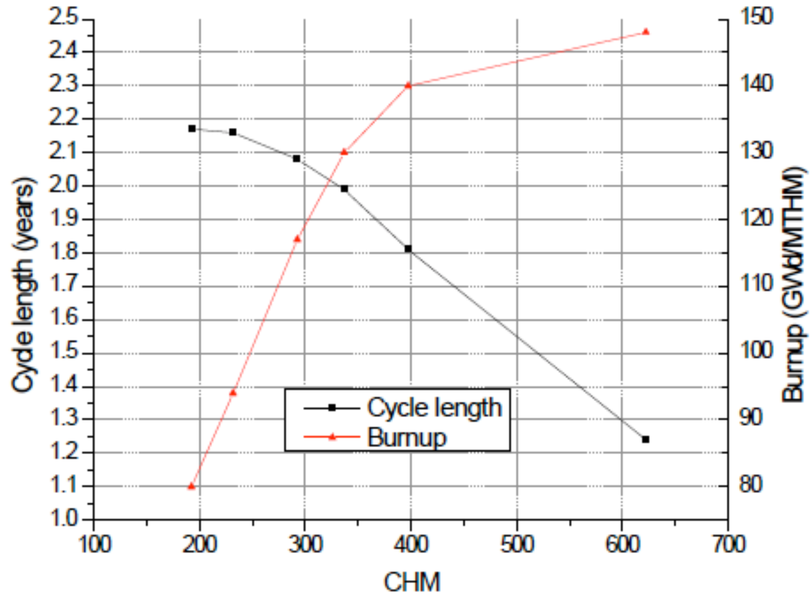

Figure 2.6: Cycle length (years) and discharge burnup (GWd/MTU) results as a function of CHM ratio for the 2-year once through reference core for ORNL's AHTR [15]

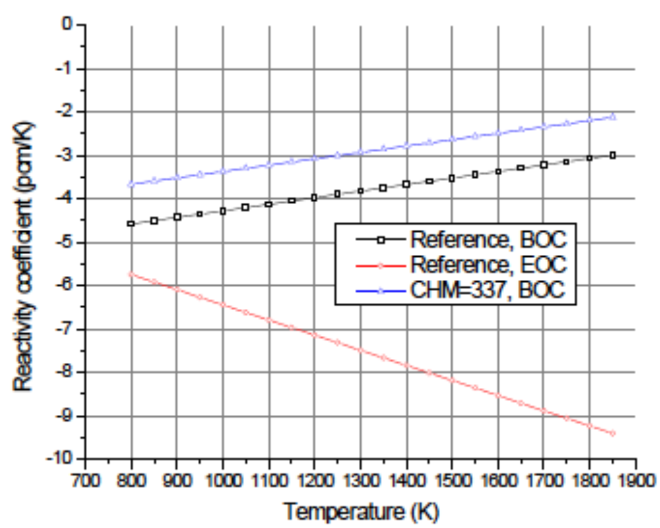

Figure 2.7: Temperature reactivity coefficient for reference designs and a CHM of 337 design [15]

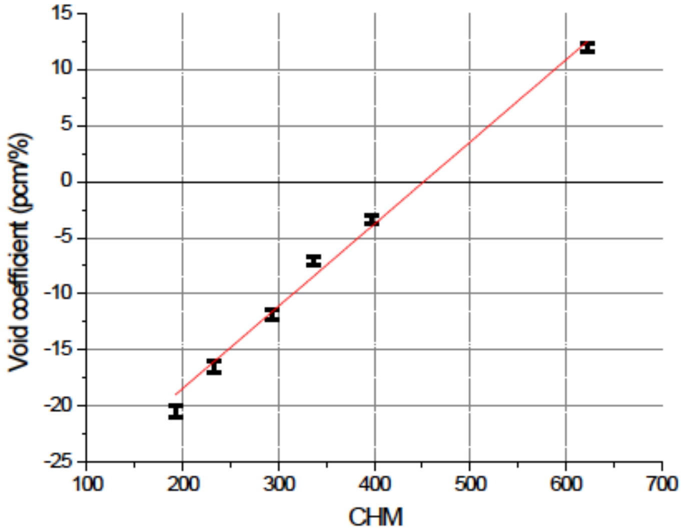

Figure 2.8: Void reactivity coefficient for a fresh core as a function of CHM ratio [15]

Certain aspects of the particle fuel design have proven to be computationally difficult to model, therefore steps have been taken to make simplifications. Simplifications decrease the time and computing resources required to run the numerous cases needed to discern an optimal configuration. The explicit grain model requiring detailed description of the fuel kernel, coating layers, and surrounding moderation is a major computational obstacle. Simple homogenization methods have shown to have a k_{eff} off by roughly 6,000 PCM compared to CE explicit grain models [16]. Another, more sophisticated homogenization method known as reactivity-equivalent physical transforms (RPT), shown in Figure 2.9, have shown burnup errors as low as 2-3% with well-matched evolutions for isotopics and multiplication factors [17]. The RPT method decreases computational time by 10-20 times over the explicit grain model.

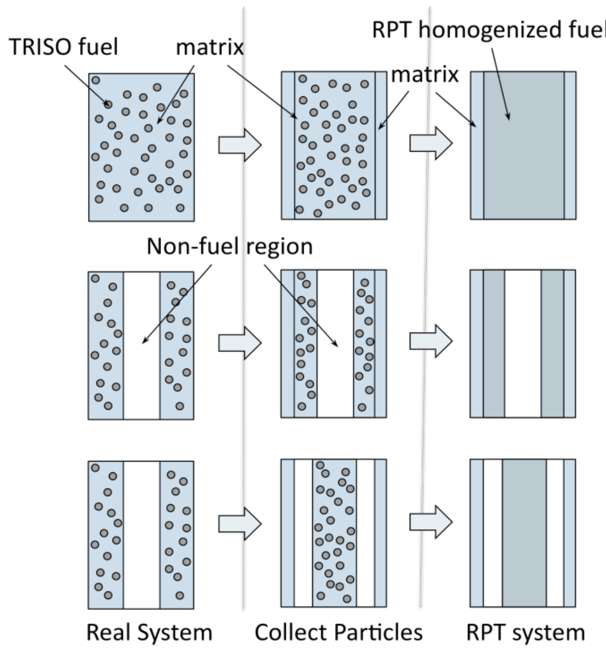

Figure 2.9: A graphical description of the RPT method. The layered slab (middle) method was more accurate but ran nearly twice as long as the solid slab approximation (bottom) [17]

Another method to properly model the physics while economizing computational resources apart from the RPT method is through the use of MG Monte Carlo calculations using Dancoff correction factors. The DOUBLEHET function, implemented in SCALE 6.1 for fuel particles in pebble bed fuel and cylindrical fuel elements, is not suitable to correctly model FHR fuel planks. Inaccuracies are present in multi-group Monte Carlo transport calculations due to the shadow effect of the neutron flux from one fuel particle on its adjacent neighbors and how this translates to cross section generation. The correction factor that exists to address this issue is known as a Dancoff-Ginsberg factor and can be used in SCALE to correct for this phenomenon [16]. These values artificially depress the escape probability (the leakage) for a neutron leaving a fuel lump, correcting the cross sections, making the model more accurate. It can be seen that for under-moderated fuel regions (low total cross section) with pitches within 2 mean free paths (modus operandi for the FHR) that the correction factors will tend to be high (closer to 1) [18]. These slight corrections will be seen to have a significant effect on burnup calculations in certain scenarios. Work has recently been completed to formulate a regression model that takes into account packing fraction, fuel enrichment, number of fuel layers, and plank thickness to yield Dancoff factors explicitly for use with the FHR model [19, 20].

Other model simplifications are more readily accepted such as the use of a perfect cubic lattice as opposed to a random distribution of fuel particles. During fabrication the particles would be arranged in a near square lattice with some manufacturing inconsistencies throughout the graphite matrix that would tend towards a random distribution. Research using a SERPENT model with built in random distribution functionality has shown that a truly random distribution has a multiplication factor, k, which differs by 150-300 PCM from the ideal square pitch case [21]. This is a relatively small error therefore it has been accepted that a cubic array provides an adequate representation.

Some other key design parameters and their effects on neutronics have been studied to varying levels of detail. Many cases have been run at various fuel enrichments ranging from 5% to 19.75% and packing factors ranging from 10% to 50% to analyze the burnup effects of replacing moderation with fuel in an under-moderated system which allows for smaller cores and initially leads to higher cycle lengths. This trend, however, will eventually hurt the system. Increasing enrichment always increases cycle length and burnup but at an increased enrichment cost and the need to increase to unprecedented (hard to license) commercial enrichments of close to 19.75% to reach the desired 2-year cycle length [3]. Also relating to neutronics, the isotopic make-up of the FLiBe coolant has been studied and results have shown that the lithium component needs to be enriched to 99.995% Li-7 for optimal performance as the natural abundance of Li-6 of about 7.5% results in a huge neutron penalty. At this phase in the FHR design many of the major obstacles in neutronic analysis have been addressed. This research will use only the most up to date models and make correction that have yet to be applied to a formal fuel cycle cost model.

2.4 Fuel Cycle Cost Model

Cost estimate models have been applied to the FHR to compare against the total cost of LWRs to see if the FHR is economically competitive. These models predict a fuel cycle cost (not accounting for the plant capital costs) that is two to four times more costly than in LWR systems but economy is saved by relatively lower capital and operation and maintenance costs [1]. These values, while good as a big picture comparison, do not account for important factors such as material and fabrication costs and burnup performance that are used in formulating the FCC model. As many of the larger components and systems in the FHR are new technologies that need many years of research and development much of the capital costs stated in these previous studies are admitted as conjecture.

The computational tools and analogous technologies exist to start piecing together a fairly comprehensive fuel cycle model that takes into account cost of material and fabrication of the fuel, reactor performance such as burnup, and outage costs. The more detailed FCC models do not, at this time, include the cost for waste disposal that is usually included in these evaluations. Spenser Lewis completed the most exhaustive FCC model to date [3]. In that model the current market uranium and enrichment costs were coupled with a range of three fuel fabrication costs, $1,300/kgU (low), $4,000/kgU (base), and $24,000/kgU (high), acquired from another study of graphite fuels. These were coupled with burnups from all variations of the enrichments (5-19.75%) and packing factors (10-50%) mentioned earlier acquired from twenty SCALE 6.1 whole core depletion runs with estimated outage costs of $20 and $50 million per outage [22]. In that study, with the use of a linear reactivity model (LRM), trends where identified over enrichments, packing factors, batch numbers, and outage costs.

It was seen that low enrichments and high packing factors were costly as they had short cycle lenghts and poor fuel utilization. At base and high fabrication costs and a high outage cost of $50 million all designs were prohibitively expensive or had cycle lenghts that were too short. This fabrication cost does not discriminate between packing factors. With increased packing factor there is more heavy metal loading per plank and the fabrication cost, ideally on a per plank basis, needs to be translated to a per kgU basis. This would give some economic incentive to higher packing factors as well as the need to make less of them to acquire the same power output. This research strives to deduce a more informed range of fabrication costs and include a correlation between fabrication cost and packing factor. If these costs prove to be significant this will effect the considerations for an optimal final design in profound ways.

CHAPTER 3: MODEL AND METHODOLOGY

3.1 Overview

The flowchart shown in Figure 3.1 is a high level overview of the process used in the analysis described in this section. The chosen fuel design influences how the neutronic corrections relating to double heterogeneity and temperature are treated as well as the specifics of materials, manufacturing, and quality assurance needed to realize the design. The neutronic corrections are used to formulate single batch data. Multi-batch data is acquired via the use of the linear reactivity model. The neutronic side of the analysis is pictured in blue and the fuel cost side in grey. The amount of materials, type of manufacturing facility, and the level of quality assurance drive fabrication cost. The uranium market drives the cost for natural uranium and enrichment. The sum of these components yields the total cost of fuel. Fuel cost and discharge burnup data can be coupled with thermal efficiency and refueling cost to yield the fuel cycle cost which is in dollars per unit energy ($/MWhe). This value is used to inform the optimal fuel design.

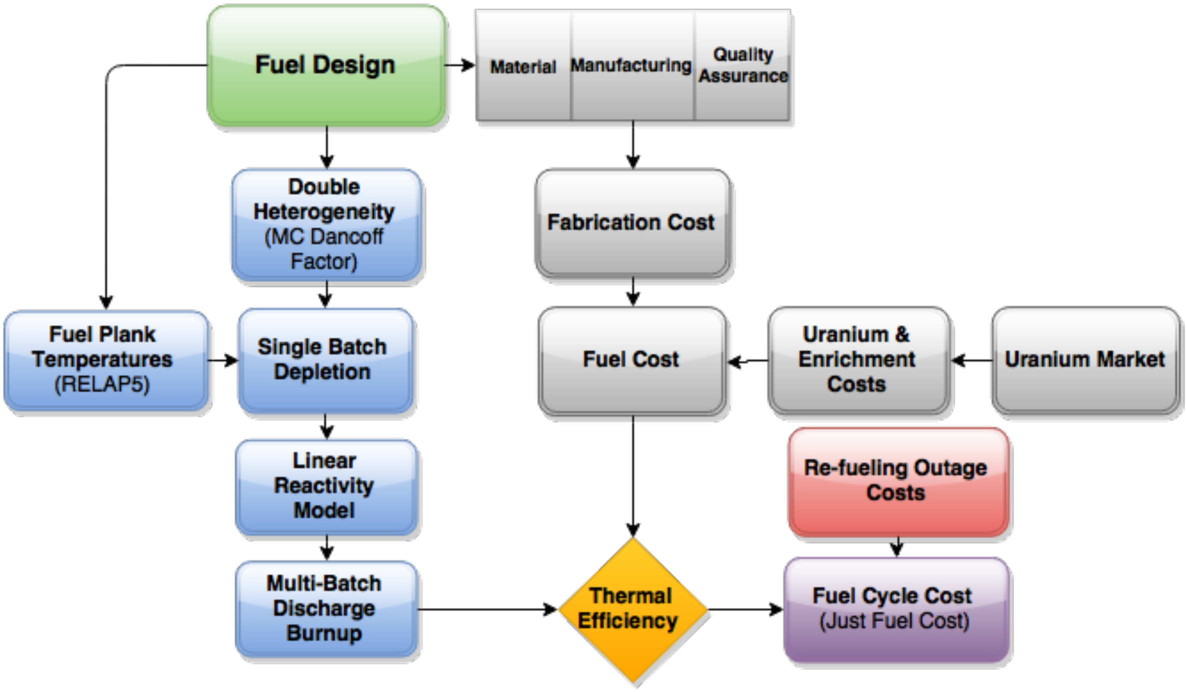

Figure 3.1: Flowchart describing analysis used

3.2 FHR Design

3.2.1 Fuel Design

The latest TRISO particle, fuel plank, and fuel assembly design iterations proposed by ORNL have dimensions presented in Table 3.1, Figure 3.2, and Table 3.2:

Table 3.1: Design details for current FHR hexagonal assembly plank fuel configuration (diagrams in cm) [23]

Characteristic	Value	Units
Total height	600	cm
Fueled region height	550	cm
Fuel assembly pitch	46.75	cm
Outer apothem	22.5	cm
Channel box wall thickness	1	cm
Y-shape thickness	4	cm
Coolant thickness between plates	7	mm
Coolant thickness between plate and wall	3.5	mm
Control blade location thickness	1	cm
Control blade location wing length	10	cm
Fuel plate thickness	2.55	cm
Number of fuel plates	18	-

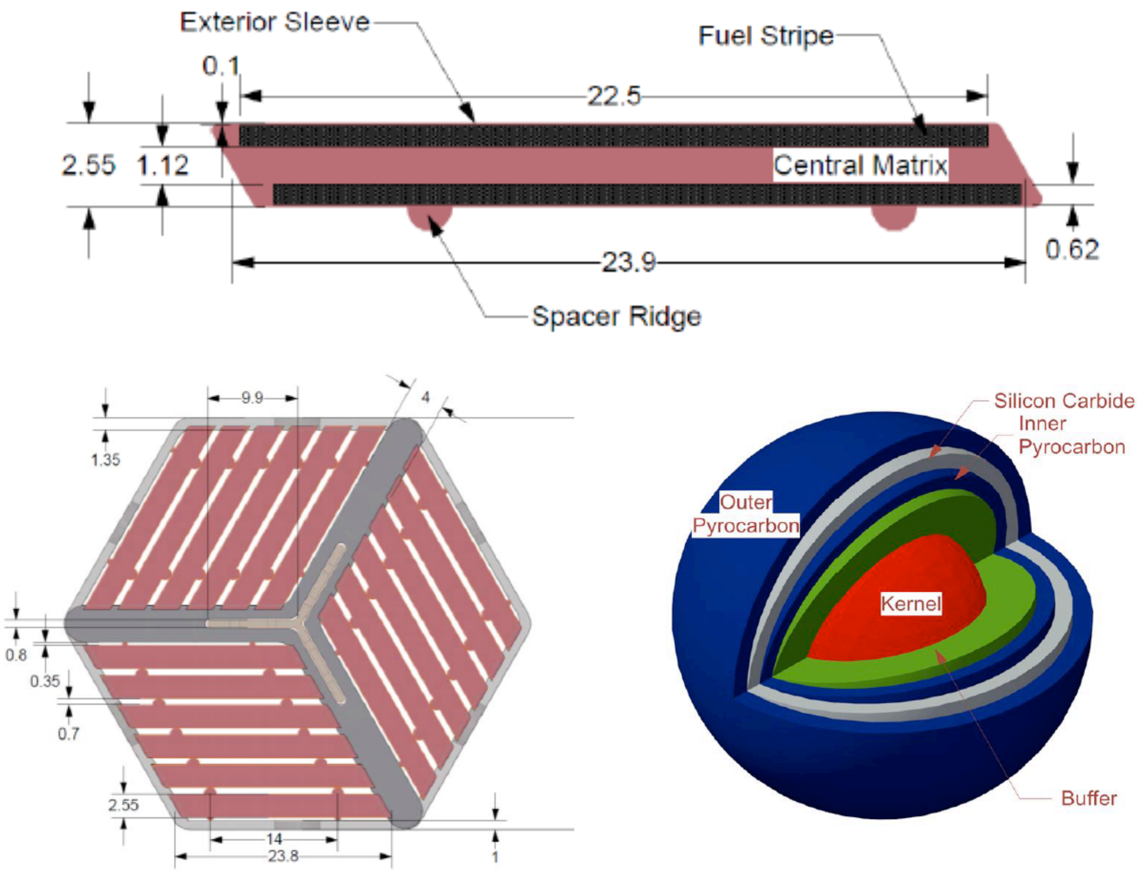

Figure 3.2: Dimension diagrams (cm) of fuel planks, hexagonal assembly, and TRISO particle [23]

Table 3.2: TRISO particle kernel and coating material thicknesses and densities

Region	Parameter	Parameter Value (μm)	Material	Density (g/cm³)
Kernel	diameter	427	Uranium Oxycarbide	10.90
Buffer	thickness	100	Porous Graphite	1.00
IPyC	thickness	35	Pyrolitic Graphite	1.90
SiC	thickness	35	Silicon Carbide	3.20
OPyC	thickness	40	Pyrolitic Graphite	1.87
Fuel Particle	diameter	847	-	-
Fuel Matrix	-	-	Carbon Material	1.59

It is important to note that these dimensions reflect the first iteration of the ORNL FHR design. As more detailed neutronic and thermal-hydraulic models continue to be developed variables such as fuel layers, plate thickness, and assembly spacing are expected to change. For the sake of pursuing a detailed fabrication cost analysis these variables will be held constant but presented in such a way that they can be readily updated as more optimal design iterations are developed.

The fuel planks each contain two rows of fuel regions that are 0.62 cm thick, 22.5 cm long, and 550 cm tall. These regions are populated with the Uranium Oxycarbide (UCO) TRISO fuel particles based on a prescribed packing fraction. Using the known spherical volume of the fuel the appropriate three-dimensional pitch between particles is calculated based on packing fraction as follows:

$$PF \cdot P^3 = \frac{4}{3}\pi\left(D/_2\right)^3$$

Eq 3.1

$$P = \sqrt[3]{\frac{4}{3}\pi\left(D/_2\right)^3 \cdot \frac{1}{PF}}$$

Where P is pitch, PF is packing factor, and D is TRISO particle diameter. The Y-dimension of the cubic lattice (number of fuel layers) is fixed at 7. To keep the fuel layer value constant the fuel strip thickness of 0.62 cm is changed based on the calculated cubic pitch. Note that due to the fixed number of fuel layers and the resulting variable fuel strip thickness, the amount of fuel is not directly proportional to PF.

Table 3.3: Calculated fuel particle cubic pitch, fuel strip thickness, and graphite meat thickness in centimeters

Packing Fraction	Pitch (cm)	Fuel Strip Thickness (cm)	Graphite Meat Thickness (cm)
10%	0.14708	1.02955	0.29090
20%	0.11674	0.81715	0.71569
30%	0.10198	0.71385	0.92230
40%	0.09265	0.64858	1.05285
50%	0.08601	0.60208	1.14583

Table 3.3 shows the calculated cubic pitch for the various packing fractions as well as the fuel strip thickness (the pitch times seven) and the graphite meat thickness, which is the difference between two fuel strip thicknesses and the total plank thickness. The planks would not be physically made this way. This assumption is for neutronic purposes only. The planks also contain two reflector regions above and below the fuel regions that are 25 cm each. These portions of the plank do not contain fuel and make the entire plank 600 cm tall. The fuel planks are placed in a hexagonal assembly with 18 planks per assembly (Figure 3.2).

There are three major types of material regions (ignoring control rods). Various carbon-carbon (graphite: ρ=1.96 g/cc) materials make up the non-fuel portion of the fuel planks, the assembly walls, and reflector regions. The fuel region temperatures have been analyzed using a RELAP5 model [4] and regression formulas were created by Michael Huang to give temperatures in Kelvin for the fuel temperature and the graphite meat temperature based on number of fuel layers (FL), plate thicknesses (PT), and packing factors (PF) as follows:

$$Fuel\ Temperature = 1151.6 + FL \cdot 5.164 - PT \cdot 0.550806 \ldots$$
$$\ldots - PF \cdot 0.890403 + 0.049156 \cdot FL \cdot PF + 0.0147657 \cdot PF^2$$ **Eq 3.2**

$$Meat\ Temperature = 1083.33 + FL \cdot 8.14124 - PF \cdot 1.40689 \ldots$$
$$\ldots + PF \cdot FL \cdot 0.077788 - 1.00339x10^{-3} \cdot PT^2 + 0.0233063 \cdot PF^2$$ **Eq 3.3**

Where fuel layers and plate thickness are fixed at 7 and 2.55 cm, respectively. The following temperatures for the range of packing factors are show in Table 3.4. All other materials are assumed to be at 948 °K.

Table 3.4: Temperatures in Kelvin for fuel and graphite meat regions calculated from regression formulas from RELAP5 model [4]

Packing Factor	10%	20%	30%	40%	50%
Fuel	1182	1181	1183	1188	1196
Meat	1134	1132	1135	1143	1155
Coolant	948	948	948	948	948

The coolant is at an average operating temperature of 948.15 °K and is comprised of Fluoride-Lithium-Beryllium (Li_2BeF_4 – FLiBe) with Lithium enriched to 99.995% Li-7 due to the high thermal neutron capture cross-section of Li-6 [3]. The boiling temperature, density, and specific heat are 1430° C, 1940 kg/m^3, and 2.34 kJ/kg °C, respectively.

The assembly channel structure is assumed to be comprised of six 1 cm thick, 600 cm tall, and 26 cm long rectangles that make up the hexagonal structure, three 23 cm long, 4 cm thick, and 600 cm tall rectangles for the inner Y-shape with a 4 cm equilateral triangle 600 cm tall to make up the middle portion of this structure. The control blade slots are assumed to be three rectangles 9.9 cm long, 0.8 cm thick, and 600 cm tall. This information will be used when required fuel fabrication materials are discussed.

3.2.2 Reactor Design

The entire core is populated with 252 assemblies with one graphite reflector/instrumentation assembly in the center of the core and more as a replaceable reflector on the core boundaries (Figure 3.3).

