DESIGN AND PERFORMANCE ANALYSIS OF A MOBILE, LAND-BASED MICRO-REACTOR FOR DOMESTIC MILITARY ENERGY PRODUCTION

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

In 1942 the U.S. achieved criticality with Chicago Pile-1 and in 1952 constructed the first nuclear-powered submarine. Given the rapid advancements in the first decade of nuclear reactor demonstration, it would not be a stretch of the imagination to think that a land-based, mobile micro-reactor would soon become a reality. However, almost 80 years have elapsed since the Chicago Pile-1 achieved criticality and land-based micro-reactors continue to face many obstacles. So, this begs the question: Are land-based, mobile micro-reactors still viable and sustainable within the scope of the Army's Mobile Nuclear Power Program?

This work examines a mobile, land-based micro-reactor concept for domestic U.S. Army installation energy production based on the mobile low power reactor prototype 1 (ML-1) concept. A detailed model of the ML-1 micro-reactor was created in MCNP® and benchmarked against experimental data from multiple demonstrations conducted between 1962-1965. A low cost-estimate of $71.1 million and high cost-estimate of $291.3 million in today's dollars for a micro-reactor design based on the ML-1 concept was obtained using program costs captured in Congressional legislative records and the average inflation rate. Lastly, improvements were made to the ML-1 design with modern evaluated nuclear data files and advanced fuel material to meet Project Pele design requirements. The calculated k_{eff} after 3 years of operation at 3 MWt is distributed between 0.9969 and 0.9996 at the 95 percent confidence interval. The k_{eff} increases in the days following shutdown due to buildup and subsequent decay of fission poisons. Regular power cycling will aid in reducing fission product poison buildup to sustain criticality at the three-year mark. Ultimately, these results suggest that a critical system with a three-year operation at threshold power is possible utilizing the ML-1 concept with HALEU fuel in uranium carbide form and replacing nitrogen coolant with helium. A map of domestic U.S. Army installations was created in Python, incorporating installation energy consumption data, U.S. census data, and drought data to help make an informed decision on the optimal siting location. The FY19 energy consumption data, remote location, and hazardous weather conditions suggest Tooele Army Depot, UT is the best location for this mobile, land-based micro-reactor concept.

DEDICATION

This work is dedicated to my family. To my wife, Jerilou, words could never express my gratitude for your perpetual encouragement, support, and patience. You are my inspiration to put my best foot forward each day and I look forward to sharing this next chapter with you, wherever it may take us.

“Winds blow south, or winds blow north,
Day come white, or night come black,
Home, or rivers and mountains from home,
Singing all time, minding no time,
While we two keep together.”
(Walt Whitman)

To our children, Malia, Luka, and Laila, thank you for bringing us so much joy. I’m going to cherish all the stick figure drawings and love notes you would hand me during Zoom meetings throughout the semester. We are very proud of you and we hope that you hold on tight to your caring, creative, and inquisitive nature.

To our parents and siblings, Jerilou and I cannot thank you enough for all your love, support, and taking the time to visit us in College Station. Seriously, I was able to accomplish a significant portion of this research while you kept the grandkids entertained. Thank you again!

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Contributors

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NOMENCLATURE

AEC	Atomic Energy Commission
ANPP	Army Nuclear Power Program
API	Application Programming Interface
BTU	British Thermal Unit
DOD	Department of Defense
DOE	Department of Energy
EIA	Energy Information Administration
FOB	Forward Operating Base
FY	Fiscal Year
ENDF	Evaluated Nuclear Data File
FOAK	First-of-a-Kind
HALEU	High Assay Low Enriched Uranium
HEU	Highly Enriched Uranium
MCNP	Monte Carlo N-Particle Code
ML-1	Mobile Low-Power Prototype 1
MNPP	Mobile Nuclear Power Plant
MW	Megawatt
NDAA	National Defense Authorization Act
NRC	Nuclear Regulatory Commission
RFI	Request for Information

ROB	Remote Operating Base
SMRs	Small Modular Reactors
TRISO	Tri-structural Isotropic
vSMR	Very Small Modular Reactor

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

1.1. Motivation

The U.S. Department of Defense (DoD) is the largest energy consumer of any agency in the U.S. government with a 76.73% share of the 889 trillion British thermal units (BTUs) consumed in fiscal year 2019 (U.S. Energy Information Administration (EIA) - Data, 2019). Each year the DoD prepares two reports to Congress regarding energy expenditures. The first report includes operational energy which accounts for the energy consumed by training, moving, and sustaining military forces and weapons platforms. The second comprises installation energy which reports on the energy consumption required to light and heat 276,561 buildings across more than 500 military installations (Office of the Assistant Secretary of Defense for Sustainment, 2019). This work explores the opportunity nuclear power provides toward simultaneously improving installation energy resilience, reducing greenhouse gas emissions, and developing a mobile reactor package that can be manufactured at a fraction of the cost of a traditional nuclear power plant.

Given the rapid advancements made in the first decade of nuclear reactor research, measured from the first criticality in 1942 at the Chicago Pile-1 to construction of the world's first nuclear-powered submarine in 1952, it would not be a stretch of the imagination to think that a land-based, mobile micro-reactor would soon become a reality. However, almost 80 years have elapsed since the Chicago Pile-1 achieved criticality and land-based micro-reactors continue to face a myriad of obstacles. This begs the question: Are land-based, mobile micro-reactors still viable and sustainable within the scope of the Army's Mobile Nuclear Power Program?

1.2. Objective

This work aims to comprehensively assess the sustainability of a mobile, land-based micro-reactor for domestic U.S. Army energy production, to include potential deployment scenarios. The computational analysis to be performed is based on the ML-1 design and will provide valuable information on the operational characteristics of micro-reactors throughout the fuel lifecycle. This data is necessary for follow-on assessments to determine the risks associated with transportation and storage of both clean and spent fuel. To achieve this objective, the study will seek to accomplish the following tasks:

- Conceptually develop an ML-1-based concept and review potential development and deployment scenarios.
- Develop a detailed ML-1 model for use with MCNP.
- Computationally evaluate the ML-1 characteristics focusing on the viability of the design.
- Analyze ML-1 from its deployment scenario perspectives.
- Develop the ML-1-based reactor concept taking advantage of contemporary tools as well as advantages of advanced materials and material forms.
- Using ML-1 data, assess the pros and cons of deploying nuclear-powered systems in viable energy-demanding environments.

1.3. Approach

A general Monte Carlo n-particle (MCNP) transport code will be used to model the ML-1 reactor based on the geometry and material composition provided within the final design report. The final design report contains experimental data on the thermal hydraulics, geometry, material composition, and neutronics for benchmarking. A simple, homogenized core model will be developed and simulated using the built-in KCODE function along with the ENDF/B-VIII cross section library. Due to the complexity of the tapered blade-type control rods, the MCNP model will assume that all control rods are fully out of the core. Once the simplified model agrees with the published data, a detailed model will be developed, incorporating Project Pele design parameters such as HALEU and TRISO fuel to evaluate safe operating distances and shielding requirements. Python will be used for data visualization relating to potential siting locations. The siting locations will be sourced from the Department of Defense Annual Energy Management and Resilience Report for Fiscal Year 2019. This report provides energy requirements by U.S. Army installation in city, state format. These locations can be parsed and run through a geolocation API to generate coordinates for data visualization. Additionally, this can be combined with data from the U.S. Census Bureau to identify proximity to population clusters.

1.4. Impact

This research will utilize modern neutronics code and updated cross section libraries to evaluate a demonstrated, land-based micro-reactor. The significance of this effort is that, not only does it allow for the simulation of a demonstrated system, it allows for the improvement upon the design by incorporating advanced fuel and shielding materials in an effort to meet today's regulatory requirements. Building upon a tested prototype yields additional benefits in terms of streamlining development time, such that many of the tactics, techniques, and procedures involved in the transport and shutdown have already been developed for the design. Lastly, many emerging advanced reactors are pursuing FOAK mobile reactor concepts that are likely to experience similar, if not identical, challenges that faced the ML-1 program.

2. BACKGROUND

2.1. A Brief History of the Mobile Low Power Prototype 1 (ML-1) Program

The concept of small, self-contained, portable nuclear reactors is nothing new. One could argue the U.S. Navy accomplished this feat with the first nuclear powered submarine, the USS Nautilus, which was authorized by Congress in 1951, constructed in 1952, and launched in 1954. The success of this program likely spurred support toward the Army Nuclear Power Program (ANPP), established in 1954, as a joint effort between the U.S. Army Corps of Engineers (USACE) and Atomic Energy Commission (AEC). In 1957, the ANPP developed its first prototype reactor at Ft. Belvoir, Virginia and over the next two decades it designed, constructed, and operated eight reactors. Most notably, the Mobile Low Power Reactor Prototype Number 1 (ML-1), shown in Figure 1, was developed under the ANPP and made its debut in September 1962 as a high-temperature, gas-cooled, water-moderated reactor with compact power conversion equipment. The reactor weight was 40 tons.

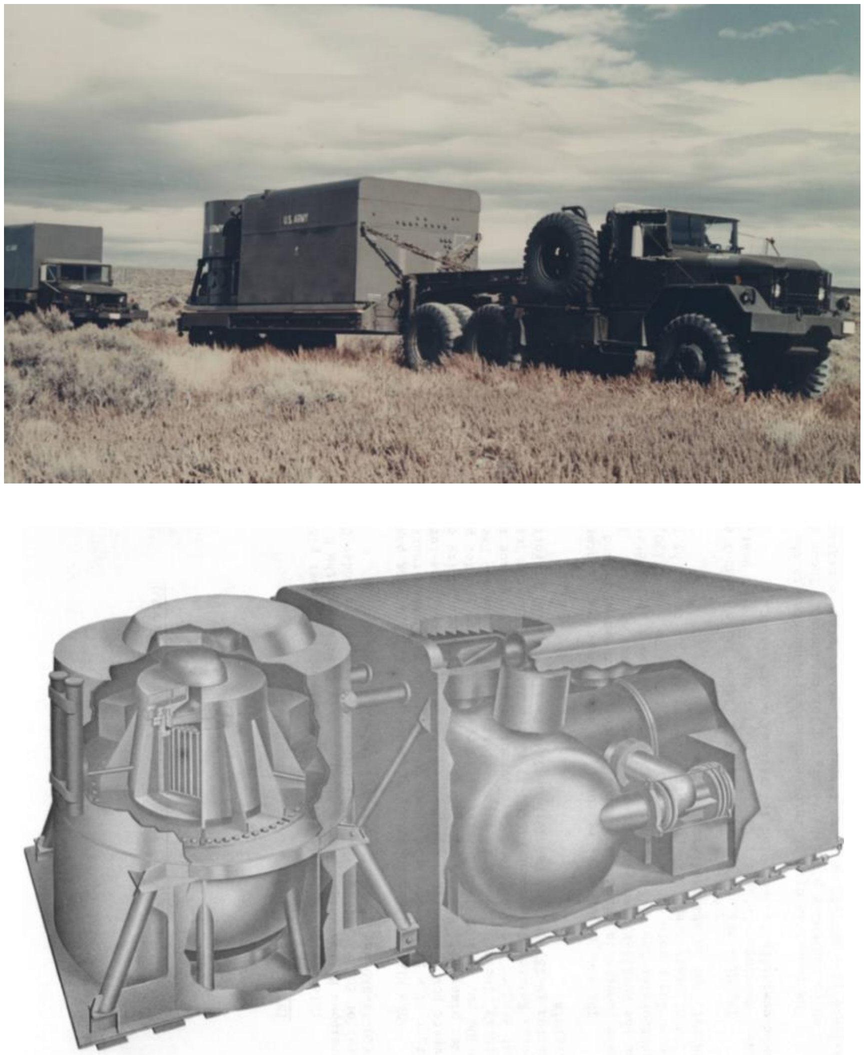


Figure 1. Photograph (top) of a lead vehicle pulling the ML-1 power conversion skid and nuclear reactor skid followed by a trailing vehicle carrying the control cab. A 3D rendering of the nuclear reactor and power conversion skid (bottom). Reprinted from (U.S. Army Corps of Engineers, 2017).

The ML-1 reactor is of particular interest for its first of a kind technology, 100-hour demonstration, and publicly available documentation from design through the final safety report. Table 1 includes initial operating characteristics for the design to be capable of generating between 300-500 kWe. The operating characteristics were expected to be achieved through a unique core design shown in Figures 2-4 (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960).

Table 1. ML-1 reactor general design characteristics and requirements. Adapted from (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960).

Characteristic	Requirement
Electrical Output	300-500 kW, 2400/4160 V, 3-phase, 50-60 cycles, at ambient temperatures ranging from -65 °F to +100 °F
Weight	15 tons per package 40 tons total
Lifetime	10,000 hrs between refueling 50,000 hrs overall
Exposure Rate	15 mR/hr at 25 ft in forward direction 24 hrs after shutdown
Installation Time	12 hrs
Preparation Time for Relocation	6 hrs
Operating Supplies	Demineralized water: 2900 gal Nitrogen (0.5 vol% Oxygen): 1800 ft^3 Oxygen: 200 ft^3 Anyhdrous Boric Acid (B_2O_3): 1200 lb Mixed bed ion exchange resin: 900 lbs Lubricating Oil: 180 gal

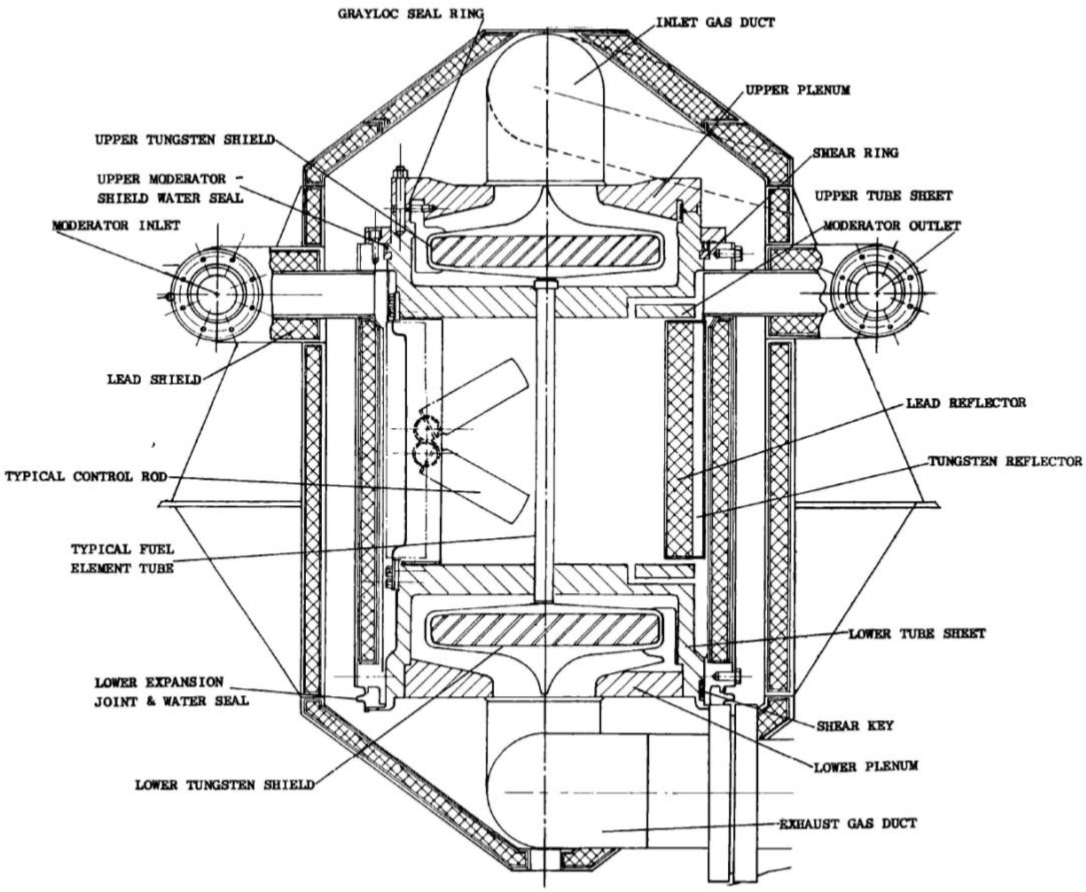


Figure 2. Side view of ML-1 reactor vessel. Reprinted from (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960).