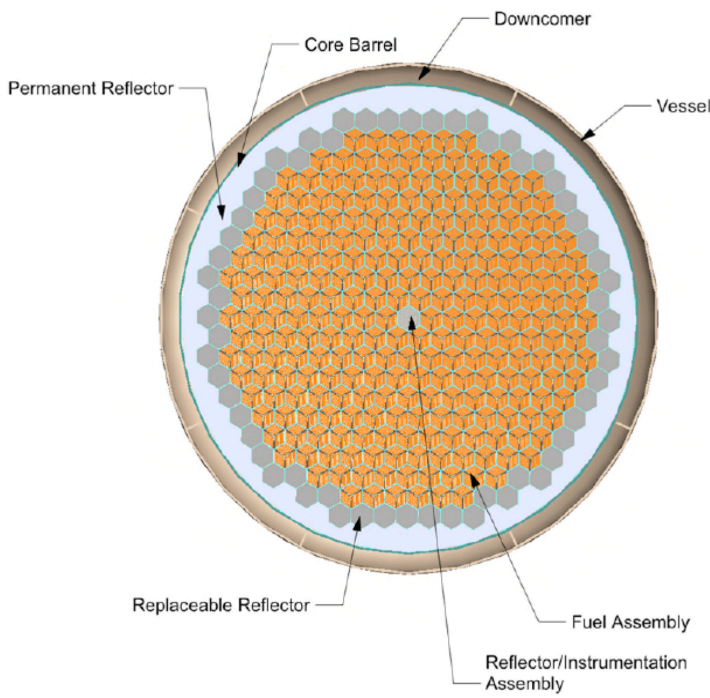

Figure 3.3: FHR core diagram [15]

The total thermal output is rated at 3400 MW with a conversion factor estimated at 44.12% yielding an electric output of 1500 MW. The range of packing factors have a varying level of heavy metal loading for a fixed number of assemblies. A specific power can be calculated based on the rated thermal output and the number of particles in a core and the heavy metal loading in each particle (3.97×10^{-7} kgU) to yield the following Table 3.5:

Table 3.5: Heavy metal loading and specific power of the core based on packing fraction [3]

Packing Fraction	Core Power (MW)	Heavy Metal Mass (kg)	Specific Power (MW/MT)
10%	3400	13785	246.65
20%	3400	21769	156.19
30%	3400	28596	118.90
40%	3400	34621	98.21
50%	3400	40200	84.58

An important component of the FCC model is the associated outage costs. For LWRs it is common to assume about a million dollars for every outage day but with the FHR this number will depend on the number of batches and the size of the reactor. As little is known on the efficiency of the refueling mechanism or what batch number will likely be used as pseudo-online refueling is a possibility for this type of reactor two outage costs will be assumed. For this analysis a base and high outage cost of $20 and $50 million will be used.

3.3 Neutronic Analysis

The TRISO particle is approximated in the neutronic model as a fuel region comprised of U-235, appropriately enriched, U-238, U-234, O-16, and C-graphite (from SCALE 6.1 standard composition library) with the outer regions smeared into a homogeneous mixture of C-graphite and silicon. The entire core is modeled in the X-Y dimensions with only a slice modeled in the Z dimension. The Z-dimension array number is fixed at one hundred so the modeled height of the reactor is one hundred times the calculated pitch of the TRISO particles (a representative slice from the middle of the reactor) optimized for computation time and accuracy [3]. A vacuum boundary condition was placed on the X-Y boundary faces (reactor outer boundary) as this will account for leakage in the reactor with mirror boundary conditions on the Z boundary faces. The reflector region of the core boundary is a series of replaceable hexagonal graphite blocks similar to the fuel assemblies, roughly 88 cm thick. This region is bounded by two alloy vessels with coolant between the vessels.

A detailed equilibrium cycle was not used in this reactor model therefore enrichment is uniform throughout the reactor and core depletion as a single zone was imposed (judged to provide more representative results than multi-zone depletion, since it is starting with a uniform enrichment distribution). Depletion was analyzed for about 100 to 1000 days depending on the fuel enrichment, with 8 to 18 burn steps going in 1 day, 2 day, 3 day, 5 day, 10 day, 20 day, 60 day, and 100 day increments, with every subsequent step being 100 days. The models were run with 400 generations, 20,000 particles per generation, with 40 skipped generations, the statistics used in the previous FCC model [3]. While this is likely not enough to generate local results of acceptable statistical quality, it was deemed adequate for the purpose of this study, i.e., cycle length estimates. The errors on k_{eff} associated with these parameters ranged between about 15-30 PCM.

To calculate the discharge burnup linear interpolation is used between the two burnsteps surrounding the shift from supercritical to subcritical k_{eff} to determine the effective full power days (EFPD). The EFPD is then multiplied by the specific power (for the appropriate packing factor) and the discharge burnup in GWd/MTU is determined.

Using multiple refueling batches increases fuel utilization (increases discharge BU) at the cost of shorter cycle length. This model will use a linear reactivity model (LRM) to calculate multi-batch cycle lengths and discharge burnups as follows [2]:

$$BU_N = \frac{2 \cdot N}{N+1} BU_1 \quad \textbf{Eq 3.4}$$

$$CycL_N = \frac{2}{N+1} CycL_1 \quad \textbf{Eq 3.5}$$

Where N is the batch number, BU_1 is the once through discharge burnup, and $CycL_1$ is the once through cycle length. Other non-linear reactivity models could be used that employ higher order polynomials to map the reactivity change over burnup [17]. These models provide more accurate maximum discharge burnups, 3-4% predicated burnup error compared to within 7% for LRM, but for the sake of efficiency and comparison (Lewis's FCC model used LRM) the LRM will be used.

The major update to the neutronic model comes with the insertion of an MC Dancoff correction factor in the TRITON depletion module of a KENO VI 3-D model in SCALE 6.1. As it pertains to this model, the MC Dancoff factor is dependent on packing factor and enrichment. Sampling these variables via the help of a Latin hypercube, a data set of properly converged MC Dancoff factors was assembled [19]. The convergence criterion was based on the results of an explicit continuous energy model. It was shown that using these BOC-generated MC Dancoff factors for all depletion steps results in an observable but acceptable error of 59.2 max residual pcm [20]. With this data set a regression formula was derived with a set of fitted constants as follows:

$$MC\ Dancoff = 0.845717 + PF \cdot 3.50987x10^{-3} \ldots$$ **Eq 3.6**

$$\ldots - PF^2 \cdot 4.64103x10^{-5} - EN \cdot 8.8482x10^{-5}$$

With PF [%] as packing factor and EN [%] as enrichment. Over the range of packing factors and enrichments the following MC Dancoff factors are acquired (Table 3.6):

Table 3.6: MC Dancoff factors over the range of packing factors and enrichments acquired from Eq 3.6

PF/EN	5%	10%	15%	19.75%
10%	0.87573	0.87529	0.87485	0.87443
20%	0.89691	0.89647	0.89602	0.89560
30%	0.90880	0.90836	0.90792	0.90750
40%	0.91141	0.91097	0.91053	0.91011
50%	0.90474	0.90430	0.90386	0.90344

It is seen that the correction factors change little or not at all over enrichments for low packing factors and only slightly more for higher packing factors. Based on Eq 3.6 packing factor dominates with enrichment having little influence. The core is depleted as a single region to correspond with depletion of a single assembly and to simplify the model. While introducing inaccuracies modeling the core in this way yields acceptable depletion results [3].

3.4 Fuel Cycle Cost Model

3.4.1 FCC Breakdown

The fuel cycle cost in this model only takes into account fuel cost and outage cost ignoring waste disposal and reactor capital cost. The total fuel cost takes into account fuel ore, enrichment, and conversion cost as well as fuel fabrication cost (fabrication of TRISO particles and fabrication of fuel planks) where every cost is ultimately translated into dollars per kilogram uranium. The end of the month spot prices gathered from UxC on May 25, 2015 are as follows:

Table 3.7: Spot prices for uranium ore, conversion, and SWUs from UxC May 25th, 2015

Product	Price
U3O8 (lb)	$35.00
U3O8 (kg)	$77.16
U3O8 (kgU), $\dot{P}_{ore}$	$90.99
Conversion (kgU), $\dot{P}_{conv.}$	$7.50
UF6 (kgU)	$98.50
SWU Price (SWU), $\dot{P}_{SWU}$	$70.00

These prices were used to calculate the fuel costs with the following equations [2]:

$$F = P + W \qquad \text{Eq. 3.7}$$

$$x_f F = x_p P + x_w W \qquad \text{Eq. 3.8}$$

$$\frac{F}{P} = \frac{x_p - x_w}{x_f - x_w} \qquad \text{Eq. 3.9}$$

$$\frac{W}{P} = \frac{F}{P} - 1 \qquad \text{Eq. 3.10}$$

$$V(x_i) = (2 \cdot x_i - 1) \cdot \ln\left(\frac{x_i}{1 - x_i}\right) \qquad \text{Eq. 3.11}$$

$$S = V(x_p) + \frac{W}{P} \cdot V(x_w) - \frac{F}{P} \cdot V(x_f) \qquad \text{Eq. 3.12}$$

$$\dot{P}_{enr.U} = \left[\frac{\dot{P}_{ore}}{(1 - l_c)(1 - l_f)} + \frac{\dot{P}_{conv.}}{(1 - l_f)}\right] \cdot \frac{F}{P} + \frac{\dot{P}_{SWU}}{(1 - l_f)} \cdot S \qquad \text{Eq. 3.13}$$

$$\dot{P}_{fuel} = \dot{P}_{enr.U} + \dot{P}_{fab} \qquad \text{Eq. 3.14}$$

The input and output rates for feed, product, and tails (waste) are designated by F, P, and W, respectively. The desired fuel enrichment in weight fraction is designated by x_p, with x_f and x_w representing the feed enrichment of 0.711% and waste stream enrichment of 0.2%, respectively (percent values translate to fraction in the normal way). The separation potential, $V(x_i)$, a function of x_p, x_f, and x_w, is used in the subsequent SWU factor equation, which calculates the SWUs needed per kgU enriched. Eq. 3.13 brings the spot prices from UxC ($\dot{P}_{ore}$ for U3O8 (kgU), $\dot{P}_{conv.}$ for conversion, and $\dot{P}_{SWU}$ for SWU price) together with the SWU factor, S, and any loses that could occur from conversion and fabrication, l_c and l_f, which are assumed to be zero. This yields the total cost of enrichment ($\dot{P}_{enr.U}$) found in Table 3.8 which, when added with the fuel fabrication costs ($\dot{P}_{fab}$), results in the total cost of the fuel.

Table 3.8: The total cost of enriched uranium taking into account ore, conversion, and enrichment

x_p	x_f	x_w	Enrichment Cost ($/kgU)
5%	0.71%	0.20%	1544.74
10%	0.71%	0.20%	3349.34
15%	0.71%	0.20%	5178.35
19.75%	0.71%	0.20%	6926.44

The fuel fabrication costs used in the previous FCC model developed by Spenser Lewis were a low, base, and high cost ($1300/kgU, $4000/kgU, and $24,000/kgU, respectively) chosen to cover possible fabrication scenarios. This research looks to derive more accurate fabrication cost values accounting for specific fuel designs.

Once the total fuel cost is calculated it is coupled with the discharge burnup and conversion factor to take into account fuel utilization and electricity produced as shown in Eq 3.15. The two outage costs mentioned before are treated in a similar manner as they are coupled with the net power produced and cycle length as shown in Eq 3.16.

$$Fuel\ Cost\left(\frac{\$}{MWh_e}\right) = \frac{(Total\ Cost\ of\ Fuel)}{(BU)\cdot(Efficiency)} \qquad \textbf{Eq 3.15}$$

$$Outage\ Cost\left(\frac{\$}{MWh_e}\right) = \frac{(Outage\ Cost)}{(Power)\cdot(Cycle\ Length)\cdot(Efficiency)} \qquad \textbf{Eq 3.16}$$

Where BU and cycle length are taken from the neutronic model, the conversion factor (CF) is 44.1%, and the power is 3400 MW. The FCC is calculated by adding Eq 3.15 and Eq 3.16.

3.4.2 Fabrication Component Cost: Materials

The cost for materials is broken into a TRISO, plank, and channel component. The TRISO particles are comprised of enriched uranium kernels (427 μm diameter) and various forms of graphite and silicon carbide, yielding a total diameter of 847 μm. The total enriched fuel cost calculated before includes the price for enriched UF_6 leaving the cost for the conversion to UCO and the various coating materials for TRISO to be determined. It has been calculated for TRISO particles the cost of ore, SWUs, graphite, silicon carbide, and conversion from UF_6 to UCO for fuel that is 75% UCO enriched to 19.8% U-235 and 25% natural UCO as $5,900/kgU [24]. Since this study aims to find the fabrication cost for various enrichments, the enrichment costs need to be separated from this figure to isolate the cost of conversion and coating materials. Using the spot prices for the uranium market in 2002 [© UxC] with 75% of the fuel enriched to 19.8% and 25% kept natural, the price for enrichment is about $4600/kgU. This leaves approximately $1300/kgU for conversion and TRISO coating materials, $1,000/kgU will be assumed to take into account any fluctuations in the uranium market. This is an approximate figure but holds credibility due to the enrichment cost of uranium up to 19.8% costing no less than $5,000/kgU in present day markets based on conservative estimates. This value is the material cost of the TRISO fuel ($\dot{P}_{mat,TRISO}$).

Moving on to the plank and assembly channel materials, graphite compact material is typically 64% natural graphite, 16% synthetic graphite, and 20% phenolic thermosetting resins (by weight) to get the best adhesion between the matrix and the TRISO particles as well as overall compact strength [9]. The cost for these three materials on a per gram basis and also the cost of methanol on a per liter basis were ascertained as part of a lab scale fabrication study in which non-nuclear grade graphite was used and can be found in Table 3.9 [25].

Table 3.9: The quoted cost of materials for fuel plank fabrication and supplier sources

Variable Cost	Definition	Description	Reference
Natural Graphite, $\dot{P}_{gr,1}$	75	[$/kg] Not explicitly nuclear grade	VWR
Synthetic Graphite, $\dot{P}_{gr,2}$	65	[$/kg] Not explicitly nuclear grade	VWR
Phenolic Resin, $\dot{P}_{gr,3}$	19.5	[$/kg] Including HEXA	Hexion
Methanol, $\dot{P}_{gr,4}$	2.5	[$/L]	VWR

Certain fuel fabrication facilities have the capacity to purify graphite on site in a two-step chemical pulping treatment process so cost of purified graphite can be assumed to be lumped into the fabrication facility cost discussed in the next section [10]. Also the need for bulk purchase would likely keep the price of graphite low. The assembly channels are assumed to be replaced at a rate of one for every eighteen fuel planks replaced and since the density is higher than the fuel plank and would require a different ratio of component graphite materials the highest cost, natural graphite, was assumed to make up the entire channel as a conservative estimate.

Idaho National Laboratory suggests GrafTech International's PCEA and PGX grade graphite as worthy candidates for high dose-regions in high temperature prismatic cores [26]. The more recent B&W research used Hexion SD-1708 and Plenco 14838 for resins, Asbury 3482 for natural graphite, and SGL Carbon KRB-2000 and GrafTech GTI-D for synthetic graphite in development of AGR fuel compacts [12]. The appropriate volumes, densities and material mass fractions were used (Table 3.10) to calculate the heavy metal (uranium) and graphite loading per plank as well as other component materials, such as methanol, for various packing fractions (Table 3.11). These figures, when coupled with the cost of graphite per gram ($\dot{P}_{gr,i}$ in Eq. 1, i is the index for the graphite components), will yield the cost of graphite materials per plank. This can then be divided by the heavy metal loading per plank to give a price on a per kilogram uranium basis ($\dot{P}_{mat,gr}$ in Eq. 3.17) that can then be incorporated into the greater cost estimate model.

Table 3.10: Volumes, material characteristics, and other material factors used to calculate the cost of materials in FHR plank fabrication

Vol. TRISO (cc)	0.000318162
Vol. TRISO Kernel (cc)	4.07645E-05
Vol. Entire Plank (cc)	36567
Vol. Plank w/ Fuel (cc)	33519.75
Vol. Channel (cc)	249000
Channel C-C Density (g/cc)	1.96
Graphite Matrix Density (g/cc)	1.59
UCO Density (g/cc)	10.9
Uranium Density (g/cc)	9.74
Mass Fraction Natural Graphite	0.64
Mass Fraction Synth. Graphite	0.16
Mass Fraction Phenolic Resin	0.2
L of Methanol per gram of powder	0.00616
Vol. Chan/Vol. Plank	7.428

Table 3.11: Amount of TRISO and component graphite and methanol for planks and channel for range of packing factors

	Packing Factor				
	10%	20%	30%	40%	50%
Vol. Fuel Stripe (cc)	12740.7	10112.3	8833.9	8026.1	7450.8
TRISO Particles Per Plank	8008921	12713370	16659227	20181216	23418227
kg U per TRISO Particle	3.97046E-07	3.97E-07	3.97E-07	3.97E-07	3.97E-07
kg U per Plank, $M_{U/plank}$	3.2	5.0	6.6	8.0	9.3
Graphite per Channel (g), $m_{gr,ch}$	488040	488040	488040	488040	488040
Graphite Per Plank (g)	54090.0	51710.1	49714.0	47932.3	46294.8
Nat. Graphite Per Plank (g), $m_{gr,1}$	34617.6	33094.5	31817.0	30676.7	29628.6
Synth. Graphite Per Plank (g), $m_{gr,2}$	8654.4	8273.6	7954.2	7669.2	7407.2
Phenolic Resin Per Plank (g), $m_{gr,3}$	10818.0	10342.0	9942.8	9586.5	9259.0
Methanol per Plank (L), $m_{gr,4}$	333.2	318.5	306.2	295.3	285.2

$$\dot{P}_{mat,gr} = \frac{1}{M_{U/plank}} \cdot \sum_{i=1}^{4} m_{gr,i} \cdot \dot{P}_{gr,i} + \frac{m_{gr,ch} \cdot \dot{P}_{gr,1}}{M_{U/plank} \cdot 18_{planks}/_{assembly}} \quad \textbf{Eq. 3.17}$$

In review, the material costs for fuel fabrication aside from the enriched uranium are distributed between the conversion and layer materials of the TRISO particle and the various graphite and methanol materials used to make the FHR plank and assembly channels (Eq. 3.18).

$$\dot{P}_{mat} = \dot{P}_{mat,gr} + \dot{P}_{mat,TRISO} \quad \textbf{Eq. 3.18}$$

3.4.3 Fabrication Component Cost: Manufacturing

An attempt was initially made to analyze the minutiae of the FHR plank manufacturing process, assimilated from similar graphite compact fuel manufacturing processes, and attribute a cost to every major step. This approach introduced too many unknowns such as cost of presses and furnaces, number of personnel, power/fuel consumption of equipment, etc. and was therefore abandoned. The new approach is to compare, wholesale, the manufacturing process to more developed particle/graphite fuels such as spherical and cylindrical compacts and even LWR oxide fuels. Details such as the capital cost of fabrication facilities, operation and maintenance (O&M) cost for these facilities, and yearly manufacturing capacities are available and can be translated to the FHR plank design. Cost discrepancies are likely to exist between these fuel designs but approximations will be made to take into account FHR specific parameters such as packing factor.

Comparing the fabrication process for spherical and cylindrical fuel with LWR oxide fuel many similarities can be discerned and can be applied to the FHR plank. The powders need to be processed to ensure consistent grain size, flowability, and agglomeration. The graphite compacts need to have phenolic resin for structure and strength and methanol to help with particle coating. The particle coating process for spherical and cylindrical compacts will be exactly the same for FHR planks with coating thickness determining packing fraction. The pressing process is nearly similar for all fuels considered with a pre-pressing phase forming green compacts that are machined and then baked in one or more annealing phases at various temperatures.

The spherical compacts are surrounded by a fuel-free region and are thusly the most similar to the type of layering that needs to occur in the FHR plank. Various regions of the fuel will be pre-formed such as the two fuel strip regions and possibly the graphite meat middle portion and then placed in a mold with the 1 mm thick outer coating pre-filled into the mold. The entire form will then be pressed at approximately 300 MPa before being baked in a rather large furnace in two phases similar to the other graphite compacts. The lab scale fabrication study carried out at Georgia Tech has shown some issues with pressing pre-formed fuel layers together but with the proper compression dies and carefully controlled compression rates and pressures this should be achievable [25]. Once baked the fuel can be further machined and inspected and is then ready for either the core or, in the case of LWR fuel, to be put into cladding and then into assemblies.

Identifying the manufacturing similarities allows comparison of capital and O&M costs and capacity. A detailed study was carried out by Fluor-Daniel to appraise the cost of building a 3 MTU/yr facility to manufacture Modular HTGR prismatic fuel enriched to 93% [24]. This study reported a capital cost of $355 million and an O&M cost of $22.6 million per year. A ballpark estimate provided by Westinghouse for a LWR fuel fabrication facility was $400-500 million for a 200-400 MTU/year facility with an annual O&M cost of $120 million [5]. Its is difficult to discern the yearly capacity of an FHR fuel fabrication facility but it is logical to assume that a single facility will need to support multiple FHRs. A Typical LWR fuel fabrication site supports 50 reactors but due to the novelty of the fabrication techniques and the size of the FHR planks it will be assumed that a single site can support about 10-25 FHRs. A single FHR site will need roughly 125-250 assemblies replaced annually depending on reload cycle. This corresponds to an estimated fabrication capacity of about 1500-4500 assemblies, or about 27,000-81,000 fuel planks. Table 3.12 shows the MTU per year capacity over a few values of the assumed annual fuel plank fabrication capacity for various packing factors.

Table 3.12: FHR plank MTU/yr capacity conversions for various packing factors

	Packing Factor				
	10%	20%	30%	40%	50%
27,000 Plank/Year	85.86	136.29	178.59	216.35	251.05
54,000 Plank/Year	171.72	272.58	357.18	432.70	502.10
81,000 Plank/Year	257.57	408.87	535.77	649.04	753.15

Yearly capacity has a significant influence on the capital and O&M costs distributed over every plank produced over the amortization period of the fabrication facility. The equipment and type of facility required to manufacture FHR fuel was shown to be similar enough to graphite compacts and on some degree to LWR fuel that assuming a capital cost of about twice the $500 million cost given for LWR fuel is a reasonable estimate. On the low and high end of this approximation a half billion and $1.5 billion dollar capital cost, respectively will also be analyzed. An amortization period of 15, 20, and 30 years and an effective return on investment (ROI) of 4%, 8%, and 12%, taking into account inflation and profit, will be used to analyze the yearly cash flow that will be distributed over the yearly capacity. The following equations describe this analysis:

$$C_{flow} = Capital \cdot \frac{i \cdot (1+i)^N}{(1+i)^N - 1} \qquad \textbf{Eq. 3.19}$$

$$\dot{P}_{capital}\left[\frac{\$}{kg_U}\right] = C_{flow}\left[\frac{\$}{year}\right] \cdot Capacity^{-1}\left[\frac{year}{plank}\right] \cdot \left[\frac{plank}{kg_U}\right]_{PF} \qquad \textbf{Eq 3.20}$$

Where i is the effective ROI, C_{flow} is the capital recovery uniform yearly cash flow, capital is the assumed initial capital cost, and plank per kgU is dependent on packing factor. Eq 3.20 is the capital cost portion of the manufacturing cost. The O&M cost is calculated in a similar fashion:

$$\dot{P}_{O\&M}\left[\frac{\$}{kg_U}\right] = P_{O\&M}\left[\frac{\$}{year}\right] \cdot Capacity^{-1}\left[\frac{year}{plank}\right] \cdot \left[\frac{plank}{kg_U}\right]_{PF} \qquad \textbf{Eq. 3.21}$$

Where $P_{O\&M}$ is approximated at \$120 million/year.

To calculate the manufacturing cost estimate for the assembly channels a ratio of channel volume to plank volume is calculated (found in Table 3.10) to find the equivalent number of planks that would need to be fabricated that would amount to the volume of the assembly channel. This value is then divided by 18 to account for having one assembly for every 18 planks (Eq 3.22). This value, $\eta_{channel}$, is presently equal to 0.4123.

$$\eta_{channel} = \frac{Vol.of\ Channel}{Vol.of\ Plank}\left[\frac{Planks\ Manu.}{Channel\ Manu.}\right]\cdot\frac{1\ Channel}{18\ Planks} \qquad \textbf{Eq 3.22}$$

The manufacturing process for TRISO particles is very well understood and therefore a cost is readily available per particle. Research accomplished in the 1960's calculated the bench scale TRISO fabrication cost as about \$0.20 per particle but more recent research has projected full scale production costs as low as \$0.00001 (¢0.001) per particle [24]. These are very disparate numbers with a range that can make fabrication prohibitively expensive. The low figure seems optimistic but the fabrication technology has progressed significantly since the 60's so the actual fabrication is most likely lower than \$0.2. A range of costs between the two figures above has been calculated to show the cost per kilogram of uranium of just TRISO fabrication (Table 3.13).

Table 3.13: Cost range for TRISO fabrication, $\dot{P}_{manu,TRISO}$

\$/particle	\$/kgU
0.00001	25.19
0.001	2518.60
0.01	25185.98
0.2	503719.53

Combinations of the capital cost component based on a range of ROI, capacities, interest rates, initial capital, and return periods, the O&M cost component, and the various TRISO manufacturing costs will be analyzed in detail (Eq. 3.23). Trends will be determined and a selection of values dependent on packing fraction mimicking the low, base, and high fabrication costs previously used will then be applied to the FCC model. The values used in this cost component, like all component costs, are based on analogous technologies and rational estimates and are simply applied to a framework that describes how to calculate the component cost. This framework can be used and figures updated whenever more concrete up-to-date values can be ascertained.

$$\dot{P}_{manu} = (1 + \eta_{channel})\left(\dot{P}_{capital} + \dot{P}_{O\&M}\right) + \dot{P}_{manu,TRISO} \qquad \textbf{Eq. 3.23}$$

3.4.4 Fabrication Component Cost: Quality Assurance

Quantifying the cost that goes into quality assurance is accomplished by associating a percentage of the total fabrication cost between materials, fabrication, and QA. It is common for new nuclear reactor technologies to have a fairly high percentage of the total cost (as high as 30%) going into QA due to the complexity of the systems and the safety requirements [27]. The following image shows how involved the QA process can be for graphite compacts with up to eight QA hold points with varying levels of scrutiny:

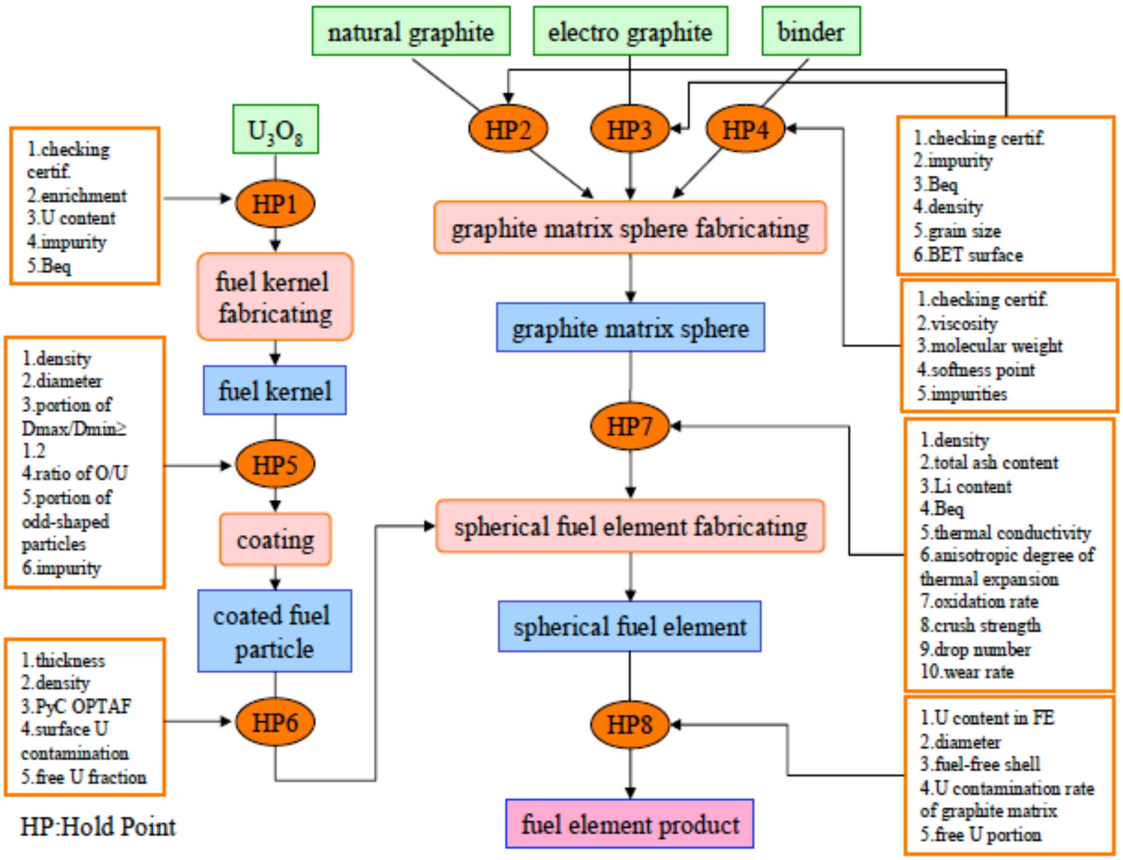

Figure 3.4: Process diagram of Chinese pebble fuel fabrication showing the specifics of QA hold points (HP) [10]

The QA cost for the TRISO particles might be much less than that for the finished plank fuel due to the manufacturing knowledge base being much more developed. Also the FLiBe coolant acts as secondary containment for fission products from TRISO particles that might have defective outer coatings, leading to an increased level of tolerance in the QA process. Overall QA for FHR plank manufacturing might be lower than 30% due to the precision and quality control needed for the plank fuel design which is a much larger single item compared to many hundreds or thousands more equivalent amounts of fuel cladding materials or fuel pellets needed.

For this stage of the fabrication cost model an initial portion of 10% (x_{QA}) will be allotted to QA. This leaves 90% ($x_{mat} + x_{fab}$) of the total fabrication cost belonging to materials and fabrication with an attempt at allotting percentages to each component withheld until further research can provide the appropriate numbers to calculate the costs for materials and fabrication, explicitly.

$$\dot{P}_{QA} = x_{QA} \cdot \frac{\dot{P}_{mat} + \dot{P}_{manu}}{(1 - x_{QA})}$$ **Eq. 3.24**

The total fabrication cost is the sum of the component costs described above (Eq. 3.25). To reiterate, based on the combinations over the range of variables that go into these component costs a base, low, and high fabrication cost will be calculated that will be dependent on packing fraction. These will be used to update the FCC model.

$$\dot{P}_{fab} = \dot{P}_{mat} + \dot{P}_{manu} + \dot{P}_{QA} = \frac{\dot{P}_{mat} + \dot{P}_{manu}}{(1 - x_{QA})}$$ **Eq. 3.25**

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Neutronic Analysis

The MC Dancoff and temperature corrections made in the neutronic model will affect the FCC model when total fuel cost is coupled with discharge burnup. Correcting the cross sections to properly treat fuel particles packed in close proximity will have a larger affect, as the temperatures did not change that drastically from the previous model. The BOC multiplication factors and associated MC statistical uncertainties are seen in Table 4.1. The average error is around 29 PCM and the excess reactivity increases with enrichment. All enrichments except 5% have multiplication factors that decrease with increasing packing factor. This is due to the replacement of moderation with fuel reducing fuel utilization. The 5% enrichment scenario has a local maximum at a packing fraction of 20% due to the fissile content being so low that the configuration benefits from having the extra fuel present. The trend becomes negative pass the 20% packing fraction because of the decreased moderation (hardening of the neutron spectrum).

Table 4.1: BOC multiplication factor and associated statistical uncertainty (1-sigma)

		Uranium Enrichment											
		5%			10%			15%			19.75%		
Packing Fraction	**10%**	1.16269	±	0.00023	1.35276	±	0.00026	1.44175	±	0.00031	1.47477	±	0.00026
	20%	1.17379	±	0.00025	1.31862	±	0.0003	1.3515	±	0.00028	1.41053	±	0.00028
	30%	1.15942	±	0.00033	1.28323	±	0.00029	1.33578	±	0.00031	1.40501	±	0.00026
	40%	1.13036	±	0.00033	1.24413	±	0.00033	1.29524	±	0.00029	1.32676	±	0.00028
	50%	1.08586	±	0.00038	1.19529	±	0.00027	1.24808	±	0.00026	1.28219	±	0.00025

Many of the results presented will be compared directly or indirectly with the uncorrected data acquired from Spenser Lewis's previous FCC analysis [3]. This data can be found in Appendix A of this document. The following tables and figures (Table 4.2, Figure 4.1, Figure 4.2, and Figure 4.3) show visually and with a relative percent difference the disparity between the multiplication factors of the corrected and uncorrected models over the cycle. At low packing factors the differences are not very large but become larger with increasing packing fraction with

40% and 50% packing factors showing large disparities of hundreds of EFPD. The corrected data consistently falls under the uncorrected data. This will be an important factor when FCC is analyzed further on.

Table 4.2: The relative difference in corrected and uncorrected multiplication factors at BoC and near EoC and the difference between the two

PF/EN	5%			10%			15%			19.75%		
	BOC	100 EFPD	Diff.	BOC	280 EFPD	Diff.	BOC	480 EFPD	Diff.	BOC	680 EFPD	Diff.
10%	-2.12%	-2.77%	0.65%	-1.67%	-2.24%	0.57%	-0.84%	-1.81%	0.98%	-1.40%	-1.88%	0.48%
20%	-2.82%	-2.68%	-0.14%	-2.26%	-2.26%	0.00%	-3.97%	-5.81%	1.84%	-2.03%	-1.81%	-0.21%
30%	-3.20%	-3.18%	-0.02%	-2.85%	-2.66%	-0.19%	-2.61%	-2.21%	-0.40%	0.21%	0.85%	-0.64%
40%	-4.58%	-4.43%	-0.14%	-4.13%	-3.73%	-0.39%	-3.77%	-3.16%	-0.61%	-3.58%	-2.71%	-0.88%
50%	-7.44%	-6.99%	-0.45%	-6.48%	-5.91%	-0.57%	-5.80%	-5.04%	-0.76%	-5.34%	-4.45%	-0.89%

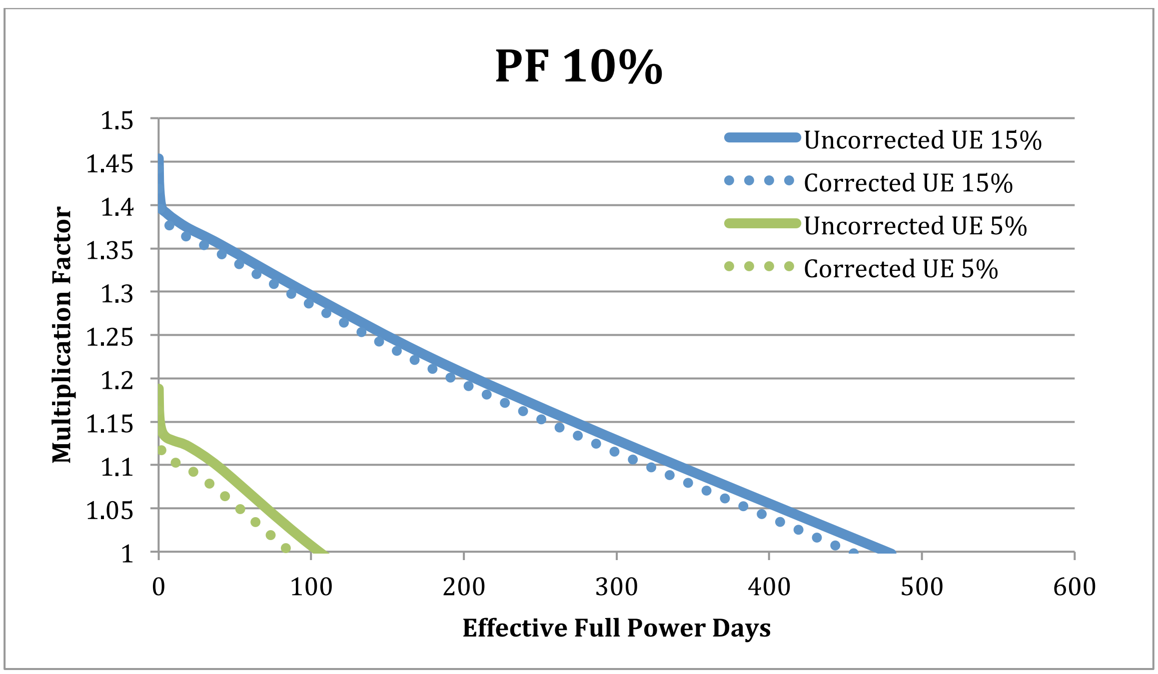

Figure 4.1: Corrected and uncorrected multiplication factor evolution for 5% and 10% enrichment for 10% packing factor fuel design

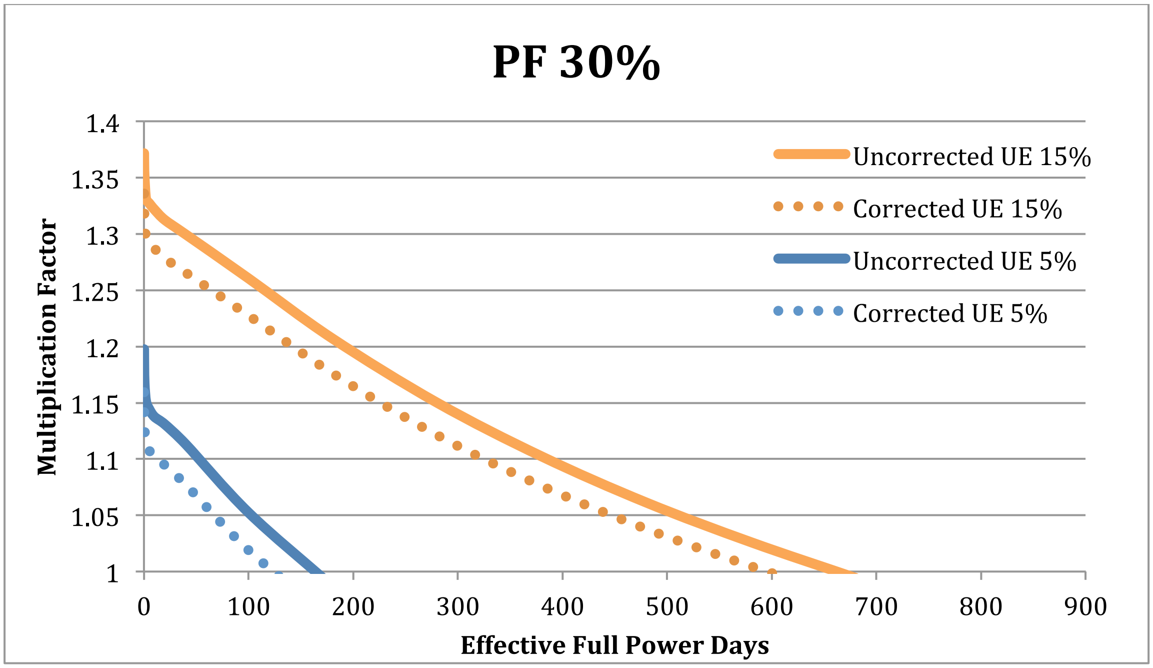

Figure 4.2: Corrected and uncorrected multiplication factor evolution for 5% and 10% enrichment for 30% packing factor fuel design

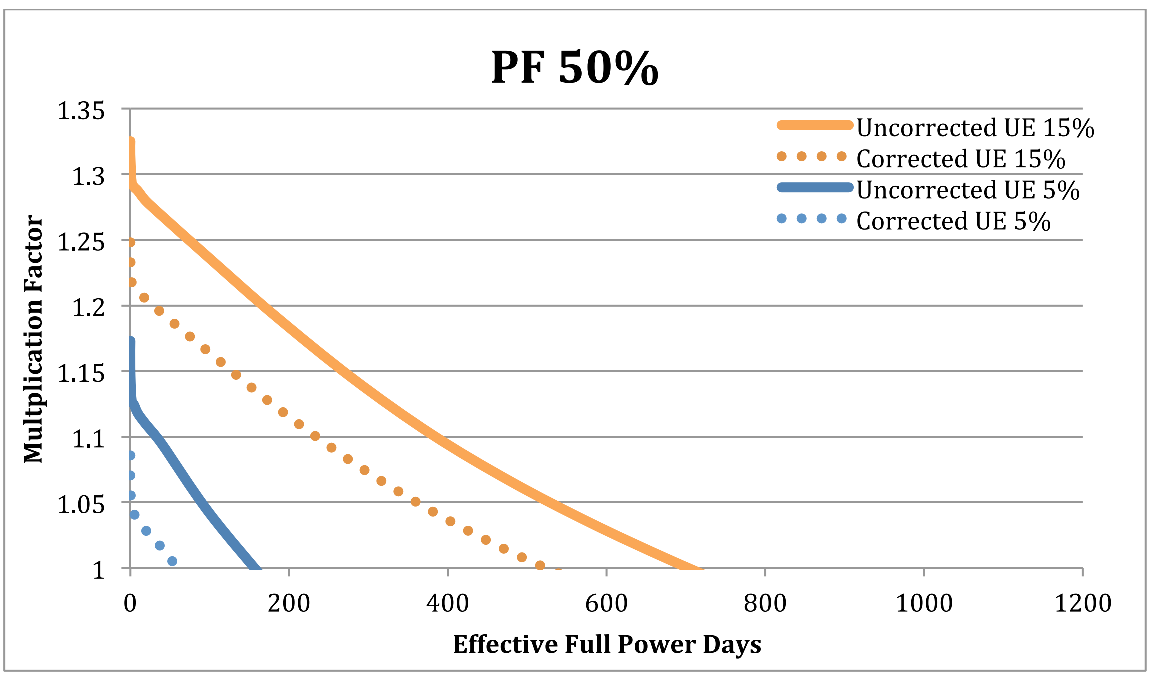

Figure 4.3: Corrected and uncorrected multiplication factor evolution for 5% and 10% enrichment for 10% packing factor fuel design

Traditional LWRs have discharge burnups on the order of 50 GWd/MTU and the target cycle length for the FHR is about 2 years (730 days). Table 4.3 shows the multi-batch (via LRM calculations) cycle lengths (EFPD) and discharge burnups (GWd/MTU) for 1 to 3 batches and Table 4.4 shows this data for 4 through 6 batches. The discharge burnups for all enrichments steadily decrease with increasing packing fraction related to replaced moderation with fuel, hardening the neutron spectrum. All enrichments have a maximum cycle length between 20% and 30% packing fractions. For 5% enrichment there is no hope of reaching a cycle length over a year (high of 300 days) while the discharge burnup only approaches 36.37 GWd/MTU for 6 batches and 10% packing fraction, with cycle length under one month. For 10% enrichment only 10% and 20% packing factors have discharge burnups over 50 GWd/MTU with cycle lengths approaching 356.53 days for once-through 20% packing fraction fuel. Discharge burnups are quite large for all 15% and 19.75% enriched cases, reaching about 106 GWd/MTU and 147 GWd/MTU, respectively, for 10% packing fractions. The once-through cycle lengths reach north of 2 years above 20% packing fraction for 19.75% enriched fuel but not longer than about 600 days for 15% enriched fuel.

Table 4.3: Discharge BU (GWd/MTU) and cycle length (EFPD) for 1 through 3 batches

Batch		1		2		3	
Enrichment	**Packing Factor**	**Cycle Length (d)**	**Dis. BU (GWd/MTU)**	**Cycle Length (d)**	**Dis. BU (GWd/MTU)**	**Cycle Length (d)**	**Dis. BU (GWd/MTU)**
5%	**10%**	86.01	21.22	57.34	28.29	43.01	31.82
	20%	125.16	19.55	83.44	26.07	62.58	29.32
	30%	124.77	14.84	83.18	19.78	62.39	22.25
	40%	101.34	9.95	67.56	13.27	50.67	14.93
	50%	59.67	5.05	39.78	6.73	29.83	7.57
10%	**10%**	278.48	68.69	185.65	91.58	139.24	103.03
	20%	356.53	55.69	237.69	74.25	178.27	83.53
	30%	342.99	40.78	228.66	54.38	171.50	61.17
	40%	336.08	33.01	224.05	44.01	168.04	49.51
	50%	276.04	23.35	184.02	31.13	138.02	35.02
15%	**10%**	433.12	106.83	288.75	142.44	216.56	160.25
	20%	566.98	88.56	377.99	118.07	283.49	132.83
	30%	595.86	70.85	397.24	94.46	297.93	106.27
	40%	578.75	56.84	385.84	75.78	289.38	85.26
	50%	525.17	44.42	350.11	59.22	262.58	66.63
19.75%	**10%**	597.21	147.30	398.14	196.41	298.61	220.96
	20%	756.92	118.22	504.61	157.63	378.46	177.33
	30%	886.40	105.39	590.93	140.52	443.20	158.09
	40%	822.77	80.80	548.52	107.74	411.39	121.20
	50%	786.03	66.48	524.02	88.64	393.02	99.72

Table 4.4: Discharge BU (GWd/MTU) and cycle length (EFPD) for 4 through 6 batches

Batch		4		5		6	
Enrichment	**Packing Factor**	**Cycle Length (d)**	**Dis. BU (GWd/MTU)**	**Cycle Length (d)**	**Dis. BU (GWd/MTU)**	**Cycle Length (d)**	**Dis. BU (GWd/MTU)**
5	**10**	34.40	33.94	28.67	35.36	24.57	36.37
	20	50.07	31.28	41.72	32.58	35.76	33.51
	30	49.91	23.74	41.59	24.73	35.65	25.43
	40	40.54	15.92	33.78	16.59	28.96	17.06
	50	23.87	8.07	19.89	8.41	17.05	8.65
10	**10**	111.39	109.90	92.83	114.48	79.57	117.75
	20	142.61	89.10	118.84	92.81	101.87	95.46
	30	137.20	65.25	114.33	67.97	98.00	69.91
	40	134.43	52.81	112.03	55.01	96.02	56.58
	50	110.41	37.35	92.01	38.91	78.87	40.02
15	**10**	173.25	170.93	144.37	178.05	123.75	183.14
	20	226.79	141.69	188.99	147.59	161.99	151.81
	30	238.34	113.36	198.62	118.08	170.25	121.45
	40	231.50	90.94	192.92	94.73	165.36	97.44
	50	210.07	71.07	175.06	74.03	150.05	76.14
19.75	**10**	238.89	235.69	199.07	245.51	170.63	252.52
	20	302.77	189.15	252.31	197.03	216.26	202.66
	30	354.56	168.63	295.47	175.65	253.26	180.67
	40	329.11	129.28	274.26	134.67	235.08	138.52
	50	314.41	106.37	262.01	110.80	224.58	113.97

4.2 Fabrication Cost Analysis

One of the components of the fabrication cost that this analysis will keep static will be the material cost. As stated above these costs might change due to the wholesale price and the heightened cost that comes with nuclear grade (high purity) materials. The following table gives the cost for all FHR plank materials except fuel enrichment costs based on Eq. 3.17 and Eq. 3.18.

Table 4.5: \$/kgU for all materials except enriched uranium in a FHR plank

	Packing Fraction				
	10%	**20%**	**30%**	**40%**	**50%**
\$ Nat. Graphite	816.48	491.72	360.76	287.13	238.99
\$ Synth. Graphite	176.90	106.54	78.17	62.21	51.78
\$ Phenolic Resin	66.34	39.95	29.31	23.33	19.42
\$ Methanol	261.95	157.76	115.75	92.12	76.68
\$ Channel Graphite	639.48	402.85	307.43	253.78	218.70
\$ TRISO	1000	1000	1000	1000	1000
Total	2961.15	2198.82	1891.42	1718.57	1605.56

What is important to note is that the total for materials is already on the order of the previous low fabrication cost (\$1,300/kgU) and this is with the possibility of graphite materials being more costly than assumed here. This already shows the significance a detailed approach to fabrication cost may have. Also, depending if TRISO fabrication cost is \$0.00001/particle or \$0.01/particle, the TRISO fabrication may cost 40 times more or 25 times more. This is a large swing, which shows how the TRISO fabrication cost hedges the entire fabrication cost.