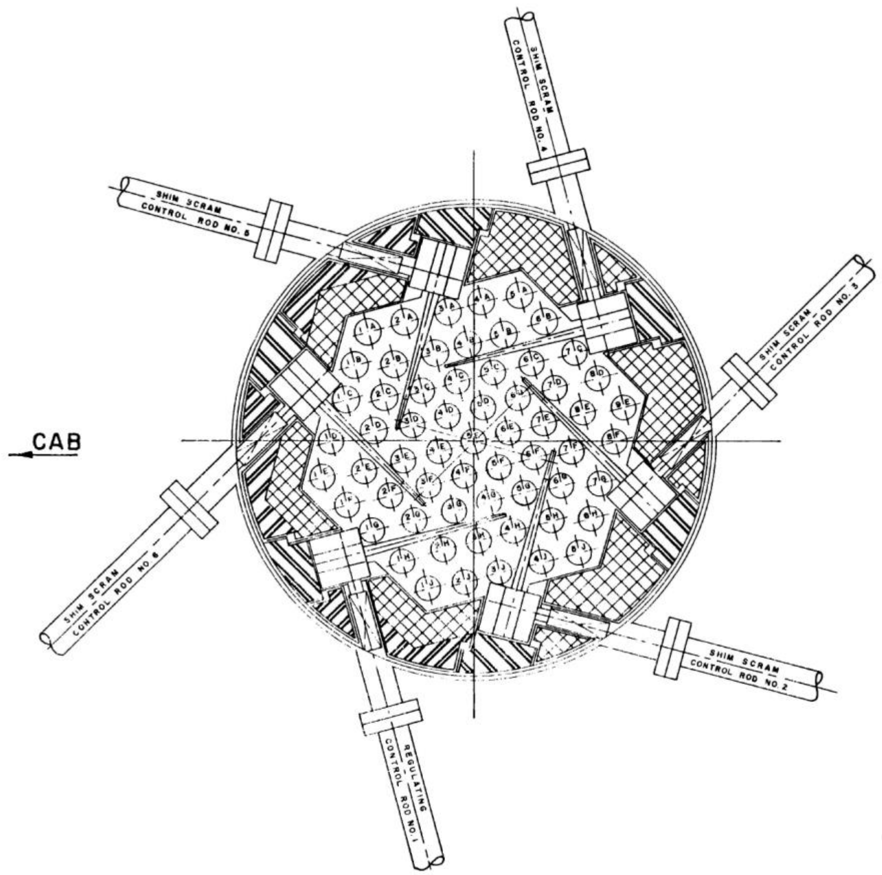


Figure 3. ML-1 reactor core (top view) including control drives. Reprinted from (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960).

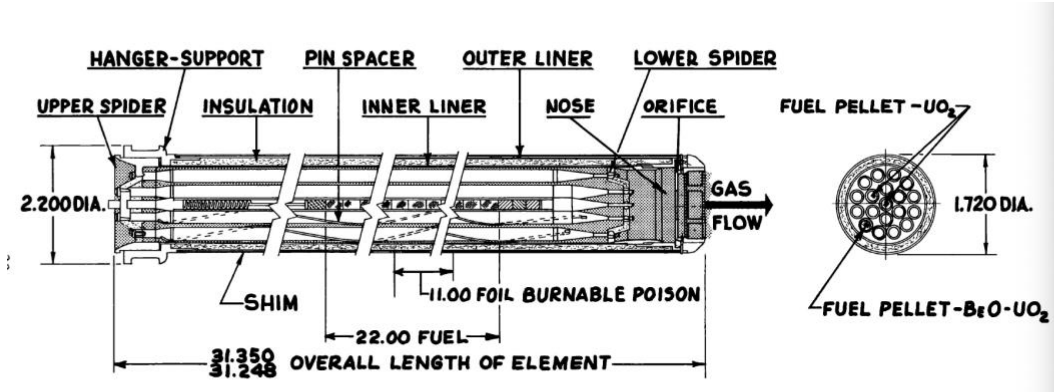


Figure 4. A single ML-1 fuel element assembly. Reprinted from (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960).

Table 2. ML-1 reactor core characteristics and composition. Adapted from (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960).

Characteristic	**Value**
Diameter	22 in.
Height	22 in
Number of fuel elements	61
Number of coolant passages	61
Number of coolant passes	1
Type and geometry of fuel	Cluster of 19 pins
U-235 Enrichment Cold, clean critical mass, no shims, no burnable poison Loading	 93.1% U-235 as UO_2 25 kg 49 kg
Materials UO_2 BeO Stainless steel Hastelloy-X H_2O	Volume % 4.3 3.3 3.6 7.0 58.6

2.2. ML-1 Program Challenges

Despite prototype construction and achieving a 100-hour operation, the ML-1 program was ultimately terminated. In 1964 a joint statement was issued by the DoD and AEC to the Congressional Joint Committee on Atomic Energy which stated "…the military power reactor program suffers from a lack of direction as to what military applications will be made of its products rather than any technology deficiency." (United States Congress Joint Committee on Atomic Energy, 1964). The report concluded that the ML-1, from the standpoint of economics, power level, and logistics advantage is unlikely to find any application in the DOD (United States Congress Joint Committee on Atomic Energy, 1964).

One significant challenge was that the economics did not work in favor of the ML-1 program. At the time, the Army could acquire fuel at a cost of 20 cents per gallon compared to the 70-90 cents per gallon cost equivalent proposed by the ML-1 prototype (United States Congress Joint Committee on Atomic Energy, 1964). The AEC report concluded that the only competitive use for the ML-1 would be in the Antarctic. It is worth noting that the AEC did not establish the initial design requirements and therefore the approach to the ML-1 project was more of a capability test than an optimization to make the system more cost competitive.

Another significant challenge was that requirements had not developed as anticipated. For example, a missile defense system required 2.5 MW at all times which resulted in the consumption of 15,000 gallons of petroleum per day (United States Congress Joint Committee on Atomic Energy, 1964). A transportable reactor capable of

10,000 hours of operation between refueling cycles would have provided a logistical advantage over transporting 6.24 million gallons of petroleum over that same time frame. However, the missile defense system was abandoned for one with lower power requirements which reduced the advantage the ML-1 offered over conventional fossil fuels. Furthermore, the results of the 100-hour test demonstrated the reactor could only produce 300 kW versus the expected 500 kW (United States Congress Joint Committee on Atomic Energy, 1964).

Another series of obstacles, though not as significant as the aforementioned, were the mechanical issues involved with the demonstration of a first of a kind system. Following the 100-hour demonstration:

1. A leak was found in the pressure vessel,
2. A problem was identified with the turbine blading and bearings, and
3. The spiders in the bottom part of the fuel elements had corroded.

One subject matter expert attested in a Congressional hearing that the expertise and technology was available at the time to remediate these issues (United States Congress Joint Committee on Atomic Energy, 1964). However, the significance is that the issues prevented start-up during a key moment, when Congress was making a funding decision on whether the program should continue. Funding was reduced from $10 million to $5 million to continue development without construction of a prototype. Additionally, the mobile reactor was intended to power an energy depot, which was ill-defined in terms of what fuel to produce and what raw materials to use.

2.3. Renewed Interest in Energy Security and Resilience

There has been renewed interest over the last decade to improve energy security and resilience. A memorandum of understanding (MOU) was signed on July 22, 2010 by the Department of Defense (DoD) and Department of Energy (DOE) concerning cooperation in a strategic partnership to enhance energy security (U.S. Department of Energy, 2010). Presidential Policy 21, published February 12, 2013, advances a national unity of effort to strengthen and maintain secure, functioning, and resilient critical infrastructure and explicitly identifies energy as uniquely critical for its enabling role across all critical infrastructure sectors (Presidential Policy Directive 21, 2013). Senate Report 113-44, which accompanied the National Defense Authorization Act (NDAA) for Fiscal Year 2014, directed the Secretary of Defense to submit a report to the Senate Armed Services Committee on progress made regarding the 2010 MOU no later than January 1, 2014. Additionally, the Senate Armed Services Committee directed the DoD to submit a report to the congressional defense committees on the challenges, operational requirements, constraints, cost, and life cycle analysis for a small modular reactor of less than 10 megawatts (MW) (U.S. Congress, 2013).

In February 2014, the Under Secretary of Defense for Acquisition and Sustainment established the Defense Science Board Ad Hoc Committee ("Task Force") on Energy Systems for Forward/Remote Operating Bases. The task was to examine the feasibility of deployable, cost-effective, regulated, and secure micro-reactors with a modest output of electrical power (less than 10 MW) to improve combat capability and improve deployed conditions for the DoD. The final report was published August 1, 2016 and the Task Force concluded "…energy usage on the battlefield is likely to increase significantly over the next few decades…alternative energy sources, such as wind, tidal, solar, and other sources, were unlikely to meet current or future energy demands for forward operating bases, remote operating bases, and expeditionary forces...U.S. military could become the beneficiaries of reliable, abundant, and continuous energy through the deployment of nuclear energy power systems."

On August 19, 2018 the DOE issued a request for information (RFI) on input on a pilot program for micro-reactor demonstration. This RFI was intended to gather information for DOE's report to Congress on the various nuclear technology options available for consideration. Another MOU was signed as recently as September 28, 2020 between the DOE and DOD in support of enhancing energy resilience of military installations and the associated commercial electrical grid (U.S. Department of Energy, 2020).

More recently, on January 5, 2021 an executive order was issued pertaining to the demonstration of commercial reactors to enhance energy flexibility at a defense installation (Executive Order on Promoting Small Modular Reactors for National Defense and Space Exploration, 2021). The significance of this measure is that micro-reactors have received support at the highest levels of government between the Executive Branch issuing this order and the Legislative Branch provisioning funds for micro-reactor development and demonstration under Section 327 of NDAA 2019 (John S. McCain National Defense Authorization Act for Fiscal Year 2019, 2018). Furthermore, the executive order specified identifying domestic military installations where micro-reactor capabilities could enhance or supplement the fulfillment of installation energy requirements, taking into account considerations that are unique to national defense needs and requirements that may not be relevant in the private sector, such as:

1. The ability to provide resilient, independent energy delivery to installations in the event that connections to an electrical grid are compromised;
2. The ability to operate for an extended period of time without refueling;
3. System resistance to disruption from an electro-magnetic pulse event; and
4. System cybersecurity requirements.

3. APPLIED CODE SYSTEM AND MODELING APPROACH

3.1. Monte Carlo N-Particle (MCNP®) Computational Method

MCNP® is a general-purpose, continuous-energy, generalized geometry, time-dependent, Monte Carlo radiation-transport code designed to track many particle types over broad ranges of energies (C.J. Werner et al., 2017). The origins of the Monte Carlo method for radiation transport date back to the 1940s at Los Alamos National Laboratory where they originally existed as a separate series of special-purpose codes, which were eventually combined in 1977 to create the first general MCNP® radiation transport code (Sood, 2017). Due to the complex geometries and material composition of the ML-1 design and the limitations associated with the analytical approach, the MCNP® computational method was utilized. Monte Carlo is well suited to solving complicated three-dimensional, time-dependent problems because there are no averaging approximations required in space, energy, and time (X-5 Monte Carlo Team, 2003). This is important in allowing detailed representation of all aspects of physical data.

The current version of MCNP is a hybrid code system that includes composition depletion capabilities via CINDER90 deterministic depletion based on Markov chains. This effort is taking advantage of this capability to simulate not only static configuration capabilities but also operation characteristics accounting for composition changes (X-5 Monte Carlo Team, 2003).

3.1.1. Cell Flux (F4) Tally

Unlike deterministic transport methods, which solve the transport equation for the average particle behavior, the MCNP® approach simulates individual particles and records some aspects (i.e. tallies) of their average behavior (X-5 Monte Carlo Team, 2003). The cell flux tally is used to calculate the average particle flux in a cell through, $\bar{\phi}_V$, by summing the track lengths of all particles within that cell. This can be described through the following integral:

$$\bar{\phi}_V = \frac{1}{V}\int dE \int dV \int ds\, N(\vec{r}, E, t) \quad (3.1)$$

All space within an MCNP model is bound by geometric surfaces, which can be combined to create user-defined cells. The primary geometric surfaces used in the ML-1 detailed model included planes, cylinders, spheres, and truncated right-angle cones. The F4 tally was primarily used to evaluate the neutron flux averaged over the reactor core volume of the ML-1 model. Additionally, the track lengths were binned into ten energy bins to produce a plot of the neutron energy spectrum for each model.

3.1.2. Criticality Calculations

In addition to the geometry description and material cards, a KCODE card and initial spatial distribution of fission points using the KSRC card were used to calculate the k_{eff} for each model. The KCODE card has four components:

1. The number of source histories, *N*, per k_{eff} cycle;
2. An initial guess for k_{eff};
3. The number of inactive cycles (i.e. cycles to skip before active cycle accumulation); and
4. The total number of cycles.

In MCNP the definition of k_{eff} is:

$$k_{eff} = \frac{\rho_a \int_V \int_0^\infty \int_E \int_\Omega \nu\sigma_f \Phi dVdtdEd\Omega}{\int_V \int_0^\infty \int_E \int_\Omega \nabla\cdot J dVdtdEd\Omega + \rho_a \int_V \int_0^\infty \int_E \int_\Omega (\sigma_c+\sigma_f+\sigma_m)\Phi dVdtdEd\Omega} \tag{3.2}$$

where the phase-space variables are time, t, energy, E, and direction, Ω. The denominator is the loss rate, which is the sum of leakage, capture (n,0n), fission, and multiplicity (n,xn) terms (X-5 Monte Carlo Team, 2003). The result from a criticality calculation is a confidence interval formed by the final estimated k_{eff} and the estimated standard deviation.

3.1.3. Depletion Calculations

Unlike the preceding calculations, depletion calculations are linked hybrid calculations involving MCNP and the CINDER90. First, MCNP runs a steady-state calculation to determine the system eigenvalue, 63-group fluxes, energy-integrate reaction rates, fission multiplicity, and recoverable energy per fission (Q-values) (C.J. Werner et al., 2017). The results are passed to CINDER90 which performs the depletion calculation to generate new atom densities at each specified time step. MCNP then takes the new atom densities and generates a new set of fluxes and the process is repeated through the final user-specified time step.