Moving on to the influence of effective ROI and payment period on the capital cost component, $\dot{P}_{capital}$, of the manufacturing cost, a stronger relation is seen for ROI compared to payment periods. For various yearly capacities and a \$1 billion initial capital cost Table 4.6 shows the capital cost component for a range of periods, effective ROIs, and packing factors. The negative slope exhibited in Figure 4.4 reflects the decrease with increasing payment period that becomes shallower with increasing effective ROI. Figure 4.5 shows the strength of effective ROI with positive slopes that become steeper with increasing payment period. These graphs are for the 27,000 planks/year case but the relative trends are the exact same over packing fraction and capacity. The changes in component cost are not trivial and can have a relative change of about 50% for 20 and 30 year payment periods from 4% to 12% effective ROI. For this reason the fabrication cost scenarios to be determined will take into account appropriate payment periods and effective ROIs to calculate corresponding component capital costs.

Table 4.6: $\dot{P}_{capital}$ for various yearly fabrication capacities packing factors, Effective ROIs (%), and amortization periods (years)

		27,000 Planks/Year			54,000 Planks/Year			81,000 Planks/Year		
		Effective ROI (%)								
		4%	8%	12%	4%	8%	12%	4%	8%	12%
Periods (years)		**10% Packing Fraction**			**10% Packing Fraction**			**10% Packing Fraction**		
	15	1047.56	1360.74	1710.09	523.78	680.37	855.04	349.19	453.58	570.03
	20	857.02	1186.29	1559.31	428.51	593.15	779.66	285.67	395.43	519.77
	30	673.56	1034.59	1445.92	336.78	517.29	722.96	224.52	344.86	481.97
		20% Packing Fraction			20% Packing Fraction			20% Packing Fraction		
	15	659.92	857.21	1077.29	329.96	428.60	538.64	219.97	285.74	359.10
	20	539.89	747.32	982.30	269.94	373.66	491.15	179.96	249.11	327.43
	30	424.31	651.75	910.88	212.16	325.88	455.44	141.44	217.25	303.63
		30% Packing Fraction			30% Packing Fraction			30% Packing Fraction		
	15	503.61	654.17	822.13	251.81	327.09	411.06	167.87	218.06	274.04
	20	412.01	570.31	749.64	206.01	285.15	374.82	137.34	190.10	249.88
	30	323.81	497.38	695.13	161.91	248.69	347.56	107.94	165.79	231.71
		40% Packing Fraction			40% Packing Fraction			40% Packing Fraction		
	15	415.72	540.01	678.65	207.86	270.00	339.32	138.57	180.00	226.22
	20	340.11	470.78	618.81	170.05	235.39	309.41	113.37	156.93	206.27
	30	267.30	410.58	573.82	133.65	205.29	286.91	89.10	136.86	191.27
		50% Packing Fraction			50% Packing Fraction			50% Packing Fraction		
	15	358.26	465.36	584.84	179.13	232.68	292.42	119.42	155.12	194.95
	20	293.10	405.71	533.28	146.55	202.85	266.64	97.70	135.24	177.76
	30	230.35	353.82	494.50	115.18	176.91	247.25	76.78	117.94	164.83

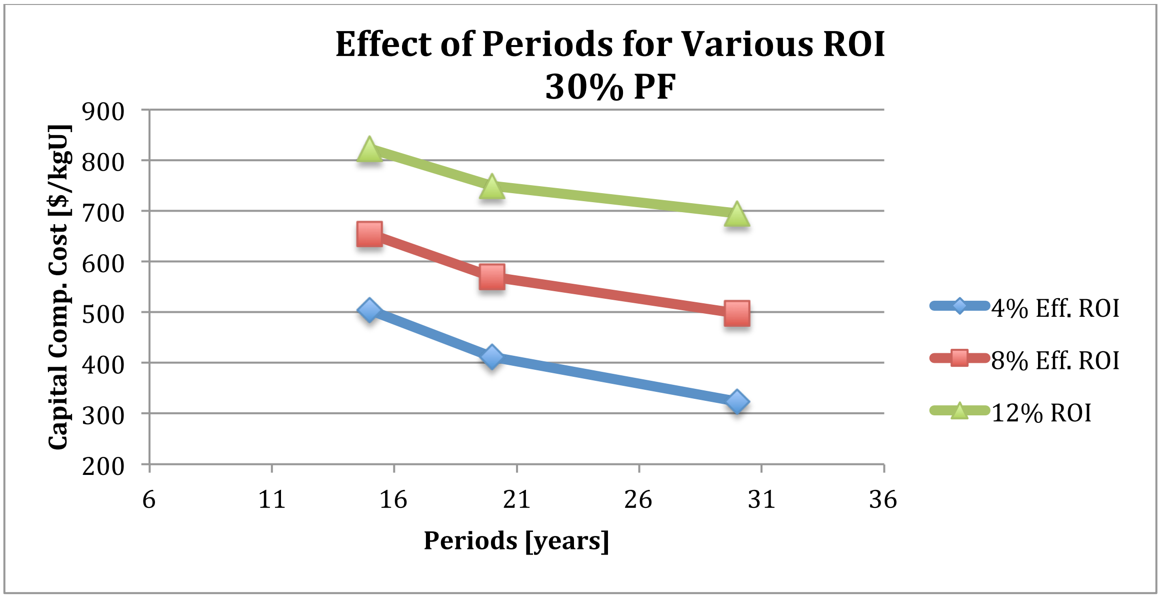

Figure 4.4: The effect of amortization period on $\dot{\boldsymbol{P}}_{\boldsymbol{capital}}$ for various ROI percentages for a 30% packing factor fuel design

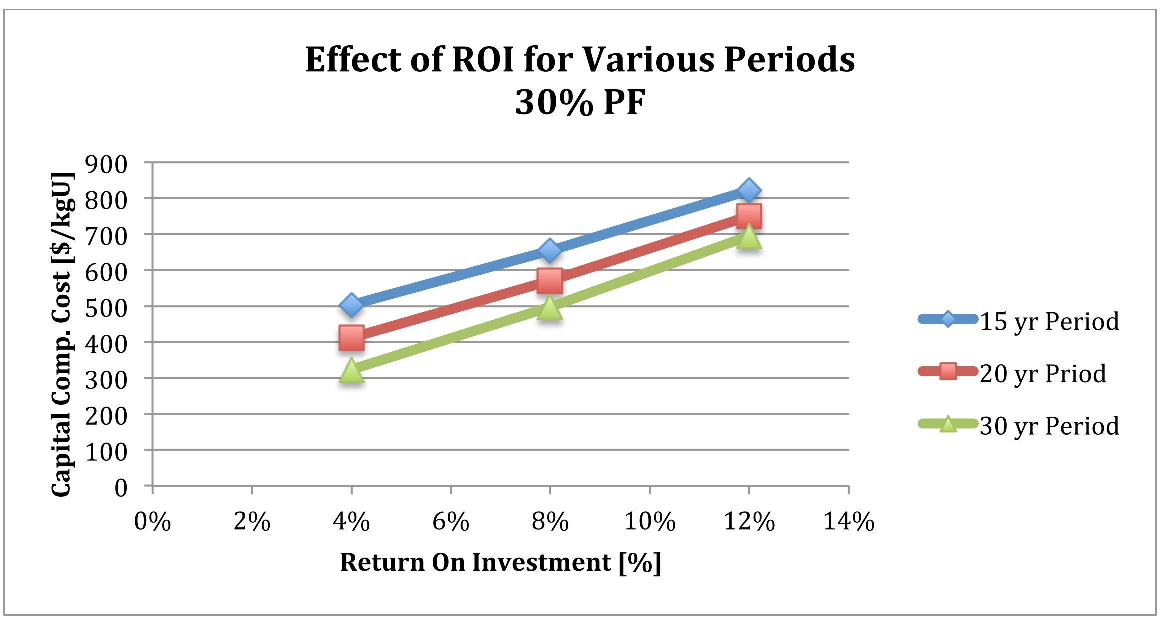

Figure 4.5: The effect of ROI percentage on $\dot{\boldsymbol{P}}_{\boldsymbol{capital}}$ for various amortization periods for a 30% packing factor fuel design

Other factors, aside from TRISO fabrication costs, that might significantly hedge the entire fabrication cost are initial capital costs of a facility and yearly capacity. Based on Table 4.7, Table 4.8, Figure 4.7, and Figure 4.8 it can be seen that both $\dot{P}_{capital}$ and $\dot{P}_{O\&M}$ have an inverse relationship to capacity for which the price does not significantly decrease after about 75,000 planks per year. The initial capital cost shows a linear relationship with $\dot{P}_{capital}$ of about \$0.29/kgU per \$1 million in initial capital, which is dependent on packing fraction. This ratio will go down to about \$0.20/kgU per \$1 million for 50% packing factor. As manufacturing capacity is related to initial capital cost in a yet to be determined manner and a relationship not assumed in this study Figure 4.6 implies a limit of about 80,000 planks per year to save on capital costs as a matter of depreciating returns.

Table 4.7: $\dot{P}_{capital}$ and $\dot{P}_{O\&M}$ for various capacity factors

Plank/Year	O&M (\$/kgU)	Capital (\$/kgU)
27000	671.93	570.31
31000	585.23	496.72
35000	518.34	439.95
39000	465.18	394.83
43000	421.91	358.10
47000	386.00	327.62
51000	355.73	301.93
55000	329.85	279.97
59000	307.49	260.99
63000	287.97	244.42
67000	270.78	229.83
71000	255.52	216.88
75000	241.89	205.31
79000	229.65	194.92
83000	218.58	185.52

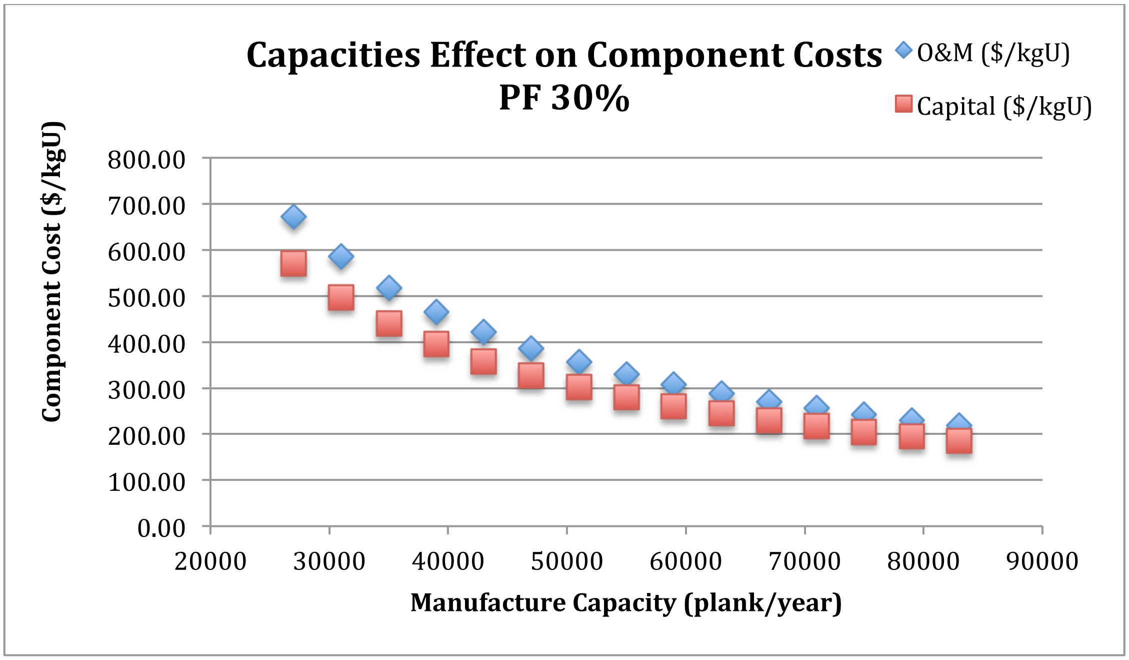

Figure 4.6: The trend of $\dot{P}_{capital}$ and $\dot{P}_{O\&M}$ for various manufacturing capacities

Table 4.8: $\dot{P}_{capital}$ for various initial capital costs

Capital Cost ($ millions)	Capital ($/kgU)
500	142.58
600	171.09
700	199.61
800	228.12
900	256.64
1000	285.15
1100	313.67
1200	342.19
1300	370.70
1400	399.22
1500	427.73

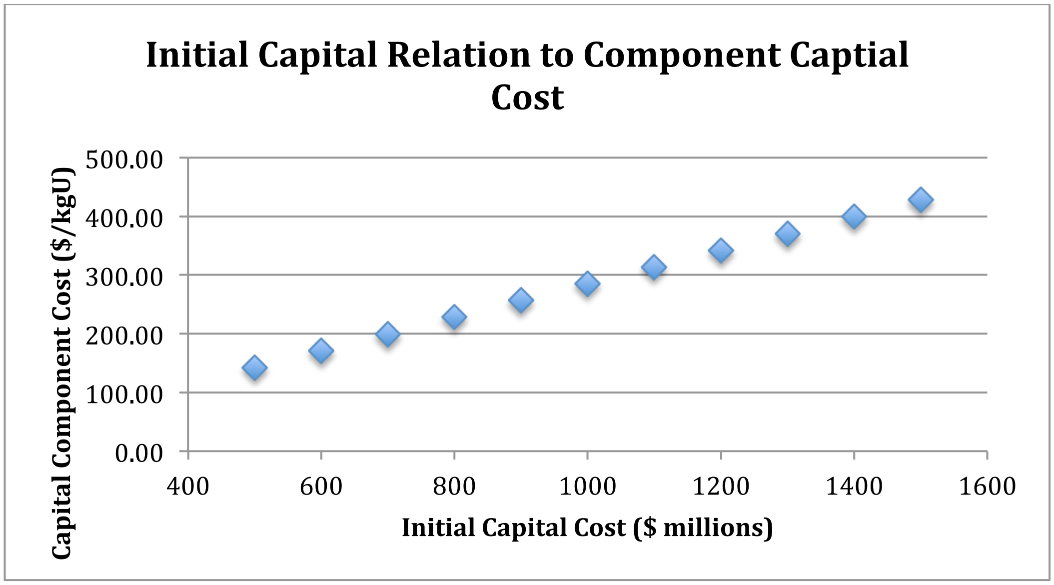

Figure 4.7: The linear trend of $\dot{P}_{capital}$ for various initial capital costs

Having analyzed the trends that certain manufacturing parameters have on cost three fabrication cost scenarios have been discerned in Table 4.9. They cover a range of possible financial and commercial outcomes that could develop with emerging technologies. Following an abbreviation convention popular in audio analysis the cost scenarios will be referred to as lo, mid, and hi cost scenarios. The lo scenario benefits from a low effective ROI, a long payment period, a high fabrication capacity, and a relatively low initial capital and TRISO fabrication cost. The mid scenario suffers from a shorter payback period and higher effective ROI with a decreased manufacturing capacity but still benefits from lower TRISO fabrication costs. The hi scenario has the lowest manufacturing capacity and the highest TRISO fabrication price, the two biggest influences on fabrication cost, as well as a short payment period, high effective ROI, and the highest capital cost.

Table 4.9: New fabrication cost scenarios covering a range of possible financial outcomes

Case	Lo	Mid	Hi
Period (years)	30	20	15
Effective ROI (%)	4	8	12
Initial Capital ($ billion)	0.5	1	1.5
Capacity (plank/year)	81,000	54,000	27,000
TRISO Fabrication ($/particle)	0.001	0.003	0.01

The next three tables show the component cost breakdowns for the three scenarios listed above with the QA factor tacked on last based on Eq. 3.25. Changes in the period, effective ROI, and initial capital cost only influence the capital cost component. The capacity effects the capital and O&M cost components and the TRISO fabrication cost translates directly to $/kgU and is constant for all packing factors.

Table 4.10: Lo fabrication cost scenario

Lo - Component and Total Price [$/kgU] for Fuel Materials, Fabrication, and Quality Assurance					
Packing Fraction	10%	20%	30%	40%	50%
Materials					
$ Natural Graphite	816.48	491.72	360.76	287.13	238.99
$ Synth. Graphite	176.90	106.54	78.17	62.21	51.78
$ Phenolic Resin	66.34	39.95	29.31	23.33	19.42
$ Methanol	261.95	157.76	115.75	92.12	76.68
$ Channel Graphite	639.48	402.85	307.43	253.78	218.70
$ TRISO	1000	1000	1000	1000	1000
Total - Mat	**2961.15**	**2198.82**	**1891.42**	**1718.57**	**1605.56**
Fabrication					
$ TRISO	2518.60	2518.60	2518.60	2518.60	2518.60
$ Plank Fab. Capital	112.26	70.72	53.97	44.55	38.39
$ Plank Fab. O&M	465.89	293.49	223.98	184.89	159.33
$ Channel Fab. Capital	46.33	29.19	22.27	18.39	15.84
$ Channel Fab. O&M	192.27	121.12	92.43	76.30	65.75
Total - Fab.	**3335.34**	**3033.11**	**2911.25**	**2842.72**	**2797.92**
QA					
Total (w/o QA)	**6296.49**	**5231.93**	**4802.67**	**4561.30**	**4403.48**
Total (w/ QA)	**6996.10**	**5813.25**	**5336.30**	**5068.11**	**4892.76**

The lo fabrication cost (Table 4.10) ranges from about $7000/kgU to $4900/kgU with increasing packing factor, significantly higher than the low fabrication cost used in the previous FCC analysis. This is keeping most factors at favorable levels that help to keep the price down. When all major components of FHR fuel fabrication are accounted for the sum is found to be close to other particle fuel designs. The average for this scenario is around the low, $5,000/kgU (Figure 4.8), of other particle fuel designs.

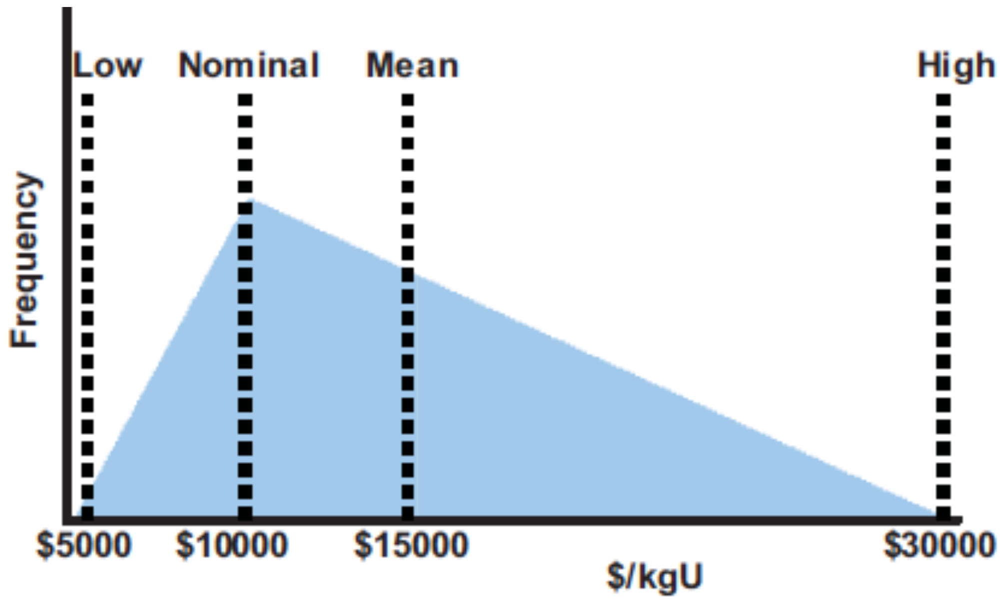

Figure 4.8: Gas cooled reactor particle fuel fabrication cost frequency distribution [24]

Table 4.11: Mid fabrication scenario

Mid - Component and Total Price [$/kgU] for Fuel Materials, Fabrication, and Quality Assurance					
Packing Fraction	10%	20%	30%	40%	50%
Materials					
$ Natural Graphite	816.48	491.72	360.76	287.13	238.99
$ Synth. Graphite	176.90	106.54	78.17	62.21	51.78
$ Phenolic Resin	66.34	39.95	29.31	23.33	19.42
$ Methanol	261.95	157.76	115.75	92.12	76.68
$ Channel Graphite	639.48	402.85	307.43	253.78	218.70
$ TRISO	1000	1000	1000	1000	1000
Total - Mat	**2961.15**	**2198.82**	**1891.42**	**1718.57**	**1605.56**
Fabrication					
$ TRISO	7555.79	7555.79	7555.79	7555.79	7555.79
$ Plank Fab. Capital	593.15	373.66	285.15	235.39	202.85
$ Plank Fab. O&M	698.83	440.24	335.96	277.33	239.00
$ Channel Fab. Capital	244.79	154.21	117.68	97.14	83.72
$ Channel Fab. O&M	288.40	181.68	138.65	114.45	98.63
Total - Fab.	**9380.96**	**8705.58**	**8433.24**	**8280.11**	**8179.99**
QA					
Total (w/o QA)	**12342.11**	**10904.39**	**10324.66**	**9998.68**	**9785.55**
Total (w/ QA)	**13713.46**	**12115.99**	**11471.84**	**11109.65**	**10872.84**

Table 4.12: Hi fabrication cost scenario

Hi - Component and Total Price [$/kgU] for Fuel Materials, Fabrication, and Quality Assurance					
Packing Fraction	10%	20%	30%	40%	50%
Materials					
$ Natural Graphite	816.48	491.72	360.76	287.13	238.99
$ Synth. Graphite	176.90	106.54	78.17	62.21	51.78
$ Phenolic Resin	66.34	39.95	29.31	23.33	19.42
$ Methanol	261.95	157.76	115.75	92.12	76.68
$ Channel Graphite	639.48	402.85	307.43	253.78	218.70
$ TRISO	1000	1000	1000	1000	1000
Total - Mat	**2961.15**	**2198.82**	**1891.42**	**1718.57**	**1605.56**
Fabrication					
$ TRISO	25185.98	25185.98	25185.98	25185.98	25185.98
$ Plank Fab. Capital	2565.13	1615.93	1233.19	1017.97	877.26
$ Plank Fab. O&M	1397.66	880.47	671.93	554.66	477.99
$ Channel Fab. Capital	1058.61	666.88	508.93	420.11	362.04
$ Channel Fab. O&M	576.80	363.36	277.30	228.90	197.26
Total - Fab.	**30784.19**	**28712.63**	**27877.32**	**27407.63**	**27100.54**
QA					
Total (w/o QA)	**33745.34**	**30911.44**	**29768.73**	**29126.20**	**28706.10**
Total (w/ QA)	**37494.82**	**34346.05**	**33076.37**	**32362.45**	**31895.67**

The mid (Table 4.11) scenario range from about $13700/kgU to $10900/kgU with increasing packing factor. This scenario represents expected cost parameters such as higher initial capital, lower capacity (~170-500 MTU/yr), and higher TRISO fabrication cost to reflect what the cost of pursuing newer technologies could likely be. The mid scenario averages around $11500/kgU, close to the nominal value in Figure 4.8.

The hi cost ranges from about $37500/kgU to $31900/kgU for increasing packing fraction. This is extremely high, far surpassing the high fixed cost scenario ($24,000/kgU), and it is very unlikely that any discharge burnup the FHR can output would make up for the high cost of this fuel. The parameters chosen that drive this price upwards are not artificially inflated to present a high water mark. These parameters are based on what can be estimated as achievable in the foreseeable future. The average for this scenario is about $33000/kgU, a slightly surpassing the high value of $30000/kgU in Figure 4.8. A significant amount of research and development in fuel fabrication technologies related to TRISO fabrication and graphite compacts is needed to drive this cost down.

A summary of the total fabrication costs are compiled into Table 4.13 and Figure 4.9. The cost disparity between lo and mid scenarios is much smaller than the difference to the hi scenario.