4. METHODOLOGY

4.1. Determining Potential Installations for Deployment

Each year the DoD is required to provide an Annual Energy Management and Resilience Report to the congressional defense committees under title 10, Section 2925(a). This annual report contains an appendix listing each installation by service branch with data points corresponding to area, state, and energy delivered. The U.S. Army installation data was extracted from the FY 2019 to FY 2015 PDFs into Excel. The installations located outside of the continental U.S. (OCONUS) were removed to simplify analysis by reducing the economic, legal, and logistical complexities associated with transporting a nuclear reactor across international borders.

Since reactor power is typically expressed in Watts (W), as opposed to British thermal units (BTU), an energy conversion was performed within Excel. The billions of British thermal unit (BBTU) data extracted from the report was multiplied by the Excel function CONVERT(1,“BTU”,“Wh”) to obtain the energy data in terms of billions of Watts per hour, then multiplied by a second function CONVERT(1,“hr”,“yr”) to obtain billions of Watts per year, then multiplied once more by 1,000 to convert from billions to millions and obtain the desired unit of millions of Watts, also known as megawatts (MW), per year. Figure 5 contains the five most recent years of total energy (MW) delivered to the 120 CONUS Army installations.

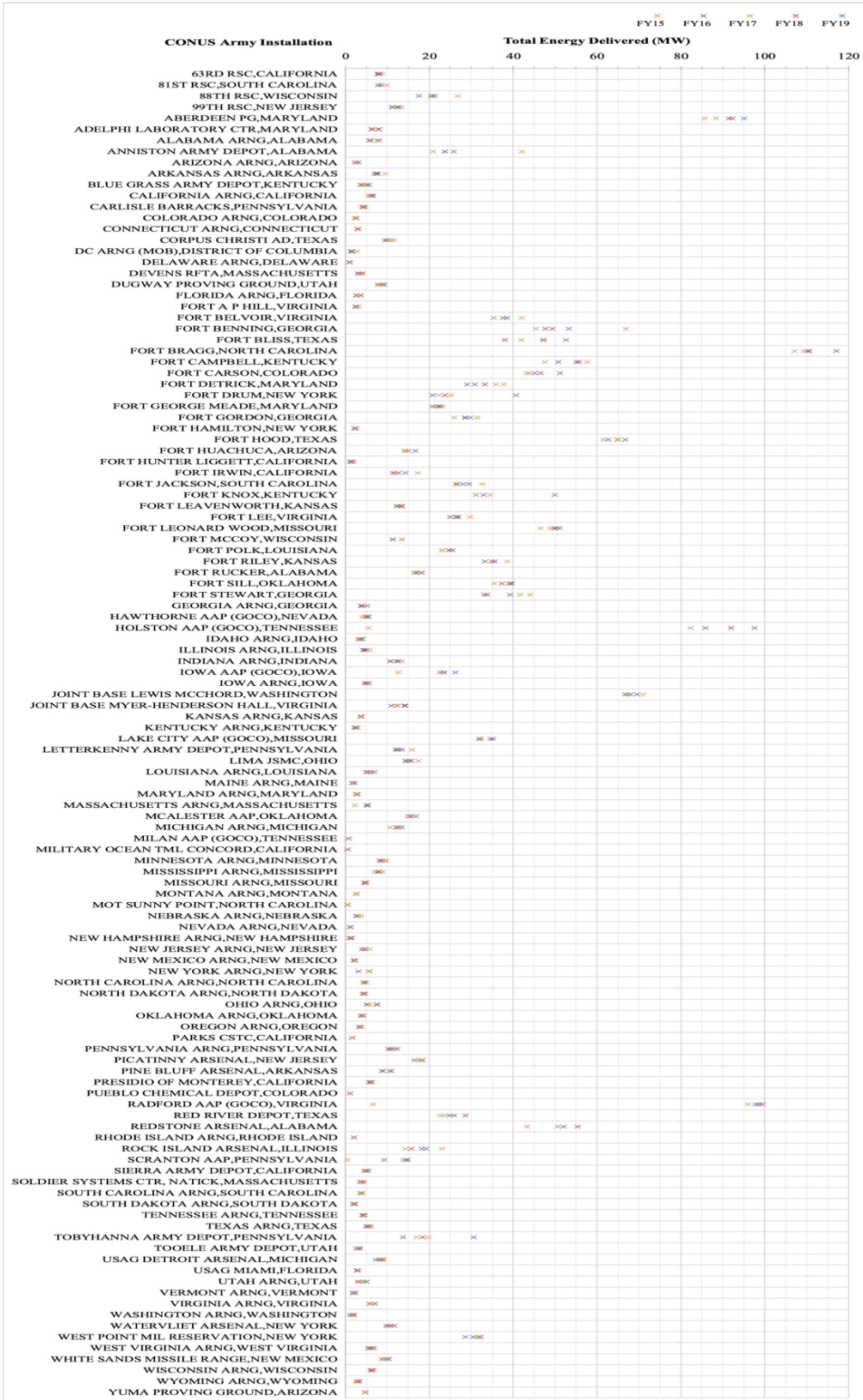


Figure 5. CONUS Installations Total Energy Delivered for FY 15 through FY 19.

4.1.1. Mobile Land-based Micro-reactor Requirements

The Office of the Secretary of Defense Strategic Capabilities Office (SCO) announced a request for solutions for the “Pele Program” (also identified as “Project Pele”) on April 29, 2019 which included the design parameters outlined in Table 3 (U.S. Department of Defense, 2019). At first glance, the ML-1 meets many of the Project Pele design requirements. However, further review of the core parameters summarized in Table 1, would make the ML-1 impractical if the design were to be left as-is with the UO_2 enriched to 93% U-235 due to proliferation concerns. Additionally, the ML-1 was only able to achieve 300 kWe during the full power, limited endurance test (Army Gas-cooled Reactor Systems Program. Full Power and Limited Endurance Test of the ML-1 Nuclear Power Plant, 1964).

Table 3. Project Pele technical requirements announced in the request for solutions. Adapted from (U.S. Department of Defense, 2019).

Technical Requirement	**Technical Objective**
Life	Able to generate threshold power (1-10 MWe) for > 3 years without refueling.
Wrap-Up	Time for planned shutdown, cool down, disconnect, prepared transport, and safe transport < 7 days.
Start-Up	Time from arrival of unit to reaching full electric power < 72 hours.
Size	All components should fit in ISO 688 certified 20’ or 40’ CONEX boxes. Government’s preference is to use 20’ standard CONEX box.
Operation	Semiautonomous; minimal manning to monitor overall reactor and power plant system health. Minimal routine preventative maintenance and repair required.

4.1.2. Data Processing

Population data was obtained from the 2010 census conducted by the U.S. Census Bureau. Although the data is a decade old, it was selected for its high geospatial resolution, accuracy, and availability. The population data set contains over 308 million data points, representing each individual accounted for in the 2010 U.S. census.

Installation energy consumption data was obtained from the Fiscal Year (FY) 2019 Department of Defense Annual Energy Management Resilience Report which was published in June 2020. This data set contains location and energy consumption information for 143 U.S. Army installations geographically dispersed throughout the U.S., Europe, and Asia.

The list of installations obtained from the Annual Energy Management Resilience Report were extracted from the PDF and placed into an Excel spreadsheet. The OpenCage Geocoder library was installed in python to allow for conversion from physical locations to a set of geographic coordinates. The Excel spreadsheet was read into a pandas data frame, then two new columns were created to store the longitudes and latitudes for each location. The OpenCage API allows for 2500 API calls per day with a free account, which was sufficient to conduct a single loop over each installation to obtain a set of coordinates. The geographic coordinates, energy consumption data, and U.S. Census data were then incorporated into a plot using the geopandas library to produce the final result.

4.2. MCNP® Modeling and Simulation

Two models were developed to evaluate the ML-1 design. The first was a simple model to determine if enough open-source information was available to recreate the dimensions and materials of the ML-1 reactor in order to obtain a k_{eff} that was within an acceptable range of the reported value. Once the calculated results were obtained and deemed acceptable, a detailed model was created to obtain more accurate simulations and experiment with different materials.

4.2.1. Simplified Homogenous Model

A simplified homogenous model of the ML-1 reactor core was developed by modeling the core as a cylinder with a 22" diameter and 22" in height (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960). The fuel (uranium dioxide) and moderator (H_2O) were homogenized throughout the cylinder and placed into a single material card as shown in Figure 6. A KCODE calculation was run on the model to obtain the k_{eff} for comparison with the reported value in the ML-1 Design Report.

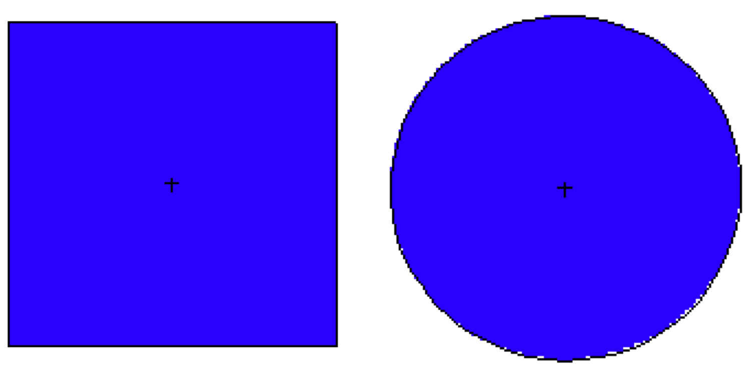


Figure 6. ML-1 simplified homogenous model side view (left) and top view (right).

4.2.2. Detailed Heterogenous Model

Starting with the fuel pins shown in Figure 7, each fuel element was modeled as a cylinder that comprised a lattice of 19 fuel pins to create a single fuel assembly. The inner fuel pins contained UO_2 while the outer 12 fuel pins contained UO_2 with a BeO diluent. The gaps between fuel pins were filled with helium coolant. The core region consisted of 61 fuel assemblies, in a hexagonal lattice, with light water occupying the gaps between assemblies to serve as a moderator. The core region was surrounded by a reflector region consisting of 2” lead in a hexagonal geometry, another 2” of tungsten from 0-180 degrees, and 2” of lead from 180-360 degrees.

The region outside of the core, shown in Figure 8, was modeled off an illustration from the ML-1A Shield Optimization Study shown in Figure 9 (Army Gas-cooled Reactor Systems Program. ML-1A Shield Optimization Study (Technical Report) | OSTI.GOV, 1965).

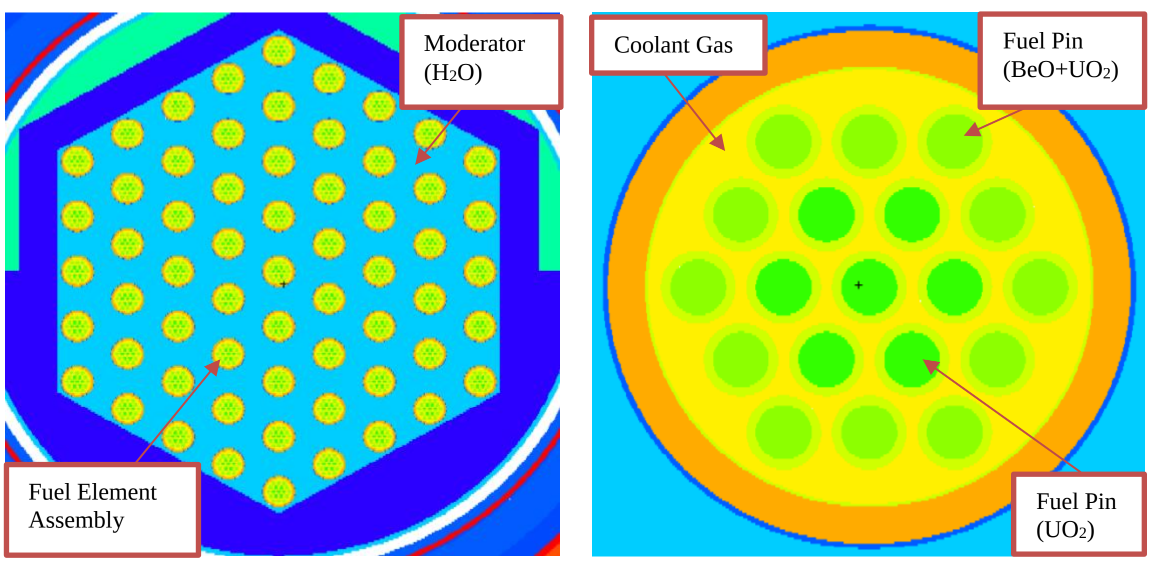


Figure 7. Top view of ML-1 detailed model core and reflector region (left) and top view of single fuel assembly (right).

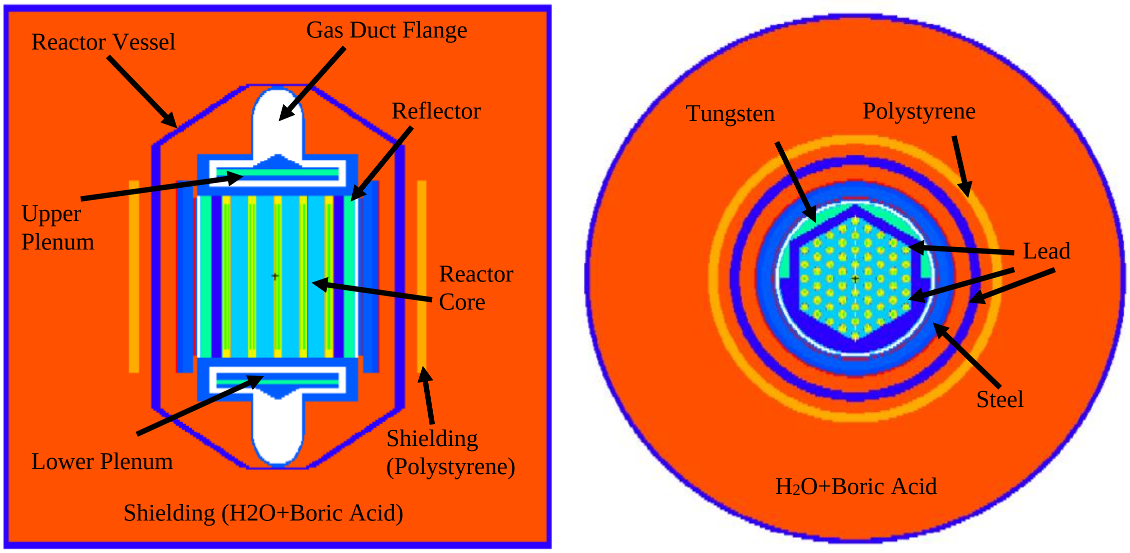


Figure 8. ML-1 detailed heterogenous model side view (left) and top view (right).

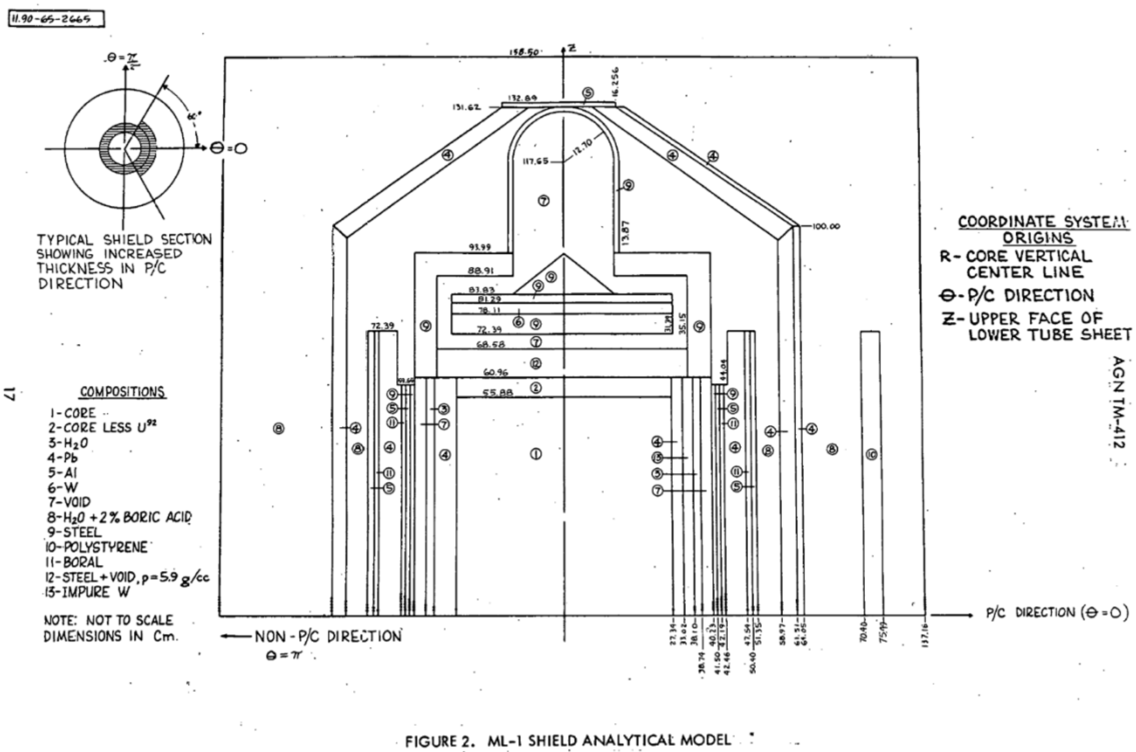


Figure 9. Reactor shielding materials and dimensions. Reprinted from (Army Gas-cooled Reactor Systems Program. ML-1A Shield Optimization Study (Technical Report) | OSTI.GOV, 1965).

5. ANALYSIS

5.1. Siting Analysis

Utilizing open-source data and Python software libraries, a geospatial map of U.S. Army installations, energy data, and population data was created to assist in site selection. Figure 10 contains the approximate locations of 120 CONUS Army installations that are represented by a circle with the radius proportional to the installation's reported energy consumption for FY19. Assuming a 33% thermal efficiency, the Project Pele requirement to generate 1-10MWe would require 3-30 MWt. Therefore, the installations were subdivided into two categories represented by red and blue circles. The red circles represent installations where energy consumption was greater than 30 MWt. The blue circles represent installations that had energy consumption less than 30 MWt.

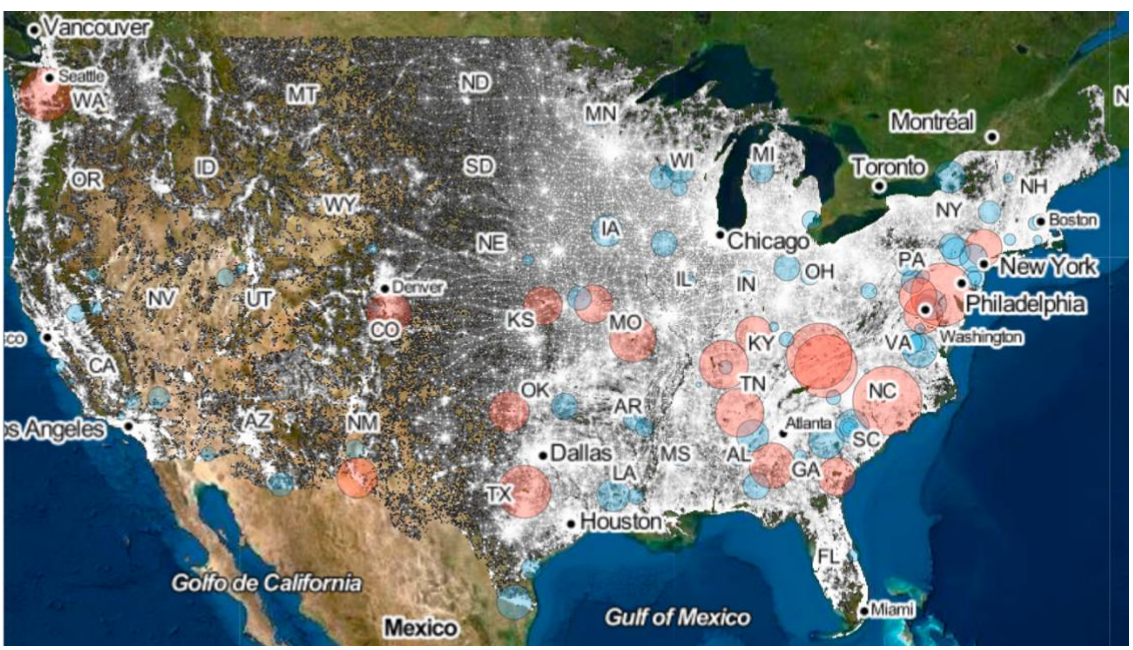


Figure 10. Continental U.S. (CONUS) Army installation energy consumption overlayed on 2010 U.S. Census data.

Figure 11 shows that while 30 MWt is capable of meeting 100% of the energy consumption for 98 installations, lowering the design goal 50% to 15 MWt would result in a decrement of just 12 installations. Halving the design goal once more to 7.5 MWt would result in another decrement of 20 installations, yet it is sufficient to provide 100% of energy consumption to 63 installations which still accounts for over half of all CONUS Army installations. A lower design goal would aid in reducing the amount of fissile material and overall dimensions required to sustain the reaction for multi-year operation, which could substantially lower the cost basis.

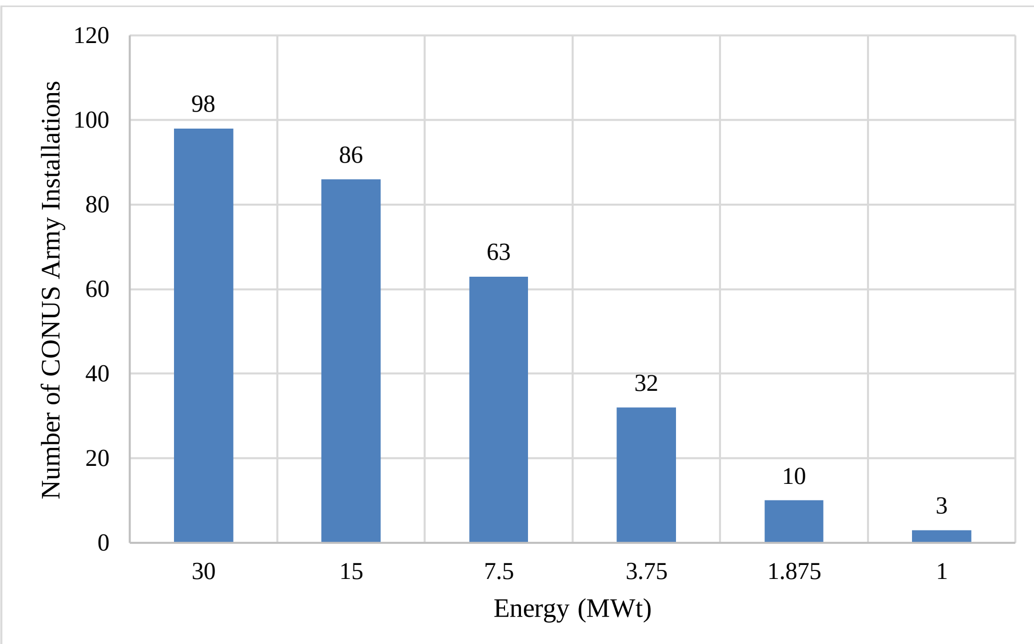


Figure 11. Number of CONUS Army installations where 100% of the FY19 energy consumption would be met by the given energy production design goal (MWt).

To further narrow site selection, drought data was introduced. The drought data assisted in determining which installations would receive the greatest benefit from nuclear energy since it has a unique advantage of being able to operate in extreme environmental conditions when compared to other clean energy sources. Drought data for the continental U.S. was obtained from the University of Nebraska's Drought Monitor and shown in Figure 12 (United States Drought Monitor, 2021). Table 4 summarizes the colors corresponding to each drought intensity. Lastly, Table 5 contains locations of U.S. Army installations located in areas of extreme and exceptional drought.

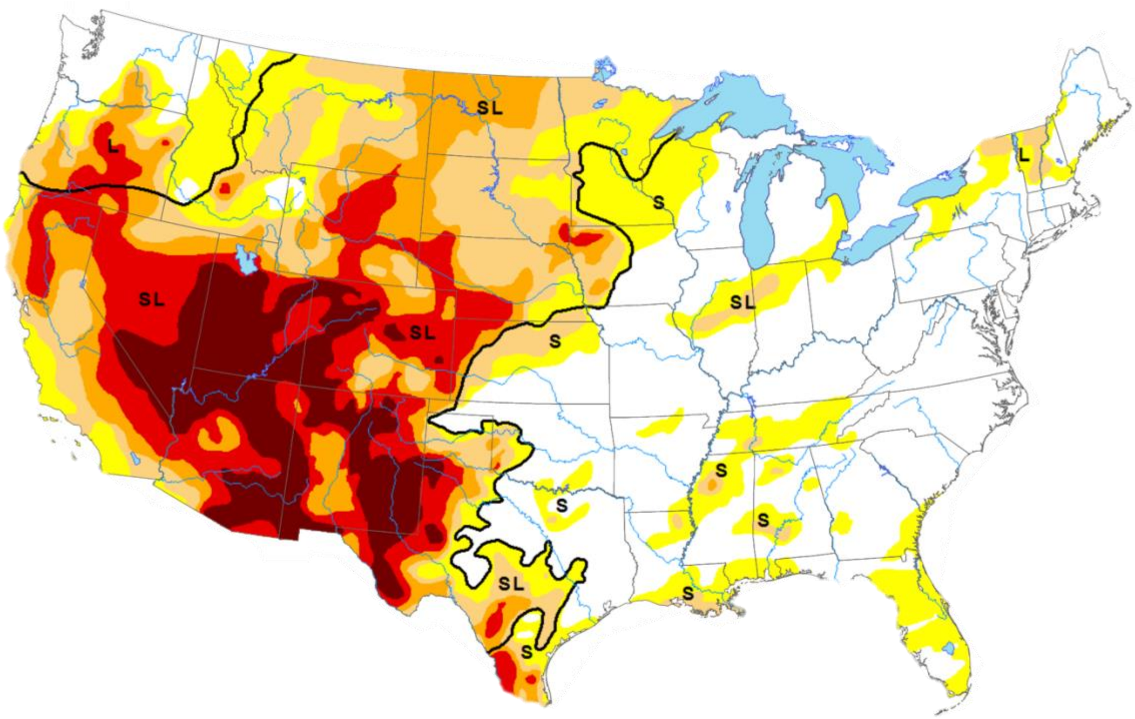


Figure 12. Drought data for continental U.S. as of February 2, 2021. Adapted from (United States Drought Monitor, 2021).

Table 4. Drought condition classification and potential impacts. Adapted from (United States Drought Monitor, 2021).

Color	Drought Condition	Possible Impacts
	None	None
	Abnormally Dry	Into drought: • Short-term dryness slowing planting, growth of crops or pastures Leaving drought: • Some lingering water deficits • Pastures or crops not fully recovered
	Moderate Drought	• Some damage to crops, pastures • Streams, reservoirs, or wells low, some water shortages developing or imminent • Voluntary water-use restrictions requested
	Severe Drought	• Crop or pasture losses likely • Water shortages common • Water restrictions imposed
	Extreme Drought	• Major crop/pasture losses • Widespread water shortages or restrictions
	Exceptional Drought	• Exceptional and widespread crop/pasture losses • Shortages of water in reservoirs, streams, and wells creating water emergencies

Table 5. CONUS Army installations located in regions of exceptional or extreme drought.

Installation	Drought Condition	FY19 Energy Consumption (MW)
Dugway Proving Ground, UT	Exceptional	7.72
Tooele Army Depot, UT	Exceptional	2.56
Fort Carson, CO	Severe	46.56
Fort Huachuca, AZ	Severe	14.20
Fort Irwin, CA	Severe	11.42
Arizona ARNG, AZ	Severe	2.53

Nuclear power holds the greatest advantage over other energy sources in remote relocations where there is a greater risk of disruption to energy supply. However, a list of remote military installations could not be located therefore a round-about approach was necessary to determine which installations qualify as remote. To qualify a location as remote TRICARE Prime Remote (TPR) data was utilized. TPR is a managed healthcare option only available to those servicemembers and their dependents located in remote areas in the United States (TRICARE Plan Finder, 2021). This approach rests on the assumption that installations within 50 miles of a military hospital or clinics has a more reliable energy infrastructure. TRICARE's online plan finder tool, shown in Figure 13, was utilized using the zip codes for each installation under consideration. A result of TRICARE Prime indicates a location that is within 50 miles of a military hospital or clinic. Table 6 shows that from the list of six installations in severe or exceptional drought areas only half qualify as remote.

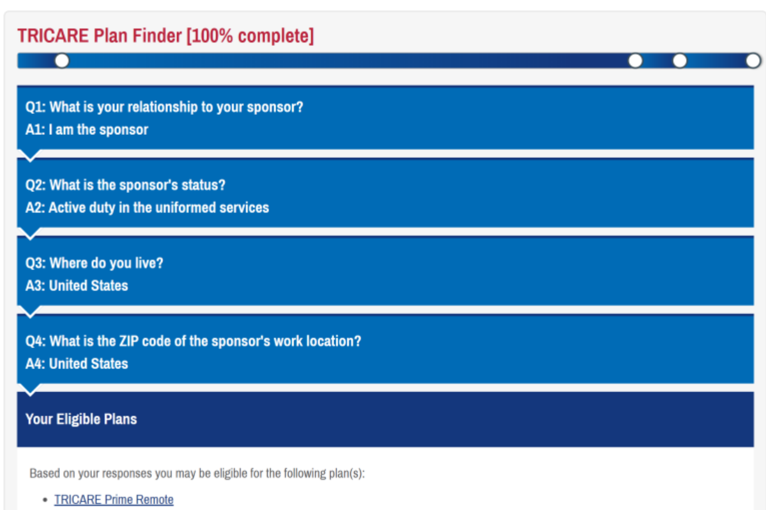


Figure 13. TRICARE plan finder tool used to determine if a location qualifies as remote. Adapted from (TRICARE Plan Finder, 2021).