Table 4.13: Total fabrication cost summary for various scenarios

Packing Fraction	10%	20%	30%	40%	50%
Lo ($/kgU)	6996.10	5813.25	5336.30	5068.11	4892.76
Mid ($/kgU)	13713.46	12115.99	11471.84	11109.65	10872.84
Hi ($/kgU)	37494.82	34346.05	33076.37	32362.45	31895.67

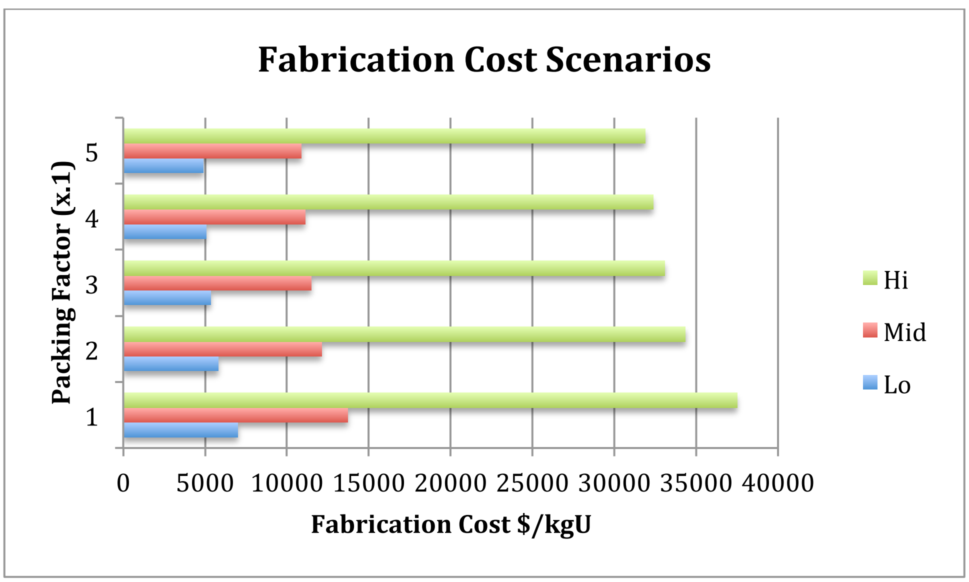

Figure 4.9: Total fabrication cost comparison amongst scenarios

4.3 Fuel Cycle Cost Analysis

The total fuel cost as calculated in Eq. 3.14 is presented in Table 4.14 for the various fuel enrichments, packing factors, and fabrication cost scenarios. The enrichment cost percentage of the total fuel fabrication cost ranges from about 20% to 60% depending on packing factor and enrichment for the lo cost scenarios. This range decreases to about 11% to 40% for mid and about 4% to 18% for the hi scenarios. As stated before, for LWR fuel the fabrication cost percentage should be as low as 12% with 64% being enrichment costs and the rest attributed to disposal and interest. This demonstrates that cost for certain FHR plank fuel configurations cannot be compared directly to LWR fuel as the relative percent of enrichment to total fabrication is much too low. For the FHR design to win economically over traditional LWR designs other features such as reactor capital costs, online refueling, process heat, and discharge burnup need to be proven design benefits that will provide economic incentive. This study showing a detailed look at FHR fuel cost emphasizes the need for such design benefits to be proven to demonstrate the viability of this reactor design.

Table 4.14: Total fuel cost as calculated in Eq. 3.14

		Lo Fabrication Cost Scenario				
		Packing Fraction				
		10%	20%	30%	40%	50%
	5%	$8,540.84	$7,357.99	$6,881.03	$6,612.84	$6,437.50
	10%	$10,345.45	$9,162.60	$8,685.64	$8,417.45	$8,242.10
	15%	$12,174.46	$10,991.61	$10,514.65	$10,246.46	$10,071.11
	19.75%	$13,922.54	$12,739.70	$12,262.74	$11,994.55	$11,819.20
		Mid Fabrication Cost Scenario				
		Packing Fraction				
		10%	20%	30%	40%	50%
	5%	$15,258.19	$13,660.72	$13,016.58	$12,654.38	$12,417.57
Enrichment	10%	$17,062.80	$15,465.33	$14,821.19	$14,458.99	$14,222.18
	15%	$18,891.81	$17,294.34	$16,650.20	$16,288.00	$16,051.19
	19.75%	$20,639.90	$19,042.43	$18,398.29	$18,036.09	$17,799.28
		Hi Fabrication Cost Scenario				
		Packing Fraction				
		10%	20%	30%	40%	50%
	5%	$39,039.56	$35,890.78	$34,621.11	$33,907.18	$33,440.40
	10%	$40,844.16	$37,695.39	$36,425.71	$35,711.79	$35,245.01
	15%	$42,673.18	$39,524.40	$38,254.73	$37,540.80	$37,074.02
	19.75%	$44,421.26	$41,272.49	$40,002.81	$39,288.89	$38,822.11

The next three tables account for the total amount of fuel in a whole core to yield the cost to populate the core with fresh fuel. For lo and mid fabrication costs the price is on the order of hundreds of millions, with the hi fabrication cost getting into the one and one and a half billion range. To give perspective to the whole core costs, which just includes the fuel cost, the DoE sponsored Energy Economics Data Base (EEDB) shows a PWR design as having a $2.9 billion price tag and that is without the cost of loading the fuel [2]. The hi fabrication cost, high enrichment, and high packing factor scenario placed just the fresh fuel at $1.5 billion. While this perspective of comparison seems favorable for the FHR design the heavy metal loading for a typical 4-loop LWR core is about 80,000-95,00 kgU, nearly twice as much as the FHR core with 50% packing factor fuel [2]. This is why coupling cost with discharge burnup (cycle length) in a FCC analysis is a more descriptive means of comparison.

Table 4.15: The whole core fuel cost for the lo fabrication cost scenario

Lo Fabrication Cost (whole core)					
		Uranium Enrichment			
		5.00%	10.00%	15.00%	19.75%
Packing Fraction	10%	$114,077,011.25	$138,952,644.48	$164,164,702.13	$188,261,247.71
	20%	$156,538,637.25	$195,822,638.00	$235,637,925.62	$273,691,578.60
	30%	$193,122,410.27	$244,726,129.31	$297,027,750.24	$347,015,276.45
	40%	$225,299,707.86	$287,776,674.07	$351,098,594.76	$411,618,825.55
	50%	$255,143,818.77	$327,689,345.38	$401,215,996.24	$471,489,447.06

Table 4.16: The whole core fuel cost for the mid fabrication cost scenario

Mid Fabrication Cost (whole core)					
		Uranium Enrichment			
		5.00%	10.00%	15.00%	19.75%
Packing Fraction	10%	$202,160,495.28	$227,036,128.50	$252,248,186.16	$276,344,731.73
	20%	$289,252,484.29	$328,536,485.03	$368,351,772.66	$406,405,425.64
	30%	$364,072,025.05	$415,675,744.09	$467,977,365.03	$517,964,891.23
	40%	$429,965,719.09	$492,442,685.30	$555,764,605.99	$616,284,836.78
	50%	$491,044,029.24	$563,589,555.84	$637,116,206.70	$707,389,657.53

Table 4.17: The whole core fuel cost for the hi fabrication cost scenario

Hi Fabrication Cost (whole core)					
		Uranium Enrichment			
		5.00%	10.00%	15.00%	19.75%
Packing Fraction	10%	$513,093,415.26	$537,969,048.48	$563,181,106.13	$587,277,651.71
	20%	$756,378,058.72	$795,662,059.47	$835,477,347.10	$873,531,000.08
	30%	$965,029,273.95	$1,016,632,992.99	$457,395.40	$1,118,922,140.12
	40%	$1,148,928,818.38	$1,211,405,784.60	$1,274,727,705.28	$1,335,247,936.07
	50%	$1,319,328,547.79	$1,391,874,074.39	$1,465,400,725.25	$1,535,674,176.07

Table 4.18, Table 4.19, and Table 4.20 display the fuel cycle costs in $/MWhe for low ($1300/kgU), base ($4000/kgU), and high ($24,000/kgU) fuel fabrication costs, respectively. These values were calculated using the updated burnup data with the old set of fabrication costs to see how neutronic correction affects FCC. For each fuel fabrication cost, two outage costs ($20 and $50 million) are shown besides each other as well as batch values for one through six batches. A color map is imposed over the data indicating max (red) and min (green) for each set of packing factors.

The fuel cycle cost values ($/MWe) for the low fabrication costs get as high as $112.6 and as low as $5.4. The values for the base fabrication costs get as high as $142.1 and as low as $6.5. The values for the high fabrication costs get as high as $501.5 and as low as $14.7. The high values are consistently found in the 50% packing factor, $50 million outage cost, and 5% enriched data regions. The low values are found in the 10% packing factor, $20 million outage cost, and 19.75% enriched data regions.

The fabrication cost in this set is constant for all the packing factors so the premium for packing more fuel in a single plank is not accounted for. This is the reason why the low values are mostly in the 10% packing factor region coupled with the increased fuel utilization a high enriched fuel will have in a high moderation to heavy metal (CHM) ratio environment. The high values are found with high outage cost and 5% enrichment with 50% packing factor because of the lack of moderation and fissile material yielding an extremely short cycle length. A cheaper outage cost always translates to a cheaper FCC with a minimum occurring with batch number to account for the trade off between increased discharge BU and more frequent outages. The higher the initial discharge BU (higher enrichments and packing fractions) the more outages can be had before negative returns.

Table 4.18: Fuel and outage cost ($/MWhe) with a low fabrication cost scenario ($1,300/kgU)

Low Fabrication Costs												
	Outage Cost - $20 Million Number of Batches						Outage Cost - $50 Million Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$19.1	$19.2	$21.4	$24.1	$27.0	$30.0	$28.8	$33.7	$40.8	$48.3	$56.1	$63.9
10%	$8.4	$7.8	$8.3	$9.0	$9.8	$10.7	$11.4	$12.3	$14.2	$16.5	$18.8	$21.2
15%	$7.0	$6.2	$6.4	$6.8	$7.3	$7.8	$8.9	$9.1	$10.2	$11.6	$13.1	$14.6
19.75%	$6.2	$5.4	$5.4	$5.6	$6.0	$6.3	$7.6	$7.4	$8.2	$9.1	$10.1	$11.2
	Packing Factor 20%						Packing Factor 20%					
5%	$18.2	$17.0	$18.0	$19.7	$21.6	$23.6	$24.8	$27.0	$31.4	$36.3	$41.6	$46.9
10%	$9.4	$8.3	$8.4	$8.8	$9.4	$10.1	$11.8	$11.8	$13.1	$14.7	$16.4	$18.2
15%	$7.9	$6.7	$6.6	$6.8	$7.1	$7.5	$9.4	$8.9	$9.5	$10.4	$11.5	$12.6
19.75%	$7.3	$6.0	$5.9	$5.9	$6.1	$6.4	$8.4	$7.7	$8.1	$8.7	$9.5	$10.3
	Packing Factor 30%						Packing Factor 30%					
5%	$22.6	$20.3	$21.0	$22.5	$24.2	$26.2	$29.3	$30.3	$34.3	$39.2	$44.3	$49.5
10%	$12.4	$10.5	$10.4	$10.8	$11.3	$12.0	$14.8	$14.2	$15.3	$16.9	$18.6	$20.5
15%	$9.6	$7.9	$7.6	$7.7	$8.0	$8.3	$11.0	$10.0	$10.4	$11.2	$12.2	$13.2
19.75%	$8.0	$6.5	$6.2	$6.2	$6.3	$6.5	$8.9	$7.9	$8.1	$8.5	$9.1	$9.8
	Packing Factor 40%						Packing Factor 40%					
5%	$32.5	$28.5	$29.0	$30.6	$32.7	$34.9	$40.7	$40.8	$45.4	$51.2	$57.3	$63.7
10%	$15.0	$12.5	$12.2	$12.5	$12.9	$13.6	$17.4	$16.2	$17.1	$18.7	$20.4	$22.2
15%	$11.7	$9.5	$9.1	$9.1	$9.3	$9.6	$13.2	$11.7	$12.0	$12.7	$13.7	$14.7
19.75%	$10.3	$8.2	$7.8	$7.7	$7.8	$8.0	$11.3	$9.7	$9.8	$10.2	$10.8	$11.5
	Packing Factor 50%						Packing Factor 50%					
5%	$62.6	$53.9	$54.1	$56.6	$59.9	$63.7	$76.5	$74.9	$82.1	$91.5	$101.8	$112.6
10%	$20.8	$17.1	$16.6	$16.8	$17.3	$18.0	$23.8	$21.7	$22.6	$24.3	$26.4	$28.6
15%	$14.8	$11.9	$11.3	$11.3	$11.4	$11.7	$16.4	$14.3	$14.5	$15.2	$16.2	$17.3
19.75%	$12.40	$9.83	$9.21	$9.07	$9.14	$9.29	$13.46	$11.42	$11.33	$11.73	$12.32	$13.01

Table 4.19: Fuel and outage cost ($/MWhe) with a base fabrication cost scenario ($4,000/kgU)

Base Fabrication Costs												
	Outage Cost - $20 Million Number of Batches						Outage Cost - $50 Million Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$31.2	$28.2	$29.4	$31.6	$34.2	$37.0	$40.8	$42.8	$48.8	$55.8	$63.3	$70.9
10%	$12.1	$10.6	$10.7	$11.3	$12.1	$12.9	$15.1	$15.1	$16.7	$18.8	$21.0	$23.4
15%	$9.4	$8.0	$8.0	$8.3	$8.7	$9.2	$11.3	$10.9	$11.8	$13.1	$14.5	$16.0
19.75%	$7.9	$6.7	$6.5	$6.7	$7.0	$7.3	$9.3	$8.7	$9.3	$10.2	$11.2	$12.2
	Packing Factor 20%						Packing Factor 20%					
5%	$31.2	$26.8	$26.7	$27.8	$29.4	$31.2	$37.9	$36.8	$40.1	$44.5	$49.4	$54.5
10%	$14.0	$11.7	$11.4	$11.7	$12.2	$12.7	$16.4	$15.2	$16.1	$17.5	$19.2	$20.9
15%	$10.8	$8.8	$8.5	$8.6	$8.8	$9.1	$12.2	$11.0	$11.4	$12.2	$13.2	$14.3
19.75%	$9.5	$7.7	$7.3	$7.3	$7.4	$7.7	$10.6	$9.3	$9.5	$10.0	$10.7	$11.5
	Packing Factor 30%						Packing Factor 30%					
5%	$39.8	$33.2	$32.5	$33.2	$34.6	$36.2	$46.4	$43.2	$45.8	$49.9	$54.6	$59.6
10%	$18.6	$15.2	$14.6	$14.7	$15.1	$15.6	$21.1	$18.8	$19.5	$20.8	$22.4	$24.1
15%	$13.2	$10.6	$10.0	$10.0	$10.1	$10.4	$14.6	$12.7	$12.8	$13.5	$14.3	$15.3
19.75%	$10.4	$8.3	$7.8	$7.7	$7.8	$7.9	$11.4	$9.7	$9.7	$10.0	$10.6	$11.2
	Packing Factor 40%						Packing Factor 40%					
5%	$58.1	$47.7	$46.1	$46.6	$48.0	$49.9	$66.3	$60.0	$62.5	$67.2	$72.7	$78.7
10%	$22.7	$18.3	$17.3	$17.3	$17.6	$18.1	$25.2	$22.0	$22.3	$23.5	$25.0	$26.7
15%	$16.2	$12.9	$12.1	$11.9	$12.0	$12.3	$17.7	$15.0	$15.0	$15.5	$16.4	$17.3
19.75%	$13.5	$10.6	$9.9	$9.7	$9.7	$9.8	$14.5	$12.1	$11.9	$12.2	$12.7	$13.4
	Packing Factor 50%						Packing Factor 50%					
5%	$113.1	$91.8	$87.8	$88.2	$90.2	$93.2	$127.1	$112.8	$115.8	$123.1	$132.1	$142.1
10%	$31.8	$25.3	$23.9	$23.6	$23.9	$24.4	$34.8	$29.9	$29.9	$31.2	$32.9	$35.0
15%	$20.6	$16.2	$15.1	$14.8	$14.9	$15.1	$22.2	$18.6	$18.3	$18.8	$19.7	$20.6
19.75%	$16.2	$12.7	$11.8	$11.5	$11.4	$11.5	$17.3	$14.3	$13.9	$14.1	$14.6	$15.2

Table 4.20: Fuel and outage cost ($/MWhe) with a high fabrication cost ($24,000/kgU)

High Fabrication Costs												
	Outage Cost - $20 Million Number of Batches						Outage Cost - $50 Million Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$120.2	$95.0	$88.8	$87.3	$87.6	$89.0	$129.9	$109.6	$108.2	$111.5	$116.7	$122.9
10%	$39.6	$31.2	$29.1	$28.5	$28.6	$28.9	$42.6	$35.7	$35.1	$36.0	$37.5	$39.4
15%	$27.1	$21.3	$19.8	$19.3	$19.3	$19.5	$29.0	$24.2	$23.6	$24.1	$25.1	$26.3
19.75%	$20.8	$16.3	$15.1	$14.7	$14.7	$14.8	$22.2	$18.4	$17.9	$18.2	$18.9	$19.7
	Packing Factor 20%						Packing Factor 20%					
5%	$127.9	$99.3	$91.2	$88.3	$87.4	$87.6	$134.6	$109.2	$104.5	$104.9	$107.4	$110.9
10%	$48.0	$37.1	$34.1	$32.9	$32.5	$32.5	$50.3	$40.6	$38.7	$38.7	$39.5	$40.7
15%	$32.1	$24.8	$22.7	$21.9	$21.6	$21.6	$33.6	$27.0	$25.7	$25.6	$26.0	$26.7
19.75%	$25.5	$19.6	$17.9	$17.3	$17.0	$17.0	$26.6	$21.3	$20.1	$20.0	$20.3	$20.8
	Packing Factor 30%						Packing Factor 30%					
5%	$167.1	$128.7	$117.4	$112.8	$111.0	$110.5	$173.8	$138.7	$130.7	$129.5	$131.0	$133.9
10%	$65.0	$50.0	$45.5	$43.7	$42.9	$42.6	$67.4	$53.6	$50.3	$49.7	$50.2	$51.1
15%	$39.8	$30.6	$27.8	$26.7	$26.1	$26.0	$41.2	$32.7	$30.6	$30.1	$30.3	$30.9
19.75%	$28.4	$21.7	$19.7	$18.9	$18.5	$18.4	$29.3	$23.1	$21.6	$21.2	$21.3	$21.7
	Packing Factor 40%						Packing Factor 40%					
5%	$248.0	$190.1	$172.6	$165.3	$162.0	$160.7	$256.2	$202.4	$189.1	$185.8	$186.6	$189.4
10%	$79.9	$61.2	$55.5	$53.1	$51.9	$51.5	$82.4	$64.9	$60.5	$59.3	$59.4	$60.1
15%	$49.5	$37.8	$34.3	$32.7	$32.0	$31.7	$50.9	$40.0	$37.1	$36.3	$36.3	$36.7
19.75%	$36.8	$28.1	$25.5	$24.3	$23.7	$23.5	$37.9	$29.7	$27.5	$26.8	$26.8	$27.0
	Packing Factor 50%						Packing Factor 50%					
5%	$487.6	$372.7	$337.5	$322.2	$314.9	$311.6	$501.5	$393.6	$365.4	$357.1	$356.8	$360.5
10%	$112.7	$86.0	$77.8	$74.2	$72.4	$71.6	$115.7	$90.6	$83.9	$81.8	$81.5	$82.2
15%	$63.1	$48.1	$43.5	$41.4	$40.4	$39.9	$64.7	$50.5	$46.7	$45.4	$45.2	$45.5
19.75%	$44.7	$34.0	$30.7	$29.2	$28.5	$28.1	$45.7	$35.6	$32.8	$31.9	$31.7	$31.8

Results from Lewis were presented in a similar fashion, however, they were obtained without MC Dancoff correction. Table 4.21 shows the relative percent difference of the new results weighed against the old. The red indicates an increase in FCC, while green indicates a decrease. Tan colors indicate small change. The maximum increase is much greater, 163.4%, than the decrease, 21.1%. Since the Dancoff correction comes more into play at higher packing factors this could explain the large price discrepancies in that region. This also might explain why the large differences are at low enrichment fuels, as the spot prices are not as influential in these regions, relying more in differences in burnup. Interesting to note that some values changed very little (<2% difference), but with the drastic changes to spot prices and Dancoff factors, these few instances may be coincidental. This analysis shows when the fabrication variable is held constant against the neutronic correction drastic changes are present. Now lets couple this change with more informed fabrication costs.

Table 4.21: The relative difference of FCC between corrected and uncorrected data for a once-through cycle for all fabrication cost scenarios

	$20 Million Outage			**$50 Million Outage**		
	Low	**Base**	**High**	**Low**	**Base**	**High**
	Packing Factor 10%			**Packing Factor 10%**		
5%	-3.6%	0.6%	6.2%	0.1%	2.3%	6.3%
10%	-12.1%	-7.5%	0.9%	-8.2%	-5.2%	1.2%
15%	-12.5%	-8.0%	2.0%	-8.7%	-5.6%	2.4%
19.75%	-17.4%	-13.4%	-3.3%	-14.1%	-11.2%	-2.8%
	Packing Factor 20%			**Packing Factor 20%**		
5%	-0.5%	4.9%	11.3%	2.9%	6.3%	11.4%
10%	-10.3%	-4.8%	4.5%	-7.1%	-3.1%	4.7%
15%	-13.9%	-8.9%	1.7%	-11.0%	-7.2%	1.9%
19.75%	-16.2%	-11.8%	-0.8%	-13.7%	-10.1%	-0.5%
	Packing Factor 30%			**Packing Factor 30%**		
5%	8.0%	14.5%	21.7%	11.3%	15.8%	21.8%
10%	-0.1%	6.4%	17.2%	3.0%	8.0%	17.4%
15%	-11.2%	-5.9%	5.4%	-8.8%	-4.4%	5.6%
19.75%	-21.1%	-16.9%	-6.2%	-19.3%	-15.6%	-6.0%
	Packing Factor 40%			**Packing Factor 40%**		
5%	35.6%	44.1%	53.5%	39.4%	45.6%	53.6%
10%	4.7%	11.8%	23.4%	7.5%	13.2%	23.5%
15%	-3.5%	2.5%	15.0%	-1.2%	3.8%	15.2%
19.75%	-8.7%	-3.6%	8.9%	-6.8%	-2.4%	9.1%
	Packing Factor 50%			**Packing Factor 50%**		
5%	131.8%	146.9%	163.2%	137.8%	149.1%	163.4%
10%	32.4%	41.6%	56.5%	35.7%	43.3%	56.7%
15%	12.0%	19.1%	33.8%	14.4%	20.5%	34.0%
19.75%	1.9%	7.7%	21.7%	3.8%	8.9%	22.0%

Table 4.22, Table 4.23, and Table 4.24 display the fuel cycle costs in \$/MWhe for the lo, mid, and hi fuel fabrication costs, respectively. The values for the lo fabrication costs get as high as \$142.4 and as low as \$7.7. The values for the mid fabrication costs get as high as \$252.0 and as low as \$10.4. The values for the hi fabrication costs get as high as \$637.7 and as low as \$19.2. The high values are consistently found in the 50% packing factor, \$50 million outage cost, and 5% enriched, once-through data regions. The low values are found in the 10% packing factor, \$20 million outage cost, 19.75% enriched, and 3-4 batches data regions except for the hi cost scenario with the lowest being found in the 5-6 batches regions (other parameters the same).

These tables show similar trends to what was observed for the previous set of tables with some notable differences related to how the heavy metal loading is treated. At lower fabrication costs (lo and mid) the cost difference between 10-30% packing fraction is much smaller than the fixed cost scenario. The cost remains more stable, albeit increasing, with increasing packing fraction. This dampening effect of cost relates to the premium in fabrication cost from loading more heavy metal per plank. Another notable difference is that the highest cost has shifted from 6 batches to 1 batch for 5% packing, 19.75% enriched fuel. This is due to the discharge burnup being so low for this case that the increased batches offer steady cost benefits for increased burnup regardless of more outages and outage costs.

These prices, however, are all larger than what was seen in the previous study, as shown in the relative percent difference Table 4.25. The difference is mapped between the old scenarios and the new scenarios as follows: lo with low, mid with base, and hi with high. The differences are as large as 419.5% and as low as 12.4% with no configuration yielding a lower FCC. The base fixed fabrication cost in the previous study is extremely low when compared to the mid estimate assumed in this study, hence the rather large percent difference. The smallest relative difference is seen when comparing the previous low estimate with the lo estimate at middle packing fractions (20-30%) due to the much higher burnup the MC Dancoff correction resulted in for these packing fractions coupled with the heavy metal loading fabrication cost premium.

Table 4.22: Fuel and outage cost ($/MWhe) using the lo fabrication cost scenario, Table 4.14

Lo Fabrication Costs												
	Outage Cost - $20 Million Number of Batches						Outage Cost - $50 Million Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$43.3	$37.3	$37.5	$39.2	$41.5	$44.1	$53.0	$51.9	$56.9	$63.4	$70.6	$78.0
10%	$15.9	$13.4	$13.2	$13.7	$14.3	$15.1	$18.9	$17.9	$19.2	$21.1	$23.3	$25.6
15%	$11.8	$9.8	$9.6	$9.8	$10.2	$10.6	$13.7	$12.7	$13.4	$14.6	$15.9	$17.4
19.75%	$9.7	$8.0	$7.7	$7.8	$8.0	$8.4	$11.1	$10.1	$10.5	$11.3	$12.2	$13.3
	Packing Factor 20%						Packing Factor 20%					
5%	$39.2	$32.7	$32.1	$32.8	$34.2	$35.8	$45.9	$42.7	$45.4	$49.5	$54.2	$59.1
10%	$16.8	$13.8	$13.3	$13.4	$13.8	$14.4	$19.2	$17.3	$18.0	$19.3	$20.8	$22.5
15%	$12.5	$10.1	$9.7	$9.7	$9.9	$10.2	$14.0	$12.3	$12.6	$13.3	$14.3	$15.3
19.75%	$10.8	$8.6	$8.2	$8.1	$8.2	$8.4	$11.9	$10.3	$10.4	$10.9	$11.5	$12.3
	Packing Factor 30%						Packing Factor 30%					
5%	$47.5	$38.9	$37.6	$38.0	$39.2	$40.7	$54.1	$49.0	$50.9	$54.7	$59.2	$64.1
10%	$21.4	$17.3	$16.5	$16.4	$16.8	$17.2	$23.9	$20.9	$21.3	$22.5	$24.0	$25.7
15%	$14.8	$11.8	$11.1	$11.0	$11.1	$11.3	$16.2	$13.9	$13.9	$14.5	$15.3	$16.2
19.75%	$11.5	$9.1	$8.5	$8.4	$8.4	$8.5	$12.4	$10.5	$10.4	$10.7	$11.2	$11.8
	Packing Factor 40%						Packing Factor 40%					
5%	$67.3	$54.6	$52.2	$52.3	$53.5	$55.2	$75.5	$66.9	$68.6	$72.9	$78.2	$84.0
10%	$25.4	$20.3	$19.2	$19.0	$19.2	$19.7	$27.9	$24.0	$24.1	$25.2	$26.7	$28.4
15%	$17.8	$14.1	$13.2	$12.9	$13.0	$13.2	$19.3	$16.2	$16.0	$16.5	$17.3	$18.2
19.75%	$14.6	$11.4	$10.6	$10.4	$10.4	$10.5	$15.6	$13.0	$12.6	$12.9	$13.4	$14.0
	Packing Factor 50%						Packing Factor 50%					
5%	$128.1	$103.1	$97.8	$97.6	$99.2	$101.9	$142.1	$124.1	$125.8	$132.5	$141.2	$150.8
10%	$35.0	$27.8	$26.0	$25.7	$25.8	$26.3	$38.0	$32.3	$32.1	$33.2	$34.9	$36.9
15%	$22.3	$17.5	$16.3	$15.9	$15.9	$16.1	$23.9	$19.9	$19.4	$19.9	$20.7	$21.6
19.75%	$17.4	$13.6	$12.5	$12.2	$12.1	$12.2	$18.4	$15.2	$14.6	$14.8	$15.3	$15.9

Table 4.23: Fuel and outage cost ($/MWhe) using the mid fabrication cost scenario, Table 4.14

Mid Fabrication Costs												
	Outage Cost - $20 Million						Outage Cost - $50 Million					
	Number of Batches						Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$71.8	$58.7	$56.5	$57.0	$58.6	$60.7	$81.5	$73.2	$75.9	$81.2	$87.7	$94.6
10%	$24.7	$20.0	$19.1	$19.1	$19.6	$20.2	$27.6	$24.5	$25.1	$26.6	$28.6	$30.7
15%	$17.5	$14.1	$13.4	$13.3	$13.6	$13.9	$19.4	$17.0	$17.2	$18.1	$19.3	$20.7
19.75%	$13.8	$11.0	$10.4	$10.4	$10.5	$10.8	$15.2	$13.1	$13.2	$13.9	$14.7	$15.6
	Packing Factor 20%						Packing Factor 20%					
5%	$68.7	$54.8	$51.7	$51.2	$51.9	$53.0	$75.3	$64.8	$65.0	$67.9	$71.8	$76.3
10%	$27.2	$21.5	$20.2	$19.9	$20.0	$20.4	$29.5	$25.1	$24.9	$25.7	$27.1	$28.6
15%	$19.0	$15.0	$14.0	$13.7	$13.8	$14.0	$20.5	$17.2	$16.9	$17.4	$18.2	$19.1
19.75%	$15.7	$12.3	$11.4	$11.2	$11.2	$11.3	$16.8	$13.9	$13.6	$13.9	$14.5	$15.1
	Packing Factor 30%						Packing Factor 30%					
5%	$85.5	$67.5	$63.0	$61.8	$62.0	$62.9	$92.2	$77.5	$76.3	$78.5	$82.1	$86.3
10%	$35.3	$27.7	$25.7	$25.1	$25.1	$25.3	$37.7	$31.3	$30.6	$31.2	$32.4	$33.8
15%	$22.8	$17.8	$16.4	$16.0	$15.9	$16.0	$24.2	$19.9	$19.2	$19.5	$20.1	$20.9
19.75%	$16.9	$13.1	$12.1	$11.7	$11.6	$11.7	$17.8	$14.5	$14.0	$14.1	$14.4	$15.0
	Packing Factor 40%						Packing Factor 40%					
5%	$123.4	$96.6	$89.6	$87.4	$87.2	$88.0	$131.6	$109.0	$106.0	$108.0	$111.9	$116.8
10%	$42.4	$33.0	$30.5	$29.6	$29.4	$29.5	$44.9	$36.7	$35.4	$35.8	$36.8	$38.2
15%	$27.6	$21.5	$19.7	$19.1	$18.9	$18.9	$29.1	$23.6	$22.6	$22.7	$23.2	$24.0
19.75%	$21.5	$16.6	$15.2	$14.7	$14.5	$14.5	$22.5	$18.1	$17.3	$17.2	$17.6	$18.1
	Packing Factor 50%						Packing Factor 50%					
5%	$238.0	$185.5	$171.1	$166.2	$165.2	$166.0	$252.0	$206.4	$199.0	$201.1	$207.1	$214.9
10%	$58.8	$45.6	$41.9	$40.5	$40.1	$40.1	$61.8	$50.1	$47.9	$48.0	$49.1	$50.7
15%	$34.8	$26.9	$24.6	$23.7	$23.4	$23.4	$36.4	$29.3	$27.8	$27.7	$28.2	$28.9
19.75%	$25.7	$19.8	$18.1	$17.4	$17.1	$17.1	$26.8	$21.4	$20.2	$20.0	$20.3	$20.8

Table 4.24: Fuel and outage cost ($/MWhe) using the hi fabrication cost scenario, Table 4.14

	Hi Fabrication Costs											
	Outage Cost - $20 Million Number of Batches						Outage Cost - $50 Million Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$172.2	$134.0	$123.4	$119.8	$118.8	$119.3	$181.9	$148.6	$142.8	$144.0	$147.9	$153.2
10%	$55.7	$43.3	$39.8	$38.5	$38.2	$38.3	$58.7	$47.7	$45.8	$46.0	$47.2	$48.8
15%	$37.4	$29.0	$26.7	$25.8	$25.5	$25.6	$39.3	$31.9	$30.5	$30.6	$31.3	$32.3
19.75%	$28.3	$21.9	$20.1	$19.4	$19.2	$19.2	$29.7	$24.0	$22.9	$22.9	$23.4	$24.1
	Packing Factor 20%						Packing Factor 20%					
5%	$172.4	$132.6	$120.8	$116.1	$114.1	$113.5	$179.0	$142.6	$134.2	$132.7	$134.1	$136.8
10%	$63.6	$48.9	$44.5	$42.7	$41.9	$41.6	$65.9	$52.4	$49.1	$48.5	$48.9	$49.8
15%	$41.9	$32.2	$29.3	$28.0	$27.5	$27.3	$43.4	$34.4	$32.2	$31.7	$31.9	$32.5
19.75%	$32.8	$25.2	$22.8	$21.9	$21.4	$21.3	$33.9	$26.8	$25.1	$24.6	$24.7	$25.1
	Packing Factor 30%						Packing Factor 30%					
5%	$219.4	$167.9	$152.2	$145.5	$142.3	$141.0	$226.1	$177.9	$165.6	$162.2	$162.4	$164.3
10%	$84.0	$64.2	$58.2	$55.5	$54.3	$53.7	$86.4	$67.9	$63.0	$61.6	$61.6	$62.2
15%	$50.8	$38.8	$35.1	$33.5	$32.7	$32.3	$52.2	$40.9	$37.9	$37.0	$36.9	$37.2
19.75%	$35.7	$27.2	$24.6	$23.5	$22.9	$22.7	$36.6	$28.7	$26.5	$25.8	$25.7	$25.9
	Packing Factor 40%						Packing Factor 40%					
5%	$320.5	$244.5	$221.0	$210.6	$205.5	$203.0	$328.8	$256.8	$237.4	$231.2	$230.2	$231.8
10%	$101.8	$77.6	$70.1	$66.7	$65.1	$64.2	$104.3	$81.3	$75.0	$72.9	$72.5	$72.9
15%	$62.2	$47.3	$42.7	$40.7	$39.6	$39.1	$63.6	$49.5	$45.6	$44.3	$43.9	$44.1
19.75%	$45.8	$34.8	$31.4	$29.9	$29.1	$28.7	$46.8	$36.4	$33.4	$32.4	$32.1	$32.2
	Packing Factor 50%						Packing Factor 50%					
5%	$623.8	$474.8	$428.3	$407.3	$396.6	$391.0	$637.7	$495.8	$456.2	$442.2	$438.5	$439.9
10%	$142.1	$108.1	$97.4	$92.6	$90.1	$88.8	$145.2	$112.6	$103.5	$100.2	$99.2	$99.4
15%	$78.6	$59.7	$53.8	$51.1	$49.7	$48.9	$80.2	$62.1	$57.0	$55.1	$54.5	$54.5
19.75%	$55.0	$41.8	$37.6	$35.7	$34.7	$34.1	$56.1	$43.4	$39.7	$38.4	$37.9	$37.9

Table 4.25: Relative difference of FCC between corrected and uncorrected data (Lo-Low, Mid-Base, and Hi-High).

	$20 Million Outage			$50 Million Outage		
	Lo	Mid	Hi	Lo	Mid	Hi
	Packing Factor 10%			Packing Factor 10%		
5%	118.23%	131.9%	52.1%	84.0%	104.1%	48.9%
10%	66.1%	88.4%	41.9%	52.1%	73.5%	39.4%
15%	47.4%	70.9%	40.9%	40.3%	61.6%	38.8%
19.75%	29.0%	50.3%	31.6%	25.3%	44.5%	30.0%
	Packing Factor 20%			Packing Factor 20%		
5%	114.4%	130.6%	50.0%	89.9%	111.3%	48.2%
10%	59.7%	84.3%	38.6%	51.1%	74.7%	37.2%
15%	36.7%	60.9%	32.8%	33.0%	55.5%	31.8%
19.75%	23.7%	45.9%	27.9%	21.9%	42.5%	27.1%
	Packing Factor 30%			Packing Factor 30%		
5%	127.2%	146.2%	59.8%	106.1%	129.8%	58.4%
10%	72.8%	101.4%	51.5%	65.9%	93.3%	50.5%
15%	37.1%	62.6%	34.3%	34.5%	58.4%	33.6%
19.75%	13.4%	34.5%	18.1%	12.4%	32.2%	17.6%
	Packing Factor 40%			Packing Factor 40%		
5%	180.8%	206.0%	98.4%	158.5%	188.8%	97.1%
10%	78.0%	108.7%	57.1%	72.1%	101.8%	56.3%
15%	46.6%	74.7%	44.5%	44.4%	71.0%	43.9%
19.75%	29.3%	54.0%	35.3%	28.5%	51.8%	34.8%
	Packing Factor 50%			Packing Factor 50%		
5%	374.8%	419.5%	236.7%	341.5%	393.9%	234.9%
10%	122.6%	162.0%	97.4%	116.3%	154.5%	96.6%
15%	68.3%	101.2%	66.6%	66.3%	97.6%	66.0%
19.75%	42.9%	70.5%	49.9%	42.1%	68.6%	49.5%

The following tables, Table 4.26, Table 4.27, and Table 4.28, show the FCC over packing fractions for the lo, mid, hi, and high fixed ($24,000/kgU) fabrication cost scenarios using data for 10%, 15%, and19.75% enriched fuel at 2 batches and a $50 million outage cost. Figure 4.10, Figure 4.11, and Figure 4.12, show the graphical representation of these tables, respectively. The trend for fixed fabrication costs steadily increases with increasing packing fraction biasing towards lower packing fractions. The smoothness of the curves for all the enrichments is determined by the interplay of packing fraction and enrichment on depletion. This relationship is complex and it is hard to say why a knee or distinct shift in curve slope is seen in some cases.

The dampening effect seen at higher enrichments and lower packing fractions is related to the heavy metal loading fabrication cost premium mentioned earlier. For 10% packing fraction the lo fabrication cost model shows a minimum value at 20% packing fraction, albeit a rather small relative difference with the other scenarios showing a trend similar to the fixed case. The hi cost scenarios show trends most similar to the fixed case scenarios due to the high TRISO fabrication cost used in that scenario which is assumed to be a fixed cost not dependent on packing fraction. This large fixed component cost dominates the packing fraction dependent components and the trend behaves more like a fixed fabrication cost. The 19.75% enrichment with lo and mid fabrication cost scenarios show a small increase in FCC, as small as 4% to 10% from 10% to 30% packing fraction, while the FCC increases by 25.96% for the fixed cost scenario on this range. When FCC is used to drive fuel configuration optimization the difference in hi, lo, or fixed fabrication cost can result in drastic differences in design choice.

Table 4.26: Fuel cycle costs [$/MWhe] for various fabrication scenarios over packing fractions for 10% enriched fuel at 2 batches and a $50 million outage cost

	Packing Fraction				
	10%	20%	30%	40%	50%
Lo Fab Cost	$17.88	$17.29	$20.95	$24.05	$32.29
Mid Fab Cost	$24.48	$25.05	$31.33	$36.74	$50.10
Hi Fab Cost	$47.75	$52.36	$67.85	$81.33	$112.64
Fixed Fab Cost	$35.70	$40.65	$53.60	$64.92	$90.56

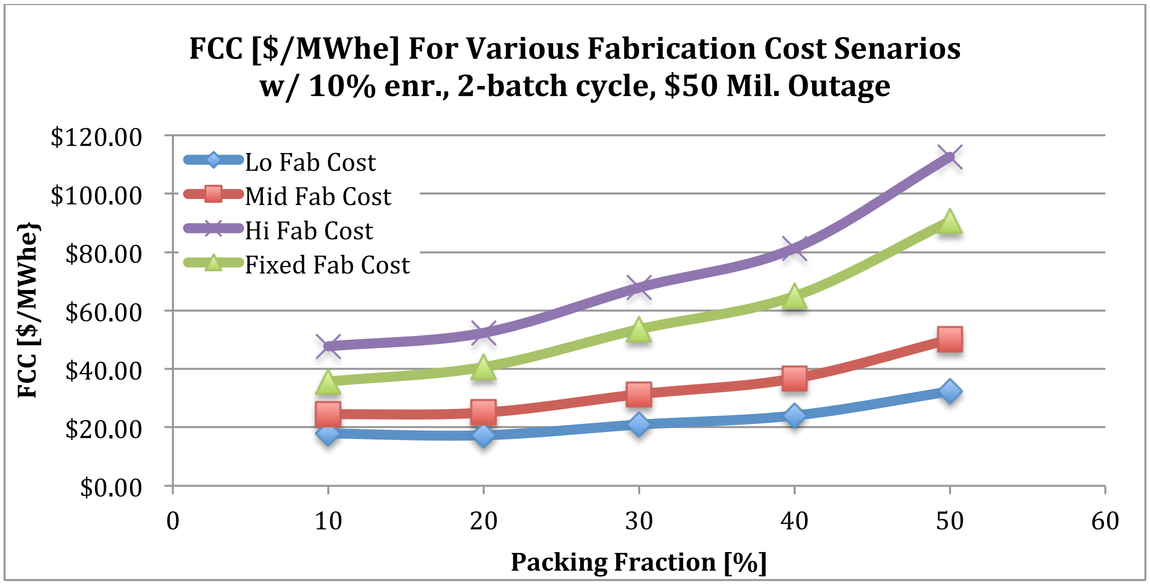

Figure 4.10: FCC over packing fractions for three fabrication cost scenarios using 10% enriched, 2-batch, $50 mil. outage cost data

Table 4.27: Fuel cycle costs [$/MWhe] for various fabrication scenarios over packing fractions for 15% enriched fuel at 2 batches and a $50 million outage cost

	Packing Fraction				
	10%	20%	30%	40%	50%
Lo Fab Cost	$12.71	$12.34	$13.89	$16.24	$19.89
Mid Fab Cost	$16.95	$17.22	$19.87	$23.61	$29.25
Hi Fab Cost	$31.91	$34.39	$40.89	$49.51	$62.12
Fixed Fab Cost	$24.17	$27.02	$32.68	$39.98	$50.52

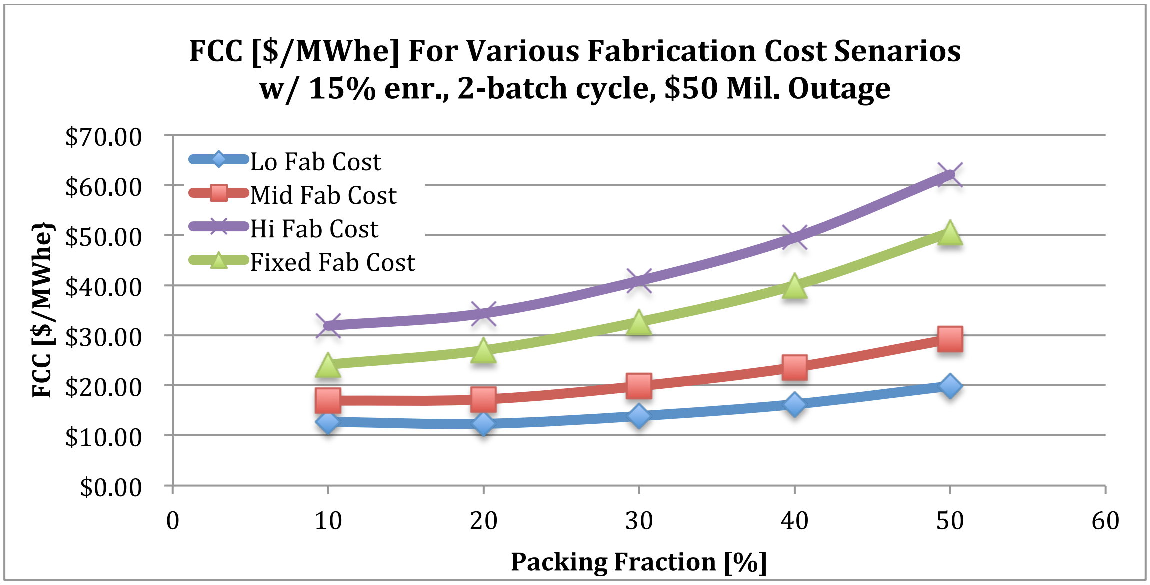

Figure 4.11: FCC over packing fractions for three fabrication cost scenarios using 15% enriched, 2-batch, $50 mil. outage cost data

Table 4.28: Fuel cycle costs [$/MWhe] for various fabrication scenarios over packing fractions for 19.75% enriched fuel at 2 batches and a $50 million outage cost

	Packing Fraction				
	10%	20%	30%	40%	50%
Lo Fab Cost	$10.06	$10.29	$10.51	$12.96	$15.15
Mid Fab Cost	$13.13	$13.94	$14.53	$18.14	$21.41
Hi Fab Cost	$23.98	$26.81	$28.66	$36.36	$43.37
Fixed Fab Cost	$18.37	$21.29	$23.14	$29.65	$35.62

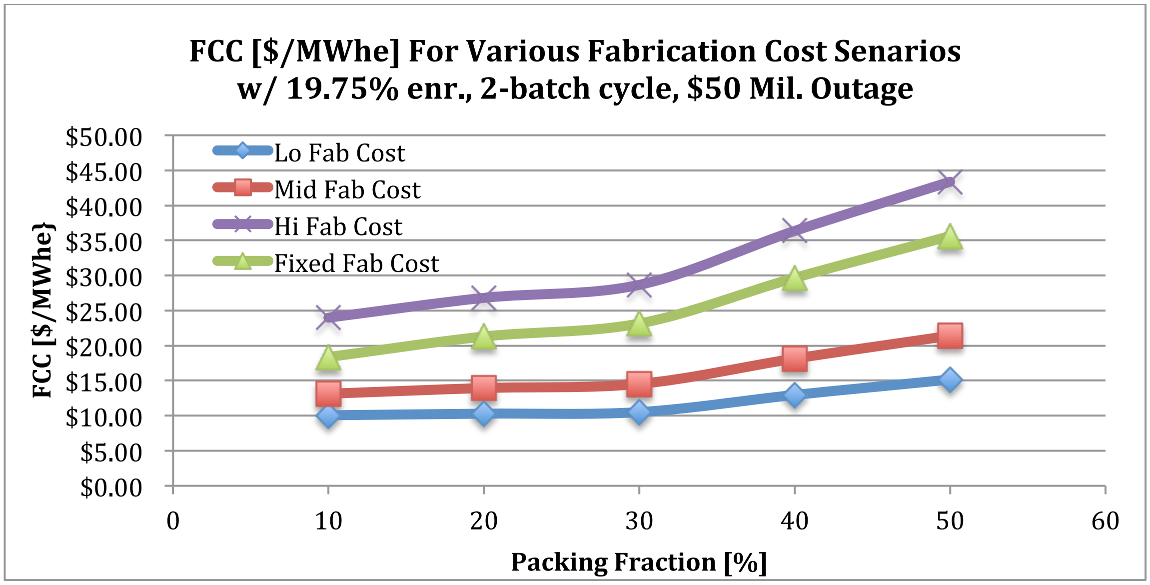

Figure 4.12: FCC over packing fractions for three fabrication cost scenarios using 19.75% enriched, 2-batch, $50 mil. outage cost data

The past few tables more than any others show the real significance of this analysis as the more detailed fabrication costs and neutronic corrections are weighed against the old analysis. The large differences speak to the concerns with using the previous FCC model. Trying to refine and limit the fabrication cost range was initially desired but a larger range was ultimately developed in that effort. The important take away is that the cost of fuel fabrication is most likely more expensive than was initially being considered with packing factor and TRISO particle manufacturing influencing fabrication cost in significant ways. Research and development for TRISO fuel manufacturing is required to drive the FCC down as this was one of the most contributing factors of cost. A more detailed economic study on the total cost of the FHR design needs to be accomplished to see if the increased FCC cost is outweighed by decreased capital costs. This study also shows that correcting the fabrication cost model and depletion models leans more favorable fuel performance on packing factors around the 30% region influencing fuel and core configuration optimization in ways not seen previously.