Table 6. CONUS Army installations located in areas of exceptional or severe drought conditions listed by TRICARE Prime Remote eligibility.

Installation	TRICARE Remote Eligible?	FY19 Energy Consumption (MW)
Dugway Proving Ground, UT	Yes	7.72
Tooele Army Depot, UT	Yes	2.56
Fort Carson, CO	No	46.56
Fort Huachuca, AZ	No	14.20
Fort Irwin, CA	No	11.42
Arizona ARNG, AZ	Yes	2.53

5.2. Neutronics Analysis

Table 7 contains the results of using the simple homogenized MCNP® model and varying the cross-section libraries from ENDF/B-I through ENDF/B-VIII. These results demonstrate that while the reported values are outside of the standard deviation for both models, the difference may be attributed to the nuclear data file and version used between calculations. It is important to note the nuclear data file library used in the design report calculations is not listed and may not have been the ENDF/B library since the design report was published eight years before the release of ENDF/B-I. The MCNP® models will utilize the ENDF-VIII cross section libraries for consistency. Furthermore, since nuclear data files are the result of the accumulated knowledge resulting from experimental measurements and theoretical calculations, the accuracy of nuclear data files have improved substantially since preparation of the ML-1 design report.

Table 7. MCNP® simplified homogenous model with varying nuclear data file versions and year released. Adapted from (Oblozinsky, 2006).

Nuclear Data File	**Year Released**	**$k_{eff} \pm 2\sigma$**
ENDF/B-I	1968	Data file unavailable
ENDF/B-II	1970	Data file unavailable
ENDF/B-III	1972	Data file unavailable
ENDF/B-IV	1974	Data file unavailable
ENDF/B-V	1978	1.11400 ± 0.00094
ENDF/B-VI	1990	1.11731 ± 0.00102
ENDF/B-VII	2006	1.10787 ± 0.00094
ENDF/B-VIII	2018	1.10865 ± 0.00094

Table 8 summarizes the criticality calculation results. It's important to note that all calculations assumed a cold, clean core with no shim liners.

Table 8. Summary of ML-1 KCODE results. Adapted from (Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV, 1960).

Model Description	**Calculated $k_{eff} \pm 2\sigma$**	**Reported k_{eff}**
Design Report, May 1960	-	1.102
Simplified Model with UO_2(93.1% U^{235})	1.10865 ± 0.00094	-
Detailed Model with UO_2(93.1% U^{235})	1.10656 ± 0.00098	-
Detailed Model with UO_2(20% U^{235})	0.96486 ± 0.00106	-
Detailed Model with UC(20% U^{235})	1.01051 ± 0.00100	-
Detailed Model with UF_6(20% U^{235})	0.74905 ± 0.00084	-
Detailed Model with UN(20% U^{235})	1.00103 ± 0.00090	-

Figure 14 is the neutron energy spectrum, averaged across the core region, for each configuration in Table 8. The spectra are consistent with the neutron energy spectrum in a thermal reactor as evidenced by the prominent peak near the thermal energy region (near 1E-07 MeV) due to moderation in light water. The second peak in the higher energy region (near 10 MeV) is due to fission neutron production. The smaller peak in the thermal energy region of the UO_2(93.1% U-235) model is expected due to the higher U-235 content which has a higher thermal absorption cross section thereby reducing the neutron flux in that energy region.

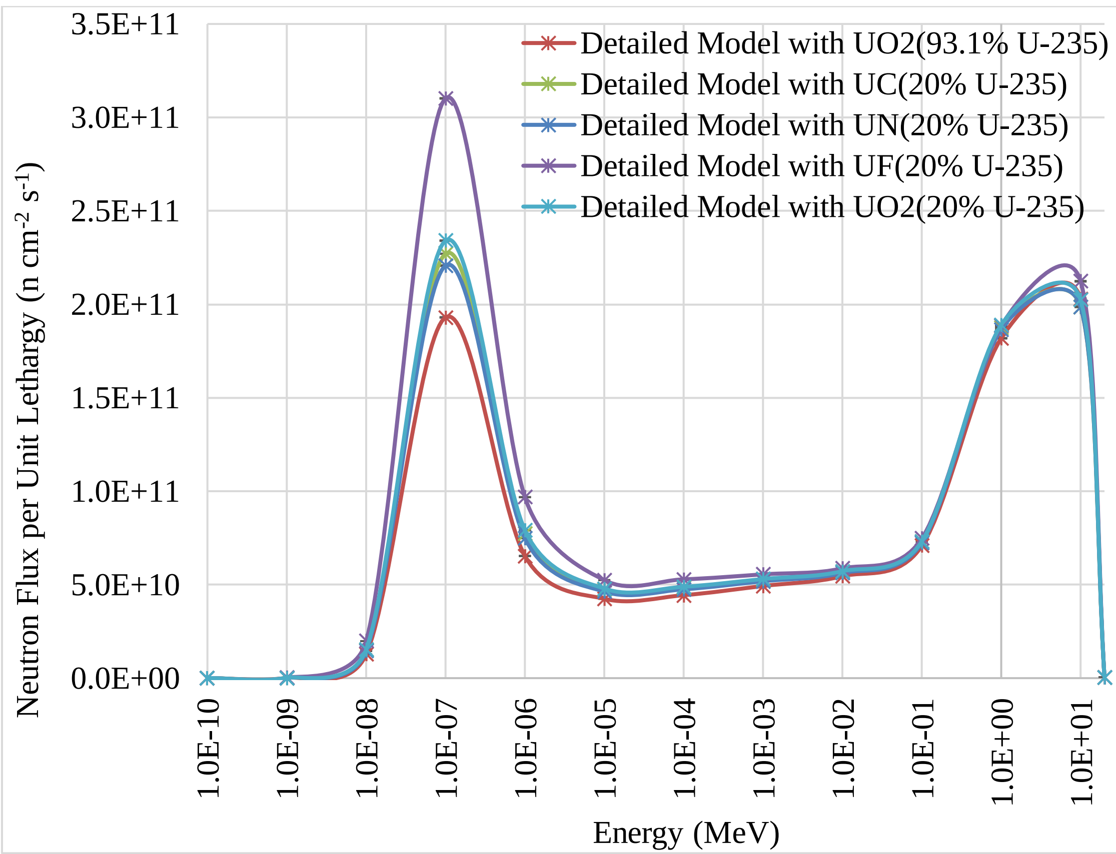


Figure 14. Neutron energy spectrums obtained from MCNP® models.

Burnup simulations were run for each critical configuration in Table 8 to determine how long a critical reaction could be sustained between refueling cycles. The subcritical configurations were excluded from burnup calculations. The 416.67 days was selected because the ML-1 was designed to operate for 10,000 hours between refueling cycles. The results of the burnup calculations are displayed in Figure 15. The results for each simulation include error bars representing two standard deviations. The low uncertainty is due to the large number of particles (10,000) averaged over 200 active KCODE cycles per simulation.

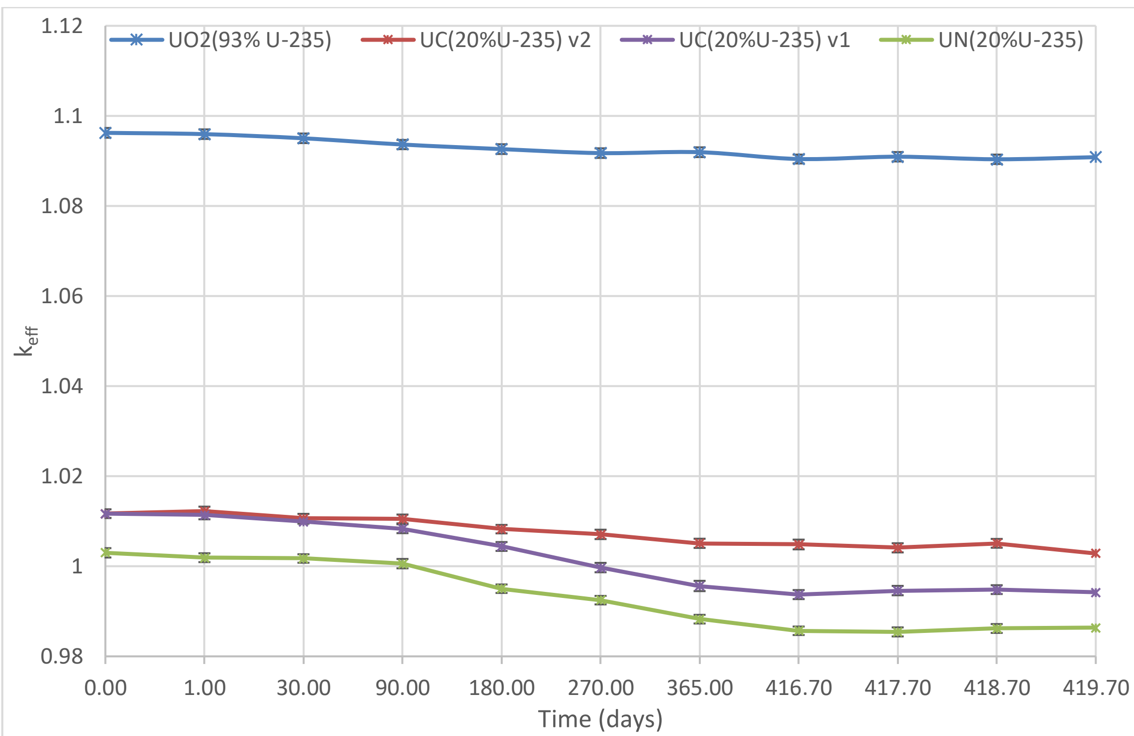


Figure 15. Plot of burn calculation results of UO_2, UC, and UN detailed models at 3.3 MWt for 10,000 hours.

The UC(20% U-235) model was then modified to determine if sustaining criticality through three years of steady state operation at threshold power is possible. A summary of the modified models is provided in Table 9.

Table 9. Summary of modifications to the ML-1 model to meet Project Pele requirements.

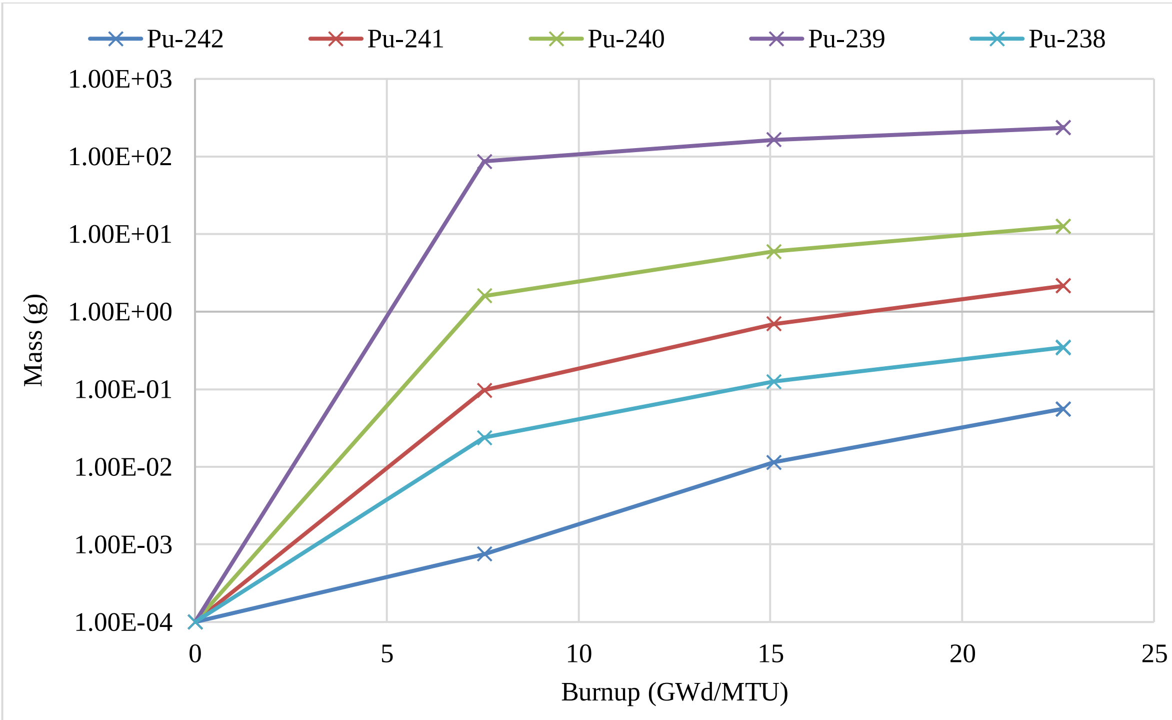
Model	**Description of Modifications**
UC(20% U-235) v1	Used detailed ML-1 model as starting point: • Replaced HEU in uranium dioxide form with HALEU in uranium carbide form.
UC(20% U-235) v2	In addition to v1 modifications: • Increased the radii of the fuel pins from 0.22487 cm to 0.22987 cm. • Replaced the center void in each fuel assembly with a fuel pin. • Removed the BeO spacers at the top and bottom of the fuel pins to allow fuel to occupy the full height between the top and bottom reflectors. • Removed the fuel diluent (BeO) from the outer fuel pins in each assembly. • Lowered power during BURN calculations from 3.3 MWt to 3.0 MWt.
UC(20% U-235) v3	In addition to v2 changes: • Replaced nitrogen coolant with helium coolant.

The results for three-year full power operation followed by a three-day shutdown period are included in Table 10. The calculated k_{eff} after 3 years of operation at 3 MWt is distributed between 0.9969 and 0.9996 at the 95 percent confidence interval. The k_{eff} increases in the days following shutdown due to buildup and subsequent decay of fission poisons. Regular power cycling will help to reduce fission product poison buildup sustain criticality at the three-year mark.

Table 10. Tabulated burn calculation results of the UC(20% U-235) v3 model.

Power (MWt)	Cumulative Time (d)	Calculated $k_{eff} \pm 2\sigma$	Burnup (GWd/MTU)
3	0	1.02199 ± 0.00102	0.00E+00
3	365	1.0152 ± 0.00100	7.54E+00
3	730	1.00724 ± 0.00102	1.51E+01
3	1095	0.9987 ± 0.00090	2.26E+01
0	1096	0.99954 ± 0.00100	2.26E+01
0	1097	0.99813 ± 0.00102	2.26E+01
0	1098	0.99957 ± 0.00106	2.26E+01

A plot of the plutonium and uranium inventories following a 3-year burn at 3 MWt are provided in Figure 16. The primary advantage of lowering the uranium enrichment is the reduction in the significant quantity of highly enriched U-235. The original ML-1 model utilized 49 kg of U-235 enriched to 93.1%. The ML-1 v3 model utilizes 29 kg of U-235 at 20% enrichment, which offers a significantly lower proliferation risk over the original design.