Keeping in mind traditional nuclear market prices are about $8/MWhe for BWR/PWR's (only accounts for fuel costs) [28] and that a 2-year (730 day), 50 GWd/MTU cycle is desired a table of the more favorable fuel design scenarios was assembled (Table 4.29) using the lo fabrication cost scenario with $20 million outage cost. The 10% and15% enrichment cases are only incorporated into this table as a 19.75% enriched fuel design is not likely to be licensed by the Nuclear Regulatory Commission (NRC) in the near future. These designs fall way short of the cycle length and FCC criteria but the discharge burnups are all beyond the desired value. The most favorable designs are all for the 19.75% enriched fuel; one with 10% packing fraction at 2 batches ($7.97/MWhe and 398 EFPD), another with 20% packing fraction at 1 batch ($10.78/MWhe and 757 EFPD), another with 30% packing fraction at 2 batches ($9.1/MWhe and 591 EFPD), and one with 30% packing fraction at 1 batches ($11.51/MWhe and 886 EFPD). The 20% and 30% packing fraction and 19.75% enriched fuel scenarios at lower batches are overall the more favorable fuel configurations.

Table 4.29: A collection of fuel designs and batch numbers that show promising cycle lengths, discharge BU, and FCC (using lo fabrication cost scenario)

Enrichment	PF	# Batches	FCC [$/MWhe]	Cycle length [EFPD]	Discharge BU [GWd/MTU]
10%	20%	1	16.82	357	55.69
15%	20%	2	10.13	378	118.07
	30%	2	11.79	397	94.46
	40%	2	14.08	386	75.78
19.75%	10%	1	9.69	597	147.3
		2	7.97	398	196.41
	20%	1	10.78	757	118.22
		2	8.64	505	157.63
	30%	1	11.51	886	105.39
		2	9.1	591	140.52
	40%	1	14.58	823	80.8
	50%	1	17.38	786	66.48

It is important to remember that many variables in the fuel design and fabrication cost model can be updated as more accurate or optimized parameters are discovered. This analysis purposely holds some factors constant in order to study others in a greater amount of detail. Moving forward this model can be easily used to apply more accurate or current information.

CHAPTER 5: CONCLUSIONS

The FHR is a novel reactor design that offers many operational and safety benefits including but not limited to high operating temperature, low operating pressure, multiple fission gas barriers, no pressure vessel, and passive safety features. Much of the design relies on well-understood if not well developed technologies such as liquid salt coolant and graphite fuels containing TRISO particles. The problem arises in the need to enrich the Li in the coolant to extremely pure levels and to keep it pure with advanced purification technology not readily available. The fuel also needs to be configured with high precision in a layered 'plank' configuration in which packing fraction, fuel strip/plank thickness, and fuel enrichment are important design parameters. This research looked to address the FHR fuel plank design as an important aspect of the FHR through a detailed fuel cycle analysis.

A fuel cycle cost analysis allowed this reactor design to be benchmarked for economic viability by coupling reactor and fuel performance via discharge burnup with the actual cost of the fuel taking into account fuel enrichment costs and fabrication cost. Previous FCC models have been developed using a broad range of fixed fabrication costs though more accurate neutronic models have since been formulated and development of a more informed range of fabrication costs was proven to be warranted. It can be deduced simply that packing fraction will affect the heavy metal loading in a single plank and that the cost to manufacture a single plank will then be decreased with increasing packing fraction on a dollar per kilogram uranium basis. Therefore, the update to the FCC model was two-fold one addressing the neutronic model and fabrication cost.

The corrected neutronics model first incorporated updated fuel region temperatures developed from a RELAP5 model that was specific to plate thickness, enrichment, and packing fraction. The second correction involved the input of a Monte Carlo Dancoff-Ginsberg correction factor which is used to correct the nuclear cross sections to properly account for the resonance escape probability in one TRISO fuel kernel so that it reaches another in the proper way. This is a major issue when modeling double-heterogeneous fuels with multi-group energy discretization. The neutron transport code package SCALE 6.1 has built in functionality to handle this computational phenomenon for TRISO contained in cylindrical and spherical graphite compacts but not for plank configurations, therefore the MC Dancoff correction was needed for the FHR depletion cases.

A detailed study was accomplished to converge proper correction factors for enrichment and packing fraction based on a continuous energy simulation. These MC Dancoff factors and updated temperatures were used for a set of twenty depletion cases covering combinations of 10%, 20%, 30%, 40%, and 50% packing fraction fuel designs with TRISO fuel enriched to 5%, 10%, 15%, and 19.75%. The cases took over a week to run and from the outputs the discharge burnups and once through cycle lengths were calculated using the appropriate specific power, which is dependent on packing fraction.

It was found that the corrected models had shorter cycle lengths and smaller discharge burnups that became more disparate with increasing packing fraction as seen with the 2-batches discharge burnup for the corrected and uncorrected model with 15% enriched fuel shown in Figure 5.1. This is due to the increased influence the MC Dancoff corrections had on fuel designs having higher densities of particles and more fuel shadowing effects. The models varied very little from the uncorrected models for lower packing factors but had cycle lengths as much as a few hundred EFPD shorter for higher packing factors.

The fuel cost was broken down into fabrication cost and enrichment cost with enrichment cost calculated in a standard way using up to date uranium market spot prices easily obtainable from market resources. The fabrication cost was broken up into three categories: materials, manufacturing, and quality assurance. The materials cost component accounted for all the materials present in a single fuel plank deduced from analogous graphite fuel compact fabrication methods and also took into account TRISO packing fraction. A separate cost was estimated for the TRISO materials apart from the enriched uranium contained within.

The manufacturing cost component was more difficult to ascertain. Capital and operation and maintenance costs of a fabrication facility and yearly capacity needed to be determined for an accurate estimate to be attributed to this component. Similar fuel design manufacturing technologies and the capital and O&M costs associated with them were analyzed in depth to look for similarities and differences. When appropriate, these figures were used to estimate a range for FHR fuel fabrication facility costs based on similarities in the manufacturing process. A range of yearly manufacturing capacities was determined in a similar manner.

The capital cost of a fabrication facility cannot be considered paid overnight but over many years with an expected return on investment percentage and a yearly inflation rate associated with the payback period. An analysis was carried out over a range of effective ROI percentages, taking into account inflation, and payback periods and it was determined that the influence over the total cost was nontrivial when compared to other factors and therefore given careful consideration in development of cost scenarios. Aside from the TRISO manufacturing costs the anticipated yearly manufacturing capacity was a large influence on overall price per plank and therefore price per kilogram uranium. The materials cost component and the capital and O&M costs were also translated to the manufacturing of the assembly channels, made of graphite, one for every 18 assemblies.

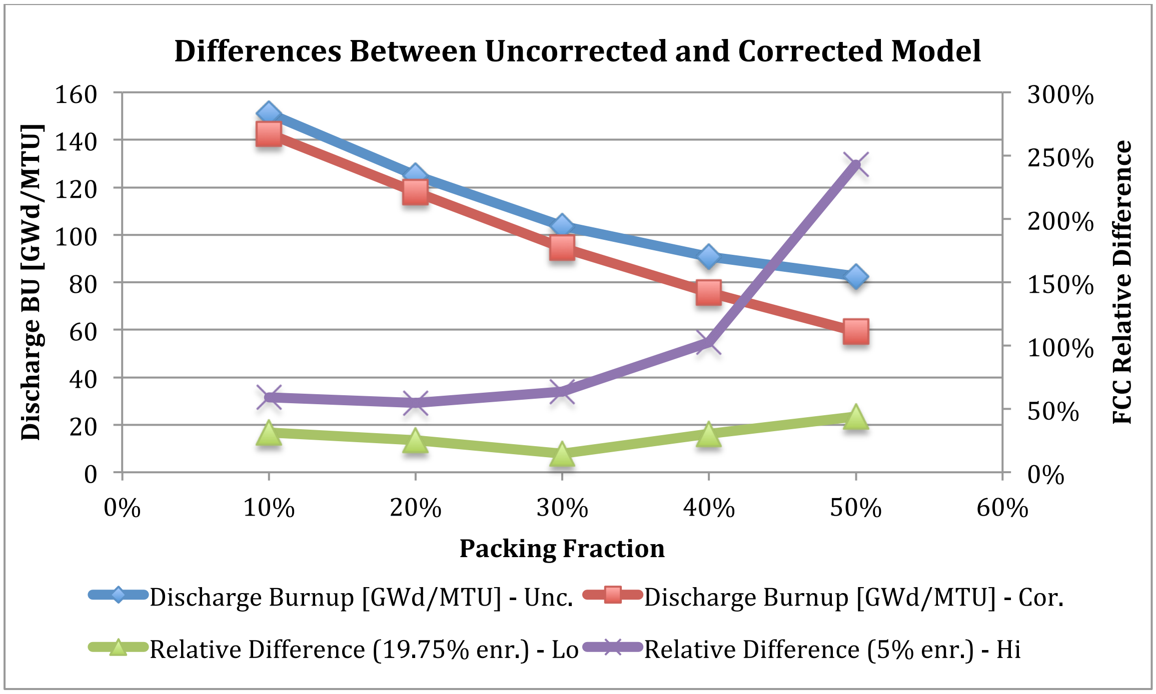

Figure 5.1: 2-batches discharge burnups (GWd/MTU) for the corrected and uncorrected models using 15% enriched fuel and the relative percent difference for the corrected and uncorrected FCC models for 19.75% enriched fuel with the lo-low cost scenario comparison and 5% enriched fuel with a hi -high cost comparison both at 2-batches

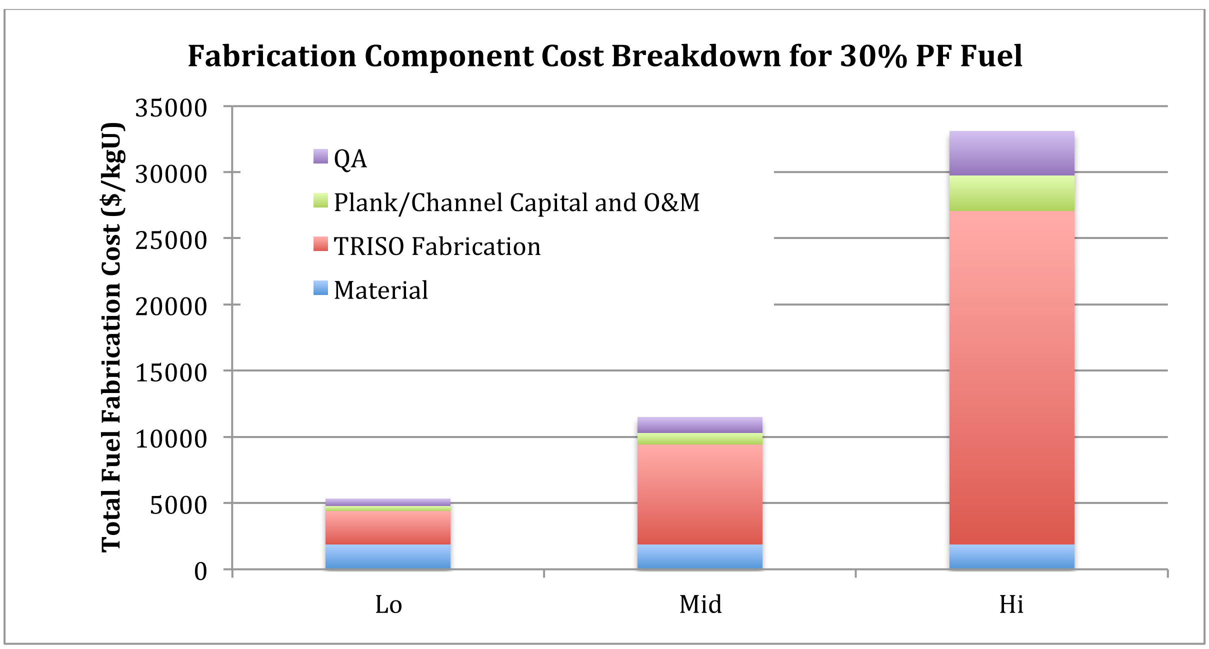

Figure 5.2: Fabrication component cost breakdown for 30% packing fraction fuel

For the TRISO manufacturing costs a range was also assumed but these values were pulled from research that covered expected present day factory scale costs on the high side (~$0.01/particle) to anticipated costs of factory scale production in the near future on the low side (~$0.001/particle). This order of magnitude change was proven to be one of the most significant factors of the fabrication costs adding about $22,700/kgU across all packing fractions and enrichments moving from the low to the high estimate.

The quality assurance cost component was assumed to be 10% of the total fabrication costs to account for the technical precision involved with novel fabrication processes so a simple factor was applied to the calculated material and manufacturing cost components to account for QA. With the three components defined involving variables that covered a range of values lo, mid, and hi cost scenarios were formulated picking values among the various ranges of fabrication cost parameters to portray low to high cost estimates. Again, anticipated yearly manufacturing capacity (capital and O&M cost) and the 10% QA cost contribution to the total is nontrivial the substantial bulk cost is attributed to the TRISO manufacturing cost as shown in Figure 5.2.

The fabrication costs among the various estimated scenarios proved overall to be much larger than the low estimates previously chosen with some overlap with the previous high scenario and the newer lo to mid scenarios depending on packing fraction. Increasing packing fraction would decrease cost by as much as $2000/kgU for the lo scenario and as much as $6000/kgU for the hi scenario, much different than the fixed cost previously assumed. Coupling this data with the multi-batch burnup data acquired from the corrected depletion cases yielded the updated FCC model.

It was determined that many of the costs are much higher using the informed fabrication costs. A new regions of interest for ideal fuel design based on lowest FCC were identified, however, that were different than what was determined with the previous FCC model. Plank fuel with 20 %or 30% packing fractions had low FCC at low fabrication cost scenarios and high enrichments. 10% packing fraction fuels were still determined to be the preferred design as they had the lowest FCC values but the costs up to 30% packing fraction were more stable (relatively constant). This is due partly to the increased burnup from the MC Dancoff corrections and to the accounting of cost premiums of loading more heavy metal into a single plank therefore decreasing manufacturing cost on a per kilogram basis. This notion is significant when it was previously determined that low packing fractions increased the fuel to moderation ratio, in turn increasing fuel utilization but the heavy metal manufacturing premium for higher packing fractions competes with the fuel utilization for higher packing factors at least up to 30%. The complex relationship these two factors have on cost cannot be overlooked (right axis trends of relative difference in Figure 5.1) and proves to favor a low to middle ranged packing factor fuel configuration. This discovery needs to be considered in optimizing fuel and core configurations for the FHR moving forward.

Future work needs to include a more detailed financial analysis of other aspects of the FHR design to see if the overall increase in FCC values will be balanced by the decreased capital and O&M costs of the entire plant, as what was determined above for FCC is not quite on a competitive footing with contemporary energy markets. Also, wherever a range was used in the fabrication cost estimate model more detail and/or research and development may come to shed light on parameters that can refine these prescribed ranges and update the model accordingly. Using the most up to date models and information available this analysis helped determine important financial concerns that need to be considered when optimizing the FHR fuel design.

APPENDIX A

FCC TABLES WITH INITIAL UNCORRECTED RESULTS

Table A. 1: BOC multiplication factor and associated error for range of packing factors and enrichments

	Uranium Enrichment											
Packing Fraction		5%			10%			15%			19.75%	
10%	1.18792	±	0.00044	1.37573	±	0.00047	1.45389	±	0.00042	1.49571	±	0.00049
20%	1.20785	±	0.00051	1.34907	±	0.00045	1.40739	±	0.00046	1.43971	±	0.00049
30%	1.19769	±	0.00052	1.32089	±	0.00053	1.37154	±	0.00053	1.40201	±	0.00047
40%	1.18456	±	0.00051	1.29767	±	0.00047	1.34604	±	0.00047	1.37608	±	0.00046
50%	1.17314	±	0.00048	1.27812	±	0.00069	1.32499	±	0.00046	1.3545	±	0.0005

Table A. 2: Multi-batch cycle lengths (EFPD) and discharge BU (GWd/MTU) for batches 1 through 3

		1 Batch		2 Batch		3 Batch	
Uranium Enrichment	Packing Factor	Cycle Length (days)	Discharge BU (GWd/MTU)	Cycle Length (days)	Discharge BU (GWd/MTU)	Cycle Length (days)	Discharge BU (GWd/MTU)
5.00%	10%	91.3	22.51	60.8	30.01	45.6	33.76
5.00%	20%	139.2	21.74	92.8	28.99	69.6	32.62
5.00%	30%	151.8	18.05	101.2	24.07	75.9	27.08
5.00%	40%	155.5	15.28	103.7	20.37	77.8	22.91
5.00%	50%	157.0	13.28	104.7	17.71	78.5	19.92
10.00%	10%	286.9	70.77	191.3	94.36	143.5	106.15
10.00%	20%	380.7	59.47	253.8	79.29	190.4	89.20
10.00%	30%	410.9	48.85	273.9	65.14	205.4	73.28
10.00%	40%	423.8	41.62	282.5	55.49	211.9	62.42
10.00%	50%	441.7	37.36	294.5	49.81	220.8	56.03
15.00%	10%	459.5	113.33	306.3	151.11	229.7	170.00
15.00%	20%	600.3	93.77	400.2	125.02	300.2	140.65
15.00%	30%	654.3	77.79	436.2	103.72	327.1	116.69
15.00%	40%	693.3	68.09	462.2	90.78	346.6	102.13
15.00%	50%	732.2	61.93	488.2	82.57	366.1	92.90
19.75%	10%	610.5	150.57	407.0	200.76	305.2	225.86
19.75%	20%	794.4	124.08	529.6	165.44	397.2	186.12
19.75%	30%	879.7	104.60	586.5	139.47	439.9	156.90
19.75%	40%	948.4	93.14	632.3	124.19	474.2	139.72
19.75%	50%	1013.6	85.73	675.7	114.30	506.8	128.59

Table A. 3: Multi-batch cycle lengths (EFPD) and discharge BU (GWd/MTU) for batches 4 through 6

		4 Batch		5 Batch		6 Batch	
Uranium Enrichment	**Packing Factor**	**Cycle Length (days)**	**Discharge BU (GWd/MTU)**	**Cycle Length (days)**	**Discharge BU (GWd/MTU)**	**Cycle Length (days)**	**Discharge BU (GWd/MTU)**
5.00%	**10%**	36.5	36.01	30.4	37.51	26.1	38.58
5.00%	**20%**	55.7	34.79	46.4	36.24	39.8	37.28
5.00%	**30%**	60.7	28.89	50.6	30.09	43.4	30.95
5.00%	**40%**	62.2	24.44	51.8	25.46	44.4	26.19
5.00%	**50%**	62.8	21.25	52.3	22.14	44.9	22.77
10.00%	**10%**	114.8	113.23	95.6	117.95	82.0	121.32
10.00%	**20%**	152.3	95.15	126.9	99.11	108.8	101.94
10.00%	**30%**	164.4	78.17	137.0	81.42	117.4	83.75
10.00%	**40%**	169.5	66.59	141.3	69.36	121.1	71.34
10.00%	**50%**	176.7	59.77	147.2	62.26	126.2	64.04
15.00%	**10%**	183.8	181.33	153.2	188.88	131.3	194.28
15.00%	**20%**	240.1	150.02	200.1	156.28	171.5	160.74
15.00%	**30%**	261.7	124.47	218.1	129.66	186.9	133.36
15.00%	**40%**	277.3	108.94	231.1	113.48	198.1	116.72
15.00%	**50%**	292.9	99.09	244.1	103.22	209.2	106.17
19.75%	**10%**	244.2	240.91	203.5	250.95	174.4	258.12
19.75%	**20%**	317.8	198.52	264.8	206.80	227.0	212.70
19.75%	**30%**	351.9	167.36	293.2	174.33	251.4	179.32
19.75%	**40%**	379.4	149.03	316.1	155.24	271.0	159.67
19.75%	**50%**	405.4	137.16	337.9	142.88	289.6	146.96

Table A. 4: Fuel and outage cost ($/MWhe) with a low fabrication cost ($1,300/kgU)

Low Fabrication Costs												
	Outage Cost - $20 Million						Outage Cost - $50 Million					
	Number of Batches						Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$19.85	$19.36	$21.19	$23.60	$26.23	$28.99	$28.80	$32.79	$39.10	$45.98	$53.09	$60.32
10%	$9.55	$8.59	$8.90	$9.53	$10.29	$11.11	$12.40	$12.86	$14.59	$16.65	$18.83	$21.07
15%	$8.02	$6.90	$6.92	$7.23	$7.65	$8.13	$9.79	$9.57	$10.48	$11.68	$12.99	$14.36
19.75%	$7.51	$6.30	$6.20	$6.37	$6.65	$6.98	$8.85	$8.31	$8.87	$9.71	$10.66	$11.67
	Packing Factor 20%						Packing Factor 20%					
5%	$18.28	$16.64	$17.40	$18.76	$20.36	$22.07	$24.15	$25.45	$29.14	$33.43	$37.96	$42.61
10%	$10.54	$8.97	$8.93	$9.27	$9.75	$10.32	$12.68	$12.19	$13.22	$14.63	$16.19	$17.83
15%	$9.16	$7.55	$7.32	$7.43	$7.68	$7.99	$10.52	$9.59	$10.04	$10.83	$11.76	$12.75
19.75%	$8.72	$7.05	$6.73	$6.73	$6.88	$7.09	$9.75	$8.60	$8.78	$9.31	$9.96	$10.68
	Packing Factor 30%						Packing Factor 30%					
5%	$20.89	$18.36	$18.71	$19.78	$21.15	$22.65	$26.27	$26.43	$29.47	$33.24	$37.29	$41.48
10%	$12.41	$10.30	$10.04	$10.24	$10.63	$11.10	$14.40	$13.28	$14.02	$15.21	$16.59	$18.06
15%	$10.78	$8.71	$8.30	$8.30	$8.47	$8.72	$12.03	$10.58	$10.80	$11.42	$12.21	$13.09
19.75%	$10.15	$8.07	$7.59	$7.50	$7.57	$7.73	$11.08	$9.47	$9.45	$9.82	$10.36	$10.98
	Packing Factor 40%						Packing Factor 40%					
5%	$23.95	$20.59	$20.64	$21.54	$22.78	$24.19	$29.21	$28.47	$31.14	$34.67	$38.53	$42.57
10%	$14.30	$11.69	$11.24	$11.34	$11.66	$12.09	$16.22	$14.58	$15.10	$16.16	$17.45	$18.84
15%	$12.16	$9.71	$9.15	$9.07	$9.18	$9.38	$13.33	$11.47	$11.51	$12.02	$12.71	$13.51
19.75%	$11.27	$8.89	$8.28	$8.12	$8.14	$8.25	$12.14	$10.18	$10.00	$10.28	$10.73	$11.27
	Packing Factor 50%						Packing Factor 50%					
5%	$26.99	$22.84	$22.62	$23.37	$24.52	$25.86	$32.19	$30.65	$33.02	$36.38	$40.12	$44.07
10%	$15.73	$12.72	$12.13	$12.14	$12.40	$12.77	$17.58	$15.50	$15.83	$16.77	$17.95	$19.25
15%	$13.24	$10.49	$9.82	$9.67	$9.73	$9.89	$14.36	$12.16	$12.05	$12.46	$13.08	$13.80
19.75%	$12.16	$9.53	$8.83	$8.61	$8.59	$8.66	$12.97	$10.73	$10.44	$10.62	$11.01	$11.48

Table A. 5: Fuel and outage cost ($/MWhe) with a base fabrication cost ($4,000/kgU)

Base Fabrication Costs												
	Outage Cost - $20 Million Number of Batches						Outage Cost - $50 Million Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$30.96	$27.69	$28.60	$30.54	$32.90	$35.47	$39.91	$41.12	$46.50	$52.92	$59.76	$66.80
10%	$13.08	$11.24	$11.25	$11.74	$12.41	$13.17	$15.93	$15.51	$16.95	$18.85	$20.95	$23.13
15%	$10.22	$8.56	$8.40	$8.61	$8.98	$9.42	$12.00	$11.22	$11.95	$13.06	$14.31	$15.64
19.75%	$9.17	$7.55	$7.30	$7.41	$7.64	$7.95	$10.51	$9.56	$9.98	$10.75	$11.66	$12.64
	Packing Factor 20%						Packing Factor 20%					
5%	$29.78	$25.27	$25.07	$25.95	$27.26	$28.78	$35.65	$34.07	$36.81	$40.62	$44.86	$49.32
10%	$14.74	$12.13	$11.73	$11.89	$12.28	$12.77	$16.89	$15.35	$16.03	$17.26	$18.71	$20.28
15%	$11.83	$9.55	$9.10	$9.09	$9.27	$9.55	$13.19	$11.59	$11.82	$12.50	$13.36	$14.31
19.75%	$10.73	$8.56	$8.07	$7.99	$8.09	$8.26	$11.76	$10.11	$10.13	$10.56	$11.17	$11.86
	Packing Factor 30%						Packing Factor 30%					
5%	$34.74	$28.75	$27.94	$28.44	$29.45	$30.73	$40.12	$36.82	$38.70	$41.89	$45.60	$49.56
10%	$17.53	$14.14	$13.45	$13.44	$13.70	$14.09	$19.51	$17.12	$17.43	$18.41	$19.66	$21.05
15%	$14.00	$11.12	$10.44	$10.31	$10.40	$10.59	$15.25	$13.00	$12.94	$13.43	$14.14	$14.96
19.75%	$12.54	$9.87	$9.18	$9.00	$9.01	$9.12	$13.47	$11.26	$11.04	$11.32	$11.79	$12.37
	Packing Factor 40%						Packing Factor 40%					
5%	$40.32	$32.87	$31.55	$31.77	$32.60	$33.73	$45.57	$40.75	$42.05	$44.90	$48.35	$52.12
10%	$20.30	$16.19	$15.25	$15.10	$15.27	$15.59	$22.23	$19.08	$19.11	$19.92	$21.05	$22.34
15%	$15.83	$12.46	$11.60	$11.36	$11.38	$11.52	$17.01	$14.23	$13.96	$14.31	$14.92	$15.65
19.75%	$13.96	$10.90	$10.07	$9.80	$9.75	$9.82	$14.82	$12.19	$11.79	$11.95	$12.34	$12.83
	Packing Factor 50%						Packing Factor 50%					
5%	$45.81	$36.96	$35.17	$35.14	$35.81	$36.84	$51.01	$44.76	$45.57	$48.14	$51.42	$55.05
10%	$22.42	$17.74	$16.59	$16.32	$16.41	$16.67	$24.27	$20.51	$20.29	$20.95	$21.96	$23.15
15%	$17.28	$13.52	$12.51	$12.19	$12.15	$12.25	$18.40	$15.19	$14.74	$14.98	$15.50	$16.15
19.75%	$15.08	$11.71	$10.77	$10.43	$10.34	$10.36	$15.89	$12.92	$12.38	$12.45	$12.76	$13.19

Table A. 6: Fuel and outage cost ($/MWhe) with a high fabrication cost ($24,000/kgU)

High Fabrication Costs												
	Outage Cost - $20 Million Number of Batches						Outage Cost - $50 Million Number of Batches					
	1	2	3	4	5	6	1	2	3	4	5	6
	Packing Factor 10%						Packing Factor 10%					
5%	$113.23	$89.40	$83.45	$81.96	$82.26	$83.46	$122.19	$102.83	$101.35	$104.34	$109.12	$114.80
10%	$39.25	$30.86	$28.70	$28.09	$28.11	$28.43	$42.10	$35.13	$34.39	$35.21	$36.65	$38.40
15%	$26.56	$20.81	$19.29	$18.82	$18.78	$18.95	$28.34	$23.48	$22.84	$23.27	$24.12	$25.18
19.75%	$21.47	$16.77	$15.50	$15.09	$15.02	$15.13	$22.81	$18.78	$18.18	$18.44	$19.04	$19.81
	Packing Factor 20%						Packing Factor 20%					
5%	$114.94	$89.14	$81.85	$79.18	$78.36	$78.46	$120.81	$97.94	$93.58	$93.85	$95.96	$99.00
10%	$45.88	$35.48	$32.49	$31.36	$30.96	$30.94	$48.03	$38.70	$36.79	$36.72	$37.40	$38.45
15%	$31.58	$24.36	$22.26	$21.44	$21.12	$21.07	$32.94	$26.41	$24.98	$24.84	$25.21	$25.83
19.75%	$25.66	$19.76	$18.02	$17.32	$17.04	$16.97	$26.69	$21.30	$20.08	$19.89	$20.13	$20.57
	Packing Factor 30%						Packing Factor 30%					
5%	$137.32	$105.68	$96.33	$92.55	$91.00	$90.56	$142.70	$113.75	$107.09	$106.00	$107.14	$109.40
10%	$55.43	$42.57	$38.72	$37.13	$36.44	$36.20	$57.42	$45.55	$42.70	$42.10	$42.41	$43.16
15%	$37.80	$28.98	$26.31	$25.19	$24.68	$24.48	$39.05	$30.85	$28.81	$28.31	$28.43	$28.85
19.75%	$30.24	$23.15	$20.99	$20.06	$19.63	$19.45	$31.17	$24.54	$22.84	$22.38	$22.42	$22.70
	Packing Factor 40%						Packing Factor 40%					
5%	$161.55	$123.79	$112.37	$107.54	$105.33	$104.45	$166.80	$131.67	$122.87	$120.67	$121.09	$122.84
10%	$64.80	$49.56	$44.91	$42.91	$41.97	$41.55	$66.73	$52.46	$48.77	$47.73	$47.75	$48.30
15%	$43.03	$32.86	$29.73	$28.36	$27.70	$27.39	$44.20	$34.63	$32.09	$31.31	$31.24	$31.51
19.75%	$33.84	$25.81	$23.33	$22.23	$21.68	$21.42	$34.70	$27.10	$25.05	$24.38	$24.27	$24.43
	Packing Factor 50%						Packing Factor 50%					
5%	$185.23	$141.53	$128.11	$122.27	$119.46	$118.17	$190.43	$149.33	$138.52	$135.28	$135.07	$136.38
10%	$71.99	$54.92	$49.64	$47.31	$46.15	$45.59	$73.84	$57.69	$53.34	$51.93	$51.70	$52.07
15%	$47.18	$35.94	$32.45	$30.88	$30.09	$29.69	$48.30	$37.62	$34.68	$33.67	$33.44	$33.60
19.75%	$36.68	$27.91	$25.17	$23.93	$23.30	$22.97	$37.49	$29.12	$26.78	$25.95	$25.72	$25.79

APPENDIX B

SAMPLE SCALE 6.1 KENO V FHR CORE DEPLETION INPUT

```
=t6-depl parm=(centrm,addnux=4)
FHR - BURNUP - Packing Factor 30%/Uranium Enrichment 15%
v7-238
' ---------- Materials ----------
' ------------------------------
read composition
' ---- Fuel, 15.00% Enrichment ----
 U-234       1  0  3.7861e-05  1182.803245    end
 U-235       1  0  0.00374777  1182.803245    end
 U-238       1  0  0.02093191  1182.803245    end
 O-16        1  0  0.0352829   1182.803245    end
 C-graphite  1  0  0.0105760   1182.803245    end
'
' ---- Buffer, IPyC, Silicon Carbide, OPyC, Matrix Material ----
 C-graphite  2  0  0.076304410   1182.803245    end
 Si          2  0  0.003755145   1182.803245    end
'
' ---- Graphite Meat ----
 C-graphite  7  0  7.97223e-02 1135.417    end
'
' ---- Sleeve/Cladding on Plate ----
 C-graphite  8  0  7.97223e-02 1135.417    end
'
' ---- FLiBe Coolant (99.995% enriched Li-7) ----
 Li-6        9  0  1.38344e-06 948.15  end
 Li-7        9  0  0.0237205   948.15  end
 Be          9  0  0.0118609   948.15  end
 F           9  0  0.0474437   948.15  end
'
' ---- Graphite in Fuel Block ----
 C-graphite  10  0  9.82741e-02 948.15  end
'
' ---- Graphite Reflector Block ----
 C-graphite  11  0  8.72433e-02 948.15  end
'
' ---- Alloy 800H Clad in CR ----
  C-graphite 12 0  3.2210e-04  923.15  end
  Al         12 0  6.7209e-04  923.15  end
  Si         12 0  6.0263e-04  923.15  end
  P          12 0  3.1225e-05  923.15  end
  S          12 0  1.5081e-05  923.15  end
  Ti         12 0  3.7884e-04  923.15  end
  Cr         12 0  1.9530e-02  923.15  end
  Mn         12 0  8.8022e-04  923.15  end
  Fe         12 0  3.8092e-02  923.15  end
  Ni         12 0  2.6777e-02  923.15  end
  Cu         12 0  2.2830e-04  923.15  end
'
end composition

' ---- Cell data ----
' ------------------
read celldata
 latticecell sphsquarep
 fuelr=0.02135 1  pitch=0.101978636 2 end
 centrm data
   dan2pitch(1)= 0.90792
 end centrm
end celldata
' ---- Depletion and Burndata ----
' ------------------------------
read depletion 1 9 end depletion
read burndata
 power=118.8996  burn=1     down=0  nlib=1  end
 power=118.8996  burn=2     down=0  nlib=1  end
```

```
 power=118.8996  burn=4     down=0  nlib=1  end
 power=118.8996  burn=6     down=0  nlib=1  end
 power=118.8996  burn=14    down=0  nlib=1  end
 power=118.8996  burn=26    down=0  nlib=1  end
 power=118.8996  burn=94    down=0  nlib=1  end
 power=118.8996  burn=66    down=0  nlib=1  end
 power=118.8996  burn=134   down=0  nlib=1  end
 power=118.8996  burn=66    down=0  nlib=1  end
 power=118.8996  burn=134   down=0  nlib=1  end
 power=118.8996  burn=66    down=0  nlib=1  end
 power=118.8996  burn=134   down=0  nlib=1  end
 power=118.8996  burn=66    down=0  nlib=1  end
 power=118.8996  burn=134   down=0  nlib=1  end
 power=118.8996  burn=66    down=0  nlib=1  end
 power=118.8996  burn=134   down=0  nlib=1  end
end burndata


' ---- Opus ----
' --------------
read opus
 matl=1 9 end
 time=days
 typarms=nucl
 units=gram
 title=Masses of Actinides and Fission Products
 symnuc=u-234 u-235 u-236 u-237 u-238 pu-238 pu-239
        pu-240 pu-241 pu-242 pu-243 np-237 am-241 am-242m am-243
        cm-242 cm-243 cm-244 cm-245 cm-246
        sr-90 i-131
        cs-133 cs-134 cs-135 cs-137 nd-143 nd-144 nd-145 nd-146
        nd-148 nd-150 pm-147 sm-147 sm-148 sm-149 sm-150 sm-151
        sm-152 eu-153 sm-154 eu-154 gd-154 eu-155 gd-155 end
new case
 time=days
 typarms=elements
 units=curies
 symnuc= Ac Ag Al Am Ar As At Au B  Ba Be Bi Bk Br C  Ca Cd Ce Cf Cl
         Cm Co Cr Cs Cu Dy Er Es Eu F  Fe Fr Ga Gd Ge H  He Hf Hg Ho
         I  In Ir K  Kr La Li Lu Mg Mn Mo N  Na Nb Nd Ne Ni Np O  Os
         P  Pa Pb Pd Pm Po Pr Pt Pu Ra Rb Re Rh Rn Ru S  Sb Sc Se Si
         Sm Sn Sr Ta Tb Tc Te Th Ti Tl Tm U  V  W  Xe Y  Yb Zn Zr end
new case
 time=days
 typarms=elements
 units=watts
 symnuc= Ac Ag Al Am Ar As At Au B  Ba Be Bi Bk Br C  Ca Cd Ce Cf Cl
         Cm Co Cr Cs Cu Dy Er Es Eu F  Fe Fr Ga Gd Ge H  He Hf Hg Ho
         I  In Ir K  Kr La Li Lu Mg Mn Mo N  Na Nb Nd Ne Ni Np O  Os
         P  Pa Pb Pd Pm Po Pr Pt Pu Ra Rb Re Rh Rn Ru S  Sb Sc Se Si
         Sm Sn Sr Ta Tb Tc Te Th Ti Tl Tm U  V  W  Xe Y  Yb Zn Zr end
new case
 time=days
 typarms=nucl
 units=gram
 title=Mass of Tritium and Lithium Isotopes
 symnuc= h-3 li-6 li-7 end
new case
 time=days
 typarms=nucl
 units=curies
 title=Radioactivity of Tritium
 symnuc= h-3 end
end opus

read model
read parameter
  cfx=yes
  flx=yes
  gen=400
  nsk=40
```

```
  npg=20000
  sig=0.0001
  tba=100
  htm=no
  plt=yes
end parameter

' ---------- Geometry ----------
' ------------------------------
read geometry
unit 1111
com="TRISO Fuel Particle"
 sphere 1  0.02135
 cuboid 2  0.0509893180820  -0.0509893180820  0.0509893180820  -0.0509893180820  0.0509893180820
-0.0509893180820
 media 1 1 1
 media 2 1 2 -1
 boundary 2
'

unit 1112
com="Fuel Portion of Fuel Plate"
 parallelepiped 1  21.47743  0.8242835  10.1978636164       30        0        0
 array 1112 1  place 1 1 1 0.0509893180820 0.0509893180820 0.0509893180820
 boundary 1
'

unit 1113
com="Graphite center with fuel plates"
 parallelepiped 1  21.47743  2.71354626519  10.1978636164        30        0        0
 hole 1112  origin  x=0.0 y=0.0 z=0
 hole 1112  origin  x=0.9446313812 y=1.6361495468 z=0
 media 7 1 1
 boundary 1
'

unit 1114
com="Complete Fuel Plate"
 parallelepiped 1  21.70837  2.944486  10.1978636164      30        0        0
 hole 1113  origin  x=0.173205 y=0.1 z=0
 media 8 1 1
 boundary 1
'

unit 1115
com="Group of Six Fuel Plates"
 parallelepiped 1  22.51666  22.51666      10.1978636164       30        0        0
 hole 1114   origin  x=0.606218 y=0.35  z=0
 hole 1114   origin  x=2.482606 y=3.6   z=0
 hole 1114   origin  x=4.358995 y=6.85  z=0
 hole 1114   origin  x=6.23583  y=10.1  z=0
 hole 1114   origin  x=8.111771 y=13.35 z=0
 hole 1114   origin  x=9.98816  y=16.6  z=0
 media 9 1 1
 boundary 1
'

unit 20
com="Fuel Assembly, 18 Fuel Plates, and Control Blade Slot"
 hexprism    10 23.375 10.1978636164 0
 hexprism    1  22.5   10.1978636164 0
  hole  1115 rotate a1=210 origin x=-2.000000   y=23.67136103   z=0.
  hole  1115 rotate a1=90  origin x=21.5        y=-10.10362971  z=0.
  hole  1115 rotate a1=330 origin x=-19.500000  y=-13.56773132  z=0.
 cuboid      2  10.  0.  0.5 -0.5 10.1978636164 0  rotate a1=-30.
 cuboid      3  10.  0.  0.5 -0.5 10.1978636164 0  rotate a1=90.
 cuboid      4  10.  0.  0.5 -0.5 10.1978636164 0  rotate a1=210.
 cylinder    5  1.2  10.1978636164  0
 media 0 1 2 -5
 media 0 1 3 -5
 media 0 1 4 -5
```

```
 media 0 1 5
 media 10 1 1 -2 -3 -4 -5
 media 9 1 10 -1
 boundary 10
'
'
unit 10
com="Graphite Reflector Block"
 cylinder    1  2.0    10.1978636164 0
 hexprism    2  23.375 10.1978636164 0
 media 9 1 1
 media 11 1 2 -1
 boundary 2
'
'
global unit 1
com="Reactor Core"
 cylinder   1 478 10.1978636164 0
 array 1 1 place 13 13 1 0 0 0
 cylinder   2 480 10.1978636164 0
 cylinder   3 513 10.1978636164 0
 cylinder   4 518 10.1978636164 0
 media 12 1 2 -1
 media 9  1 3 -2
 media 12 1 4 -3
 boundary 4

end geometry

' ---------- Array Specification ----------
' ----------------------------------------
read array

ara=1  nux=25 nuy=25 nuz=1 typ=hexagonal
  fill
      10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10
      10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10
        10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10
          10  10  10  10  10  10  10  10  10  10  10  10  10  10  20  20  20  20  20  20  10  10  10  10  10
            10  10  10  10  10  10  10  10  10  10  10  10  20  20  20  20  20  20  20  20  20  10  10  10  10
              10  10  10  10  10  10  10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10
                10  10  10  10  10  10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10
                  10  10  10  10  10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10
                    10  10  10  10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10
                      10  10  10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10
                        10  10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10
                          10  10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10
                            10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10
                              10  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10  10
                                10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10  10
                                  10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10  10  10
                                    10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10  10  10  10
                                      10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10  10  10  10  10
                                        10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10  10  10  10  10
                                10   10  10  10  20  20  20  20  20  20  20  20  20  20  20  20  10  10  10  10  10  10  10  10  10  10
                                      10  10  10  10  20  20  20  20  20  20  20  20  20  10  10  10  10  10  10  10  10  10  10  10  10 10
                                      10  10  10  10  10  20  20  20  20  20  20  10  10  10  10  10  10  10  10  10  10  10  10  10  10
                                      10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10
                                      10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10
                                      10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10  10

  end fill

ara=1112 nux=220 nuy=7 nuz=100 typ=square
 com='Fuel Arrangement in Plate'
    fill
          220r1111
          220r1111
          220r1111
          220r1111
          220r1111
          220r1111
          220r1111
          99q1540
    end fill

end array

' ---------- Plot Cross Sections ----------
```

```
' -----------------------------------------
read plot

ttl='Full Reactor Core'
  XUL=-550.0 YUL=550.0  ZUL=0.0509893
  XLR=550.0  YLR=-550.0 ZLR=0.0509893
  UAX=1 VDN=-1 NAX=12800 END

end plot

' ---------- Boundary Conditions ----------
' -----------------------------------------

read bounds
       surface(1)=vacuum
    surface(2)=mirror
       surface(3)=mirror
end bounds


end data
end model
end
```

REFERENCES

1. Holcomb, D., Peretz, F., & Qualls, A., "Advanced High Temperature Reactor Systems and Economic Analysis*,"* ORNL/TM-2011/364 Oak Ridge National Laboratory, Oak Ridge, Tenn. (September 2011).

2. Cochran, R., & Tsoulfanidis, N,.*The Nuclear Fuel Cycle: Analysis and Management* (2nd ed.), American Nuclear Society, La Grange Park, Illinois, United States of America (1990).

3. Lewis, S. M. (2014). *Simplified Core Physics and Fuel Cycle Cost Model for Preliminary Evaluation of LSCR Fueling Options.* Master's Thesis, Georgia Institute of Technology, Nuclear and Radiological Engineering, Atlanta.

4. Avigni, P., & Petrovic, B, "Fuel Element and Full Core Thermal-Hydrualic Analysis of the AHTR for the evaluation of the LOFC Transient," *Annals of Nuclear Energy*, **Volume 64**, Pages 499–510 (2014).

5. Bradfute, J., & Marshall, J., (2015, February 16th), Private communications, Fabrication Facility Estimates.

6. World Nuclear Association. (2015, April). *Molten Salt Reactors*. Retrieved April 12, 2015, from http://www.world-nuclear.org/info/Current-and-Future-Generation/Molten-Salt-Reactors/

7. Holcomb, E., Ilas, D., Qualls, A., Peretz, F., Varma, V., Bradley, E., et al., "Current Status of the Advanced High Temperature Reactor," *ICAPP '12,* Chicago, Illinois, June 24-28, Vol. 1, pages 911-920 (2012).

8. Greene, S., Gehin, J., Holcomb, D., Carbajo, J., Ilas, D., Cisneros, A., et al., "Pre-Conceptual Design of a Flouride-Salt-Cooled Small Modular Advanced High-Temperature Reactor (SmAHTR)," ORNL/TM-2010/199, Oak Ridge National Laboratory, Oak Ridge, Tenn. (December 2010).

9. Petti, D., Barrachin, M., et al., "High Temperature Gas Cooled Reactor Fuels and Materials," IAEA-TECDOC-1645, IAEA, Nuclear Fuel Cycle and Materials Section, Vienna, Austria. (March 2010).

10. Liu, B., "HTGR Fuel Fabrication and Quality Control," *IAEA Course on High Temperature Gas Cooled Reactor Technologies.* Beijing, China, October 22-26, IAEA Metting (2012).

11. World Nuclear Association. (2015, February). *China's Nuclear Fuel Cycle*. Retrieved April 1, 2015, from http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/

12. Phillips, J., & Shaber, E., “Compact Process Development at Babcock & Wilcox,” INL/EXT-11-23166, Idaho National Laboratory, Idaho Falls, Idaho (March 2012).

13. Luther, E. “Fabrication of Uranium Oxide Fuels,” *ATR User Week 2012,* Idaho Falls, Idaho, June 19-21, LA-UR-12-21451 (2012).

14. Blum, A., “The Manufacture of Uranium Dioxide Fuel In Pellet Form,” INS-MF—1966/12, Iscar LTD., Nahariya. Israel (July 1975).

15. Holcomb, D. E., Ilas, D., Varma, V. K., Cisneros, A. T., Kelly, R. P., & Gehin, J. C., “Core and Refueling Design Studies for the Advanced High Temperature Reactor,” ORNL/TM-2011/365, Oak Ridge National Laboratory, Oak Ridge, Tenn. (September 2011).

16. Kelly, R., & Ilas, D., “Verification of a Depletion Method in SCALE for the Advanced High Temperature Reactor,” *PHYSOR 2012,* Knoxville, Tenn., April 15-20, CD-ROM (2012).

17. Cisneros, A. T., & Ilas, D., “Neutronics and Depletion Methods for Parametric Studies of Flouride-Salt-Cooled High-Temperature Reactors with Slab Fuel Geometry and Multi-Batch Fuel Management Schemes”. *PHYSOR 2012,* Knoxville, Tenn., April 15-20, CD-ROM (2012).

18. Duderstadt, J. J., & Hamilton, L. J. (1976). *Nuclear Reactor Analysis.* John Wiley & Sons, Inc. Ann Arbor, Michigan, United States of America.

19. Huang, M., & Petrovic, B., “Use of MCDancoff Correction Factor for Multi-Group Fuel Depletion Analysis of Liquid Salt Cooled Reactors,” *PHYSOR 2014,* Kyoto, Japan, September 28th – October 3rd, CD-ROM (2014).

20. Huang, M. (2015, July 13). Private communications, MC Dancoff correction to the LSCR SCALE model.

21. Petrovic, B., & Maldonado, G. I., “Quarterly Progress Report (2013_Q1 October-December 2012): Fuel and Core Design Options to Overcome the Heavy Metal Loading Limit and Improve Performance and Safety of Liquid Salt Cooled Reactors,” SRC#00128483, Georgia Institute of Technology & University of Tennessee, Atlanta, Georgia (January 2013).

22. Grubert, E., & et al. “Pebble Bed Modular Reactors Versus Other Generation Technologies: Costs and Challenges for South Africa,” *Global 2011,* Makuhari, Japan, December 11-16, Paper No. 391144 (2011).

23. Ilas, D., Holcomb, D., & Varma, V. K., “Advanced High-Temperature Reactor Neutronic Core Design,” *PHYSOR 2012,* Knoxville, Tenn., April 15-20, CD-ROM (2012).

24. Shropshire, D., Williams, K., Smith, J., Dixon, B., Dunzik-Gougar, M., Adams, R., et al., "Advanced Fuel Cycle Cost Basis*,"* INL/EXT-07-12107, Idaho National Laboratory, Idaho Falls, Idaho (December 2009).

25. Kingsbury, C., Marquez, M., Sudderth, M., & Winter, T. (2015). *Fluoride-salt-cooled High-temperature Reactor Fuel Fabrication Techniques Analysis.* Advanced Reactor Design Course Final Report, Georgia Institute of Technology, Nuclear and Radiological Engineering, Atlanta.

26. Windes, W. E., Burchell, T. D., & Bratton, R., "The Next Generation Nuclear Plant Graphite Program," INL/CON-08-14693, Idaho National Laboratory, Idaho Fall, Idaho (Septebmer 2008).

27. Garkisch, H. D., Charit, I., & Ferroni, P., "Integral Inherently Safe Light Water Reactor (I2S-LWR) Conceptual Nuclear Fuel-Cladding Cost Estimate*,"* I2S-TR-14-06, University of Idaho & Westinghouse Co (October 2014).

28. Nuclear Energy Institute. (2013). *Costs: Fuel, Operation, Waste Disposal & Life Cycle*. Retrieved October 20, 2014, from Nuclear Energy Institute: http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Costs-Fuel,-Operation,-Waste-Disposal-Life-Cycle