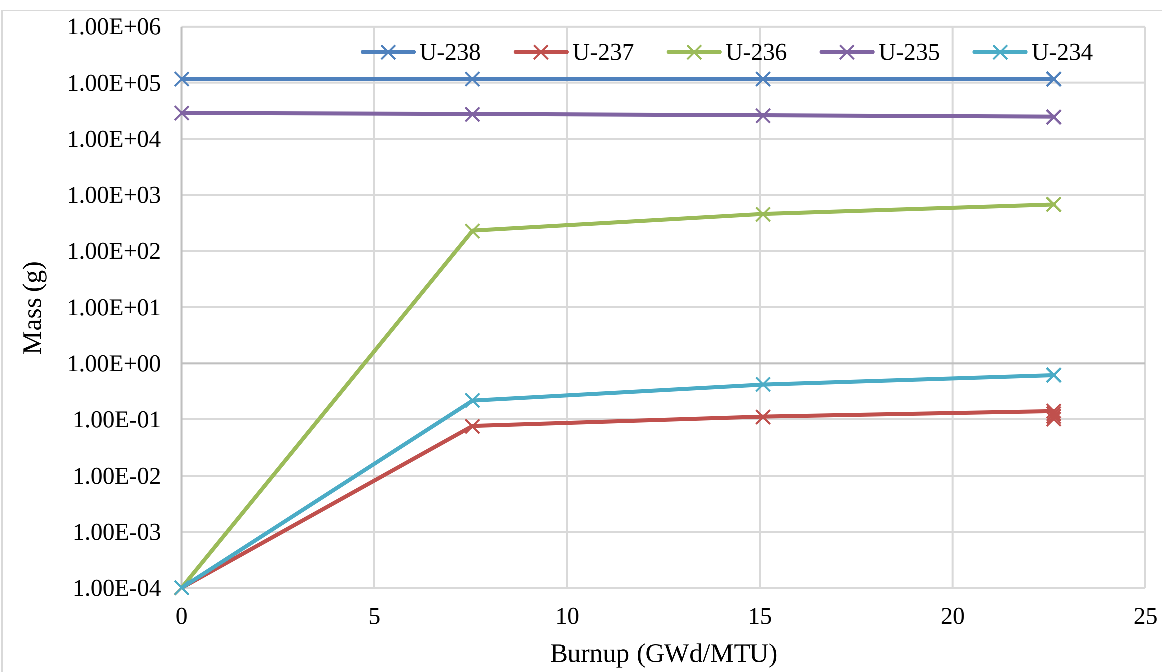


Figure 16. UC(20% U-235) plutonium inventory (top) and uranium inventory (bottom) through 3-year fuel burnup at 3 MWt.

5.3. Cost Analysis

One of the major difficulties in establishing a definitive cost analysis is that research and development costs are highly variable. For example, the original funding request to Congress in FY 1960 was entered under the title of “portable gas-cooled reactor” (project-60-e-2) to develop a prototype for $2.5 million with a total estimated project cost of $6 million. However, an additional $8 million was requested in FY 1961 “to develop the technology of beryllium oxide moderated helium cooled systems for two reasons. The technology developed will…be useful in the maritime reactor program. It looks as if the gas-cooled systems, particularly in small sizes, using beryllium oxide as a moderator, which allows considerable smaller systems than the graphite type.” (United States Congress Joint Committee on Atomic Energy, 1961).

Therefore, two approaches were taken to obtain a present-day cost estimate of a land-based microreactor prototype based on the ML-1 concept. The low estimate assumed only the operating expenses attributed to “mobile low powerplant” contributed to the cost of prototype research and development. Additionally, the high estimate included operating expenses characterized by “Army power reactors, gas-cooled [or] compact”. Only the costs from 1960 to 1965 were considered because the full power and limited endurance test was concluded in 1964 and FY 1968 legislation mentioned ML-1 activities were closed out in 1966, which suggests the costs incurred in 1966 are likely to be related to decommissioning than research and development.

Table 11. FY 1960 - FY 1962 Atomic Energy Commission operating expenses (in $USD millions). Adapted from (United States Congress Joint Committee on Atomic Energy, 1961).

Accrued Costs	**Fiscal Year 1960**	**Fiscal Year 1961**	**Fiscal Year 1962 Estimates to Congress**	
			Original	**Amended**
Raw Materials Program:				
Concentration procurement:				
United States	286.4	299.0	302.0	292.0
Canada	229.4	255.7	169.5	169.5
Overseas	110.5	101.0	103.3	97.3
Total Concentrates	696.3	625.7	574.8	558.8
All Other	19.6	10.3	3.8	3.8
Total raw materials	715.9	636.0	578.6	562.6
Special nuclear materials program	553.3	567.3	560.5	557.5
Weapons program	499.6	520.0	590.2	561.2
Reactor development program:				
Government program:				
Pressurized water reactor	19.3	20.8	21.5	21.5
Light water reactor	6.9	8.4	5.6	5.6
Heavy water reactor	6.6	6.1	7.0	7.0
Plutonium recycle reactor	7.4	6.8	6.5	6.5
Organic moderated reactor	6.9	6.8	8.5	8.5
Fast breeder reactor	10.8	12.1	12.0	12.0
Sodium graphite reactor	8.9	6.8	9.0	8.8
Gas-cooled reactor	11.2	12.8	11.0	10.7
Homogenous	5.3	3.8	0	0
New reactor experiments	7.7	8.5	11.5	12.9
Studies and evaluations	2.2	3.1	2.0	2.0
Reactor safety	9.1	8.4	11.0	12.5
Total Government program	102.3	104.4	105.6	108.0
Cooperative program	17.4	21.6	24.6	24.0
Total civilian power reactors	119.7	126.0	130.2	132.0
Euratom	0.5	1.2	2.7	2.7
Nuclear technology and general support	39.0	43.2	47.2	47.8
Merchant ship reactors	8.1	9.0	11.4	8.0
High temperature materials and high-performance reactor	....	....	....	19.0[1]
Army power reactors:				
Pressurized water	2.7	2.8	1.6	1.6
Boiling water	1.0	1.4	1.5	1.5
Gas-cooled	6.5	8.0	7.1	7.1
Compact	[2]	1.6	....	....
Byrd reactor R & D	....	....	....	0.7
General support and advanced studies	1.3	0.8	1.3	1.3
Total Army power reactors	11.5	14.6	11.5	12.2

[1]In addition $6 million included in select resources for program total of $25 million.
[2]Less than $50,000

Table 12. FY 1963 - FY 1965 Atomic Energy Commission operating expenses (in $USD millions). Adapted from (United States Congress Joint Committee on Atomic Energy, 1964).

Accrued Costs	Fiscal Year 1963	Fiscal Year 1964	Fiscal Year 1965		
			Division request	Estimates to BOB	Estimates to Congress
Raw Materials Program:					
United States……………………	243.7	193.8	182.3	182.3	182.3
Canada…………………………	140.0	39.1	22.7	22.7	22.7
Overseas…………………………	94.0	87.1	62.5	62.5	62.5
Total raw materials…………………	477.7	320.0	267.5	267.5	267.5
Special nuclear materials program……	477.9	475.4	448.4	440.0	401.5
Weapons program……………………	650.6	782.9	833.3	785.7	771.7
Civilian power reactors					
Shippingport…………………………	13.8	13.1	11.8	11.8	11.8
Large central station……………	4.9	8.5	8.5	8.5	8.5
Experimental boiling water reactor…	0.5	0.1	0.0	0.0	0.0
Boiling reactor experiment………..	1.1	1.1	1.2	1.2	0.2
Boiling nuclear superheat……………	1.0	1.2	1.3	1.3	1.2
Heavy water component test reactor...	2.4	2.9	3.2	3.2	3.2
Canadian cooperative program……	1.3	1.3	1.0	1.0	1.0
Spectral shift reactors………………	0.6	1.5	1.5	1.5	1.0
Pressurized water, other……………	0.4	0.2	0.0	0.0	0.0
Light water, other……………………	4.8	4.4	3.4	3.4	2.9
Heavy water, other…………………	2.7	2.5	4.2	4.2	4.1
Water cooled, other…………………	0.5	1.3	0.3	0.3	0.3
Organic-cooled reactor………………	6.7	0.9	0.3	0.3	0.3
Experimental gas-cooled reactor……	6.0	2.9	2.9	2.9	2.9
Gas cooled, other……………………	5.6	8.5	9.6	9.6	7.9
Experimental breeder reactor I………	0.3	0.3	0.3	0.3	0.0
Experimental breeder reactor II……	6.3	6.6	8.1	8.1	7.1
Sodium reactor experiment I………	1.9	2.2	2.2	2.2	2.2
FARET………………………………	0.4	0.8	2.1	2.1	1.3
Fast reactors, other…………………	7.2	9.6	13.3	13.3	12.0
Sodium cooled, other………………	7.4	7.7	9.0	9.0	9.0
Research and development………..	1.7	2.4	3.0	3.0	2.5
Total, civilian power reactors………..	77.5	80.0	87.2	87.2	79.4
Army power reactors					
Stationary medium plant No. 1………	0.1	0.0	0.0	0.0	0.0
Portable medium powerplant No. 1……	0.5	0.4	0.3	0.3	0.3
Stationary low powerplant……………	0.3	0.0	0.0	0.0	0.0
Antarctic reactors………………………	1.4	0.0	0.0	0.0	0.0
Water cooled, other……………………	0.9	1.0	1.0	1.0	1.0
Gas-cooled reactor experiment………	0.5	0.0	0.0	0.0	0.0
Mobile low powerplant No. 1…………	3.8	3.3	3.6	3.6	3.6
Mobile low powerplant No. 1A………	0.1	0.0	0.0	0.0	0.0
Gas cooled, other………………………	0.0	0.1	2.0	2.0	1.0
Military compact reactor………………	2.2	4.0	10.0	0.0	0.0
General R & D, Army…………………	0.9	1.5	3.5	3.5	3.1
Total, Army power reactors……	10.7	10.3	20.4	10.4	9.0

To estimate the cost of developing a micro-reactor in today's dollars based on the ML-1 concept, the future value was obtained through compound interest using the average U.S. GDP inflation rate of 3.36% between 1961 and 2019 (Inflation, GDP, 2019):

$$FV = PV(1+i)^n \tag{5.1}$$

Where,

FV is Future Value ($)

PV is Present Value ($)

i is the rate of inflation

n is number of times to compound interest (years)

The results are reported in Table 13. These calculations make several assumptions:

1. The cost of fuel, in this case UO_2(93.1% U-235), is included in the reported costs.
2. The cost of producing uranium in a new fuel form, UC(20%), is offset by the cost reduction associated with lower enrichment.
3. The increased costs associated with meeting more stringent regulatory requirements are offset by the reduced costs research and development costs afforded by building off existing work.

Table 13. Cost estimate of ML-1 based concept in today's dollars.

Fiscal Year	Low Estimate in FY Value ($millions)	Low Estimate in Today's Value ($millions)	High Estimate in FY Value ($millions)	High Estimate in Today's Value ($millions)
1960	0	0	6.5	48.8
1961	0	0	9.6	69.7
1962	0	0	7.1	49.9
1963	3.9	26.5	6.6	44.9
1964	3.3	21.7	7.4	48.7
1965	3.6	22.9	4.6	29.3
Total:	10.8	71.1	41.8	291.3

6. CONCLUSIONS

The ML-1 concept is a viable framework for developing a mobile land-based microreactor for domestic military energy production. The MCNP® model of the ML-1 approximates the reported k_{eff} reasonably well, assuming the uncertainty is largely due to the different nuclear data libraries selected for neutronic calculations. The original ML-1 design, which utilized HEU in uranium oxide form, was designed for sustained criticality through 10,000 hours of operation. Utilizing fuels with a lower U-235 enrichment can still produce a critical system within the original geometries of the ML-1 design. However, it was not possible to achieve 10,000 hours of sustained criticality by lowering U-235 content alone. Additional changes to the model to meet Project Pele design goals included:

- Changing the fuel material to UC(20% U-235) in each fuel pin.
- Increasing the radii of the fuel pins from 0.22487 cm to 0.22987 cm.
- Replacing the center void in each fuel assembly with a fuel pin.
- Removing the BeO spacers at the top and bottom of the fuel pins, such that the fuel occupies the full height between the top and bottom reflectors.
- Removing the fuel diluent (BeO) from the outer fuel pins in each assembly.

Utilizing HALEU (20% U-235) in uranium carbide form resulted in the best neutronics performance between UN, UF_6, and UO_2. Uranium carbide offers advantages of greater fuel density and improved thermal conductivity than uranium oxide. However, swelling is a greater concern with uranium carbide than uranium oxide. To accommodate for swelling, 5 mm of void space was maintained between the fuel pellets and the cladding material. The calculated k_{eff} after 3 years of operation at 3 MWt is distributed between 0.9969 and 0.9996 at the 95 percent confidence interval. The k_{eff} increases in the days following shutdown due to buildup and subsequent decay of fission poisons. Regular power cycling will help to reduce fission product poison buildup sustain criticality at the three-year mark. Ultimately, these results suggest that a critical system with a three-year operation at threshold power is possible utilizing the ML-1 concept with HALEU fuel in uranium carbide form and replacing the nitrogen coolant with helium. This reactor concept offers a unique advantage over other energy sources through the ability to operate in austere environments and provide reliable energy over a greater period when resources may be limited or otherwise interrupted. Therefore, the ideal location for this concept is an installation that consumes less than 3 MWt annually, located in a climate where hazardous weather is a common occurrence and is removed from a large urban center. There are 25 Army installations that consume less than 3 MWt annually. U.S. drought data revealed six installations located in severe or exceptional drought areas and only two of those consume less than 3 MWt annually. To qualify an area as remote, TRICARE Prime Remote (TPR) data was considered. Two installations met all three criteria, Tooele Army Depot, UT and Arizona ARNG, AZ. Between these two installations, Tooele Army Depot, UT would receive the greatest benefit from a mobile, land-based micro-reactor due to higher weather hazard classification of exceptional drought area compared to Arizona ARNG's severe classification.

Future work should include extensive thermal management evaluations to determine why the thermal efficiency was lower than expected during the full power limited endurance test and if 33% thermal efficiency or greater is still achievable with the updated design. Furthermore, additional work is required focusing on the source term of this mobile configuration including dose assessments at varying distances during operation and after shutdown to determine neutron dose rates and gamma dose rate contributions from fission products.

REFERENCES

Army Gas-cooled Reactor Systems Program. Final Hazards Summary Report for the ML-1 Nuclear Power Plant. (Technical Report) | OSTI.GOV. (1960, May 16). Retrieved from U.S. Department of Energy Office of Scientific and Technical Information: https://doi.org/10.2172/4729306

Army Gas-cooled Reactor Systems Program. Full Power and Limited Endurance Test of the ML-1 Nuclear Power Plant. (1964). Retrieved from U.S. Department of Energy Office of Scientific and Technical Information: https://doi.org/10.2172/4558814

Army Gas-cooled Reactor Systems Program. ML-1A Shield Optimization Study (Technical Report) | OSTI.GOV. (1965). Retrieved from U.S. Department of Energy Office of Scientific and Technical Information: https://doi.org/10.2172/4558814

C.J. Werner et al. (2017, October 27). *MCNP User's Manual Code Version 6.2.* Retrieved from Los Alamos National Laboratory: https://mcnp.lanl.gov/pdf_files/la-ur-17-29981.pdf

Executive Order on Promoting Small Modular Reactors for National Defense and Space Exploration. (2021, January 5). Retrieved from White House Archives: https://trumpwhitehouse.archives.gov/presidential-actions/executive-order-promoting-small-modular-reactors-national-defense-space-exploration/

Idaho National Laboratory. (2019, November). *DOE-ID NEPA CX DETERMINATION.* Retrieved from U.S. Department of Energy: https://www.energy.gov/sites/prod/files/2019/11/f68/CX-020778.pdf

Inflation, GDP. (2019). Retrieved from The World Bank | Data: https://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG?locations=US

John S. McCain National Defense Authorization Act for Fiscal Year 2019. (2018, August 13). Retrieved from Congress.gov: https://www.congress.gov/bill/115th-congress/house-bill/5515/text

Oblozinsky, P. (2006). New ENDF/B-VII Library. Upton, NY.

Office of the Assistant Secretary of Defense for Sustainment. (2019). *Annual Energy Management and Resilience Report.* Retrieved from Office of the Assistant Secretary of Defense for Sustainment: https://www.acq.osd.mil/eie/ie/FEP_Energy_Reports.html

Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. (2016, August 1). *DSB Reports.* Retrieved from Department of Defense Defense Science Board: https://dsb.cto.mil/reports/2010s/Energy_Systems_for_Forward_Remote_Operating_Bases.pdf

Presidential Policy Directive 21. (2013, February 12). *Presidential Policy Directive -- Critical Infrastructure Security and Resilience.* Retrieved from The White House: https://obamawhitehouse.archives.gov/the-pressoffice/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

Sood, A. (2017). The Monte Carlo Method and MCNP - A Brief Review of Our 40 Year History. *Int. Topical Meeting on Industrial Radiation and Radioisotope Measurement - Applications Conference.* Chicago.

TRICARE Plan Finder. (2021, February). Retrieved from TRICARE.

U.S. Army Corps of Engineers. (2017). *ML-1 Mobile Nuclear Power Plant in Idaho*. Retrieved from USACE Digital Library.

U.S. Army Office of the Chief of Engineers. (2008). *Army Nuclear Power Program.* U.S. Government Printing Office.

U.S. Congress. (2013, June 20). *Senate Report 113-44 - National Defense Authorization Act for Fiscal Year 2014.* Committee on Armed Services. Retrieved from Congress.gov: https://www.congress.gov/congressional-report/113th-congress/senate-report/44/1

U.S. Department of Defense. (2019, April 29). *Request for Solutions Pele*. Retrieved from System for Award Management (SAM): https://beta.sam.gov/opp/b9850f594c4b4313e21f9fec5cc79e9c/view#attachments-links

U.S. Department of Energy. (2010, July 22). *MoU - Department of Energy.* Retrieved from U.S. Department of Energy: http://www.energy.gov/news/documents/Enhance-Energy-Security-MOU.pdf

U.S. Department of Energy. (2020, September 28). *Departments of Defense and Energy Memorandum of Understanding to Enhance Energy Resilience.* Retrieved from U.S. Department of Energy: https://www.energy.gov/sites/prod/files/2020/09/f79/DoD-DOE%20MOU%20%28signed%29.pdf

U.S. Energy Information Administration (EIA) - Data. (2019). Retrieved from U.S. Energy Information Administration: https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T02.07#/?f=A&start=2015&end=2019&charted=1-13

United States Congress Joint Committee on Atomic Energy. (1961). *AEC Authorizing Legislation Fiscal Year 1962.* U.S. Government Printing Office.

United States Congress Joint Committee on Atomic Energy. (1964). *AEC Authorizing Legislation for Fiscal Year 1965.* U.S. Government Printing Office.

United States Drought Monitor. (2021, February 02). Retrieved from University of Nebraska - Lincoln: https://droughtmonitor.unl.edu/

X-5 Monte Carlo Team. (2003, April 24). Volume I (LA-UR-03-1987): MCNP Overview and Theory.

APPENDIX A

MCNP INPUT DECK: DETAILED MODEL

```
ML-1: HEU Detailed Model
c ***************************************************************
c *** MCNP6.2 Model developed by B. Passons, Texas A&M University ****
c ***************************************************************
c *************************** CELLS ***************************
c ***************************************************************
c ### Core - 61 Fuel Assemblies ###
   1    0        -101 102 -103 105 -104 106  fill=1 u=100
   2    0        -201 202 -203 205 -204 206  u=1 lat=2 $ROW 1
         fill=-9:9 -9:9 0:0
     7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7  $ROW 1
      7 7 7 7 7 7 7 7 7 7 7 7 7 8 7 7 7 7 7  $ROW 2
       7 7 7 7 7 7 7 7 7 7 7 8 7 7 8 7 7 7 7  $ROW 3
        7 7 7 7 7 7 7 7 7 8 7 7 8 7 7 8 7 7 7  $ROW 4
         7 7 7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7  $ROW 5
          7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7  $ROW 6
           7 7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7  $ROW 7
            7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7  $ROW 8
             7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7  $ROW 9
              7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7  $ROW 10
               7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7  $ROW 11
                7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7  $ROW 12
                 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7 7  $ROW 13
                  7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7  $ROW 14
                   7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7 7 7  $ROW 15
                    7 7 7 8 7 7 8 7 7 8 7 7 7 7 7 7 7 7 7  $ROW 16
                     7 7 7 7 8 7 7 8 7 7 7 7 7 7 7 7 7 7 7  $ROW 17
                      7 7 7 7 7 8 7 7 7 7 7 7 7 7 7 7 7 7 7  $ROW 18
                       7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7  $ROW 19
c ### Fuel Pin Assembly - 7 inner surrounded by 12 outer ###
  30    0        -10  fill=10 u=8
  31    7   -8.22 10 -11  u=8 $ Hastelloy
  32    9    -0.08 11 -12  u=8 $ Thermoflex
  33    2      -8 12 -13  u=8 $ Steel
   3    0        -301 302 -303 305 -304 306  u=10 lat=2 $ROW 1
         fill=-3:3 -3:3 0:0
     5 5 5 5 5 5 5  $ROW 1
      5 5 5 4 4 4 5  $ROW 2
       5 5 4 6 6 4 5  $ROW 3
        5 4 6 5 6 4 5  $ROW 4
```

```
          5 4 6 6 4 5 5  $ROW 5
           5 4 4 4 5 5 5  $ROW 6
            5 5 5 5 5 5 5  $ROW 7
   40     6 -5.4845 -20 -307 308  u=4 vol=9.276 $Outer Pin
   41     7   -8.22 20 -21  u=4 $Hastelloy-X
   42     8 -0.000178 21  u=4 $Gas Fill
   50     8 -0.000178 -14  u=5 $Gas Fill
   60     5  -10.96 -20 -307 308  u=6 vol=9.276 $Inner Pin
   61     7   -8.22 20 -21  u=6 $Hastelloy-X
   62     8 -0.000178 21  u=6 $Gas Fill
   70     3 -0.998207 -14  u=7 $Moderator Fill
c ### Reflector (Pb) ###
c - Radial - 0-180 deg: 1.8" Pb + 2 " W 180-360: 4" Pb
   80     1  -11.35 (101 :-102 :103 :-105 :104 :-106 ) u=100
c ### Reactor Vessel (304 Stainless Steel) ###
  100     0          (-401 402 -403 405 -404 406 )-500 600 -62  fill=100 vol=2.962E5
c ### Shielding:Radial P/C Direction (2xx); Non-P/C Direction (3xx)###
c -- H2O --
  200     3 -0.998207 62 -700 600 -63 -500 50
  300     3 -0.998207 62 -700 600 -63 -500 -50
c -- Void --
  201     0          700 -701 600 -500 -63 50
  301     0          700 -701 600 -500 -63 -50
c -- Stainless Steel --
  202     2      -7.85 701 -702 603 -503 -63 50
  302     2      -7.85 701 -702 603 -503 -63 -50
c -- Aluminum --
  203    11 -2.70 702 -703 603 -503 -63 50
  303    11 -2.70 702 -703 603 -503 -63 -50
c -- Boral --
  204    12   -2.53 703 -704 603 -503 -63 50
  304    12   -2.53 703 -704 603 -503 -63 -50
c -- Stainless Steel --
  205     2      -7.85 704 -705 602 -502 -63 50
  305     2      -7.85 704 -705 602 -502 -63 -50
c -- Boral --
  206    12   -2.53 705 -706 602 -502 -63 50
  306    12   -2.53 705 -706 602 -502 -63 -50
c -- Aluminum --
  207    11 -2.70 706 -707 602 -502 -63 50
  307    11 -2.70 706 -707 602 -502 -63 -50
c -- H2O + Boric Acid --
  208    10 -1.26604 707 -708 601 -500 -63 50
  308    10 -1.26604 707 -708 601 -500 -63 -50
```

```
c -- Lead --
 209     1  -11.35 (708 -709 616 -516 -63 50 )
 309     1  -11.35 (708 -709 616 -516 -63 -50 )
c -- Lead --
 210     1  -11.35 709 -710 616 -516 -63 50
 310     1  -11.35 709 -710 616 -516 -63 -50
c -- H2O + Boric Acid --
 211    10 -1.26604 710 -711 601 -500 50
 311    10 -1.26604 710 -711 601 -500 -50
c -- Polystyrene --
 212     9   -1.06 711 -712 602 -502 50
 312     9   -1.06 711 -712 602 -502 -50
c -- H2O + Boric Acid --
c  213    10 -1.26604 712 -713 601 -500 50
c  313    10 -1.26604 712 -713 601 -500 -50
c ### Shielding: Top (4xx) ###
c -- Core (no fissile content) --
 400     3 -0.998207 207 -500 -62
c -- Steel + Void --
 401     2    -5.9 500 -501 -714
c -- Void --
 402     0         501 -502 -407
 403     0         (407 -714 -509 501 ):(-714 507 506 -509 ):
           (-510 509 -715 507 ):(-715 509 510 -511 507 )
c -- Stainless Steel --
 404     2      -7.85 502 -504 -407
 405     2      -7.85 (-701 714 -508 500 ):(715 -714 509 -508 ):
           (-512 510 511 ):
           (-716 715 509 -511 )
c -- Tungsten --
 406     4   -19.3 504 -505 -407
c -- Stainless Steel --
 407     2      -7.85 505 -506 -407
c -- Void --
c  408     0
c -- Stainless Steel --
 409     2      -7.85 -507 506
c -- Lead --
 410     1  -11.35 513 -514 516
 411     1  -11.35 -517 518 -519
 412     1  -11.35 514 -515 516 -518
c -- Container --
 413     1  -11.35 (713 -717 -64 65 ):(60 -64 -713 ):(-61 65 -713 )
c - Bottom -
```

```
 501     2      -7.85 -600 601 -714
c -- Void --
 502     0         -601 602 -407
 503     0         (-610 -611 ):(611 -715 -608 ):(607 608 -715 ):
         (609 -606 715 -714 ):(-601 606 -714 407 )
c -- Stainless Steel --
 504     2      -7.85 -602 604 -407
 505     2      -7.85 (-612 610 -611 ):(611 -608 715 -716 ):
         (-701 715 608 -609 ):
         (-701 714 609 -600 )
c -- Tungsten --
 506     4   -19.3 -604 605 -407
c -- Stainless Steel --
 507     2      -8 -605 606 -407
c -- Void --
c 508     0
c -- Stainless Steel --
 509     2      -7.85 -607 -606
c -- Lead --
 510     1  -11.35 613 -614 -616
 511     1  -11.35 614 -615 -616
 512     1  -11.35 -517 -618 619
c ### Fill Voids ###
 994    10 -1.26604 (-60 61 -713 )(-60 519 ):(-518 516 515 -713 ):
         (512 -518 -513 511 ):(517 518 -519 -713 ):(-511 -513 716 508 ):
         (716 -516 508 -708 ):(-516 500 710 -711 ):(-516 711 -713 502 ):
         (-619 -713 61 ):(-501 -713 712 601 ):(701 -708 -508 502 ):
         (-502 701 -704 503 ):(-502 707 -708 500 ):(712 -713 501 -502 ):
         (-713 712 -601 616 ):(-711 710 -601 616 ):(-602 616 711 -712 ):
         (710 -713 -208 616 ):(618 -616 61 -713 615 ):(-618 619 517 -713 ):
         (612 618 -613 -611 ):(611 -613 -616 716 ):(616 -608 716 -708 ):
         (-708 701 608 -602 ):(-708 707 602 -601 ):(701 -704 602 -603 )
 995     8 -0.000178 -20 (307 :-308 ) u=6 $UO2 Pin
 996     8 -0.000178 -20 (307 :-308 ) u=4 $Fill Gas: BeO Pin
 997     3 -0.998207 13  u=8 $ Moderator: Distilled Water
 998     4   -19.3 (401 :-402 :403 :-405 :404 :-406 )50 -62 $ W Fill: Driver
          -500 600
 999     1  -11.35 (401 :-402 :403 :-405 :404 :-406 )-50 -62 $ Pb Fill: Rear
          -500 600
c ### Outside Environment ###
 1000     13 -0.001205  (717 :64 :-65 ) -800
c ### Graveyard ###
 1001     0  800
```

```
c **********************************************************
c *********************** SURFACES  ***********************
c **********************************************************
  30       cz 100
  40       pz 31.75
  41       pz -31.75
  50       py 0
  51       px 0
  60       pz 100.965  $ Pressure Vessel - Top
  61       pz -100.965  $ Pressure Vessel - Bottom
  62       cz 39.325316  $ Reflector - W/Pb Outer
  63       cz 70.089316  $ Moderator - H2O Outer
  64       pz 103.5497
  65       pz -103.5497
c ### Core Hex ###
 101        px 29
 102        px -29
 103         p 1 1.7320508076 0 58
 104         p -1 1.7320508076 0 58
 105         p 1 1.7320508076 0 -58
 106         p -1 1.7320508076 0 -58
c ### Fuel Element Assembly ###
  10       cz 1.81102  $ Assembly - Fuel Outer
  11       cz 1.83642  $ Assembly - Hastelloy Outer
  12       cz 2.14122  $ Assembly - Insulation Outer
  13       cz 2.1844  $ Assembly - Steel Outer
  14       cz 3  $ Assembly - Surrounding
 201        px 2.2
 202        px -2.2
 203         p 1 1.7320508076 0 4.4
 204         p -1 1.7320508076 0 4.4
 205         p 1 1.7320508076 0 -4.4
 206         p -1 1.7320508076 0 -4.4
 207        pz 40.64
 208        pz -40.64
c ### Fuel Pin ###
  20       cz 0.22987  $ Hastelloy inner radius
  21       cz 0.30607  $ Hastelloy outer radius
 301        px 0.35
 302        px -0.35
 303         p 1 1.7320508076 0 0.7
 304         p -1 1.7320508076 0 0.7
 305         p 1 1.7320508076 0 -0.7
 306         p -1 1.7320508076 0 -0.7
```

```
 307        pz 27.94
 308        pz -27.94
c ### Reflector ###
c - Radial - 0-180 deg: 1.8" Pb + 2 " W 180-360: 4" Pb
 401        px 34.08
 402        px -34.08
 403         p 1 1.7320508076 0 68.16
 404         p -1 1.7320508076 0 68.16
 405         p 1 1.7320508076 0 -68.16
 406         p -1 1.7320508076 0 -68.16
 407        cz 31.39
c ### Shielding (5xx Top; 6xx Bottom; 7xx P/C direction;
c      8xx non-P/C direction;) ###
c - Top -
 500        pz 30.48
 501        pz 34.29  $ Bottom: Void
 502        pz 36.195  $ Bottom: Steel
 503        pz 29.82
 504        pz 39.055
 505        pz 40.645
 506        pz 41.915
 507       k/z 0 0 46.995 6.25 -1
 508        pz 46.995
 509        pz 44.455
 510        sz 58.825 12.7
 511        pz 58.825
 512        sz 58.825 13.87
 513       trc 0 0 50 0 0 22.796 60.19532 13.716
 514       trc 0 0 50 0 0 22.796 62.73532 16.256
 515       trc 0 0 50 0 0 22.796 65.27532 18.796
 516        pz 50
 517        cz 16.256
 518        pz 72.796
 519        pz 73.431
c - Bottom -
 600        pz -30.48
 601        pz -34.29
 602        pz -36.195
 603        pz -29.82
 604        pz -39.055
 605        pz -40.645
 606        pz -41.915
 607       k/z 0 0 -46.995 6.25 1
 608        pz -46.995
```

```
  609        pz -44.455
  610        sz -58.825 12.7
  611        pz -58.825
  612        sz -58.825 13.87
  613       trc 0 0 -50 0 0 -22.796 60.19532 13.716
  614       trc 0 0 -50 0 0 -22.796 62.73532 16.256
  615       trc 0 0 -50 0 0 -22.796 65.27532 18.796
  616        pz -50
  617        cz -16.256
  618        pz -72.796
  619        pz -73.431
c - Radial -
  700        cz 39.96532
  701        cz 41.45532
  702        cz 42.72532
  703        cz 43.41532
  704        cz 43.68532
  705        cz 48.76532
  706        cz 51.62532
  707        cz 52.57532
  708        cz 60.19532
  709        cz 62.73532
  710        cz 65.27532
  711        cz 71.62532
  712        cz 76.62532
  713        cz 138.3853
  714        cz 35.15
  715        cz 12.7
  716        cz 13.87
  717        cz 140.97
  800        so 20000

mode  n
kcode 10000 1.00 50 250
ksrc  0.150000 0.000000 0.000000
     0.150000 0.000000 -35.000000
     0.150000 0.000000 35.000000
c 10,000 hours operation time + 24hrs + 48hrs + 72hrs
BURN TIME=1 29 60 90 90 95 51.67 1 1 1
     PFRAC=1 1 1 1 1 1 1 0 0 0
     POWER=3
     MAT=5,6
     MATVOL=3.3951E+03, 6.7902E+03
c **********************************************************
```

```
c ************************  MAT  ***************************
c **********************************************************
c ### Lead (rho: 11.35 g/cc) ###
m1    82000.                1
c ### Stainless Steel-304 (rho: -7.85 g/cc) ###
m2    6000.          -0.0008
      14000.           -0.01 24000.           -0.19 25055.           -0.02
      26000.         -0.6842 28000.          -0.095
c ### Water (rho: 0.998207 g/cc)###
m3    1001.        -0.111894  $ H-1
      8016.        -0.888106
c ### Tungsten (rho: 19.3 g/cc) ###
m4    74000.                1  $ W
c ### UO2 (rho: 10.96 g/cc) ###
m5    8016.        -0.1197
      92235.       -0.8196 92238.      -0.0607
c ### UO2 + BeO (rho: 5.4845 g/cc) ###
m6    8016.        -0.1642
      92235.       -0.7494 92238.      -0.0556 4009.       -0.0308
c ### Hastelloy-X (rho: 8.22 g/cc) ###
m7    24000.         -0.2237
      25000.         -0.0075 26000.         -0.1841 28000.          -0.48
      42000.         -0.0873 74000.         -0.0031 27000.          -0.013
c ### He Fill Gas (rho: 0.000178 g/cc) ###
m8    2000.                1
c ### Thermoflex (rho:0.080 g/cc) ###
m9    13027.         -0.1678
      14000.         -0.3174 5000.          -0.0002 8000.          -0.5113
c ### H2O + 2% Boric Acid (rho: 1.26604 g/cc)###
m10   1001.        -0.1106548
      8016.        -0.8858479 5000.      -0.00349735
c ### Aluminum-6061 (rho: 2.70 g/cc)###
m11   13027.         -0.9675
      24000.         -0.0025 25000.         -0.0015 29000.          -0.005
      26000.         -0.0085 14000.          -0.006
c ### Boral (rho: 2.53 g/cc)
m12   5000.           -0.274
      6000.           -0.076 13027.           -0.65
c ### Air (Dry, Near Sea Level) - PNNL-15870 Material Compendium  ###
m13    6000.        -0.000124
      7014.        -0.755268 8016.        -0.231781 18000.       -0.012827
imp:n   1 73r       0           $ 1, 1001
mt3 lwtr
mt10 lwtr
```

```
c ***********************************************************
c ************************  PHYS  **************************
c ***********************************************************
mphys on
F4:n 100
sd4 2.962E5
fm4 2.476E17
e4       1.00E-10 1.00E-09 1.00E-08
         1.00E-07 1.00E-06 1.00E-05
         1.00E-04 1.00E-03 1.00E-02
         1.00E-01 1.00E+00 1.00E+01 2.00E+01
C Neutrons: 3.3 MWth * 3.1E16 fiss/MW * 2.42 n/fiss
C Photons: 3.3 MWth * 3.1E16 fiss/MW * 6.6 y/fiss
C f5z:p 0 3048 0
C FM5 1.023E17
C DE5  log 0.01    0.015   0.02    0.03    0.04    0.05    0.06
c      0.08    0.1     0.15    0.2     0.3     0.4     0.5
c      0.6     0.8     1.0     1.5     2.0     3.0     4.0
c      5.0     6.0     8.0     10.0
C DF5    log 2.78e-6 1.11e-6 5.88e-7 2.56e-7 1.56e-7 1.20e-7 1.11e-7
c      1.20e-7 1.47e-7 2.38e-7 3.45e-7 5.56e-7 7.69e-7 9.09e-7
c      1.14e-6 1.47e-6 1.79e-6 2.44e-6 3.03e-6 4.00e-6 4.76e-6
C       5.56e-6 6.25e-6 7.69e-6 9.09e-6
C F15z:n 0 3048 0
C FM15 1.023E17
C de15     1.00E-09 1.00E-08 2.53E-08 1.00E-07 2.00E-07 5.00E-07 1.00E-06 2.00E-06
c         5.00E-06 1.00E-05 2.00E-05 5.00E-05 1.00E-04 2.00E-04 5.00E-04 1.00E-03
C          0.002 0.005 0.01 0.02 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 0.9 1 1.2
c         2 3 4 5 6 7 8 9 10 12 14 15 16 18 20 30 50 75 100 125 150 175 201
C df15     2.3760E-03 3.2400E-03 3.8160E-03 4.6440E-03 4.8600E-03 4.8960E-03
c         4.7880E-03 4.6440E-03 4.3200E-03 4.0680E-03 3.8160E-03 3.5640E-03
c         3.3840E-03 3.2040E-03 2.9880E-03 2.8440E-03 2.7720E-03 2.8800E-03
c         3.7800E-03 5.9760E-03 8.5320E-03 1.4796E-02 2.1600E-02 3.1680E-02
c         4.7520E-02 6.1200E-02 8.3880E-02 1.1592E-01 1.3500E-01 1.4400E-01
c         1.4976E-01 1.5300E-01 1.5120E-01 1.4832E-01 1.4688E-01 1.4580E-01
c         1.4400E-01 1.4580E-01 1.4724E-01 1.5120E-01 1.5840E-01 1.7280E-01
c         1.8720E-01 1.9440E-01 1.9440E-01 2.0520E-01 2.1600E-01 1.8540E-01
C          1.4400E-01 1.1880E-01 1.0260E-01 9.3600E-02 8.8200E-02 9.0000E-02
C          9.3600E-02
c FMESH104:n  GEOM=CYL ORIGIN=0 0 -103.5497 AXS=0 0 1 VEC=1 0 0
c        IMESH=213.083         IINTS=107
c        JMESH=226             JINTS=113
c        KMESH=1               KINTS=1
c        EMESH=10              EINTS=1
```

```
c        OUT=IJ              FACTOR=1.40E13
c FMESH204:p GEOM=CYL ORIGIN=0 0 -103.5497 AXS=0 0 1 VEC=1 0 0
c        IMESH=213.083        IINTS=107
c        JMESH=226            JINTS=113
c        KMESH=1              KINTS=1
c        EMESH=10             EINTS=1
c        OUT=IJ              FACTOR=1.02E17
c neutrons
c units: mrem/hr per n/cm^2sec = (pSvcm^2/sec)(3.6e-4)
c de104     1.00E-09 1.00E-08 2.53E-08 1.00E-07 2.00E-07 5.00E-07 1.00E-06 2.00E-06
c          5.00E-06 1.00E-05 2.00E-05 5.00E-05 1.00E-04 2.00E-04 5.00E-04 1.00E-03
c          0.002 0.005 0.01 0.02 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 0.9 1 1.2
c          2 3 4 5 6 7 8 9 10 12 14 15 16 18 20 30 50 75 100 125 150 175 201
c df104     2.3760E-03 3.2400E-03 3.8160E-03 4.6440E-03 4.8600E-03 4.8960E-03
c          4.7880E-03 4.6440E-03 4.3200E-03 4.0680E-03 3.8160E-03 3.5640E-03
c          3.3840E-03 3.2040E-03 2.9880E-03 2.8440E-03 2.7720E-03 2.8800E-03
c          3.7800E-03 5.9760E-03 8.5320E-03 1.4796E-02 2.1600E-02 3.1680E-02
c          4.7520E-02 6.1200E-02 8.3880E-02 1.1592E-01 1.3500E-01 1.4400E-01
c          1.4976E-01 1.5300E-01 1.5120E-01 1.4832E-01 1.4688E-01 1.4580E-01
c          1.4400E-01 1.4580E-01 1.4724E-01 1.5120E-01 1.5840E-01 1.7280E-01
c          1.8720E-01 1.9440E-01 1.9440E-01 2.0520E-01 2.1600E-01 1.8540E-01
c          1.4400E-01 1.1880E-01 1.0260E-01 9.3600E-02 8.8200E-02 9.0000E-02
c          9.3600E-02
c photons
c units: mrem/hr per n/cm^2sec = (pSvcm^2/sec)(3.6e-4)
c de204     0.0100 0.0125 0.0150 0.0175 0.0200 0.0250 0.0300 0.0400 0.0500
c          0.0600 0.0800 0.1000 0.1250 0.1500 0.2000 0.3000 0.4000 0.5000
c          0.6000 0.8000 1.0000 1.5000 2.0000 3.0000 4.0000 5.0000 6.0000
c          8.0000 10.0000
c df204     2.40732E-05 1.86102E-04 2.96525E-04 3.84480E-04 3.69533E-04
c          3.81615E-04 2.88631E-04 2.30116E-04 2.05350E-04 1.96844E-04
c          2.10320E-04 2.41877E-04 2.96122E-04 3.46533E-04 4.59775E-04
c          6.80119E-04 8.84520E-04 1.07614E-03 1.25346E-03 1.58080E-03
c          1.87794E-03 2.51765E-03 3.07587E-03 4.00512E-03 4.85404E-03
C           5.64282E-03 6.42776E-03 8.03196E-03 9.59904E-03
```

APPENDIX B

MCNP INPUT DECK: UC(20% U-235) DETAILED MODEL V3

```
UC(20% U-235) Detailed Model v3
c *** MCNP6.2 Model developed by B. Passons, Texas A&M University ***
c ****************************************************************
c ************************** CELLS ****************************
c ****************************************************************
c ### Core - 61 Fuel Assemblies ###
   1     0        -101 102 -103 105 -104 106  fill=1 u=100
   2     0        -201 202 -203 205 -204 206  u=1 lat=2 $ROW 1
         fill=-9:9 -9:9 0:0
     7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7  $ROW 1
      7 7 7 7 7 7 7 7 7 7 7 7 7 7 8 7 7 7 7 7 7  $ROW 2
       7 7 7 7 7 7 7 7 7 7 7 8 7 7 8 7 7 7 7  $ROW 3
        7 7 7 7 7 7 7 7 7 8 7 7 8 7 7 8 7 7 7  $ROW 4
         7 7 7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7  $ROW 5
          7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7  $ROW 6
           7 7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7  $ROW 7
            7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7  $ROW 8
             7 7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7  $ROW 9
              7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7  $ROW 10
               7 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7  $ROW 11
                7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7  $ROW 12
                 7 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7 7  $ROW 13
                  7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7  $ROW 14
                   7 7 8 7 7 8 7 7 8 7 7 8 7 7 7 7 7 7 7  $ROW 15
                    7 7 7 8 7 7 8 7 7 8 7 7 7 7 7 7 7 7 7  $ROW 16
                     7 7 7 7 8 7 7 8 7 7 7 7 7 7 7 7 7 7 7  $ROW 17
                      7 7 7 7 7 8 7 7 7 7 7 7 7 7 7 7 7 7 7  $ROW 18
                       7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7  $ROW 19
c ### Fuel Pin Assembly - 7 inner pins surrounded by 12 outer ###
  30     0         -10  fill=10 u=8
  31     7   -8.22 10 -11  u=8 $ Hastelloy
  32     9    -0.08 11 -12  u=8 $ Thermoflex
  33     2      -8 12 -13  u=8 $ Steel
   3     0        -301 302 -303 305 -304 306  u=10 lat=2 $ROW 1
         fill=-3:3 -3:3 0:0
     5 5 5 5 5 5 5  $ROW 1
      5 5 5 4 4 4 5  $ROW 2
       5 5 4 6 6 4 5  $ROW 3
        5 4 6 6 6 4 5  $ROW 4
         5 4 6 6 4 5 5  $ROW 5
```

```
           5 4 4 4 5 5 5  $ROW 6
            5 5 5 5 5 5 5  $ROW 7
   40     6 -13.63 -20 -307 308  u=4 vol=2.953 $Inner Pin
   41     7   -8.22 20 -21  u=4 $Hastelloy-X
   42     8 -0.000178 21  u=4 $Gas Fill
   50     8 -0.000178 -14  u=5 $Gas Fill
   60     5  -13.63 -20 -307 308  u=6 vol=2.953 $Outer Pin
   61     7   -8.22 20 -21  u=6 $Hastelloy-X
   62     8 -0.000178 21  u=6 $Gas Fill
   70     3 -0.998207 -14  u=7 $Moderator Fill
c ### Reflector (Pb) ###
c - Radial - 0-180 deg: 1.8" Pb + 2 " W 180-360: 4" Pb
   80     1  -11.35 (101 :-102 :103 :-105 :104 :-106 ) u=100
c ### Reactor Vessel (304 Stainless Steel) ###
  100     0         (-401 402 -403 405 -404 406 )-500 600 -62  fill=100
c ### Shielding:Radial P/C Direction (2xx); Non-P/C Direction (3xx)###
c -- H2O --
  200     3 -0.998207 62 -700 600 -63 -500 50
  300     3 -0.998207 62 -700 600 -63 -500 -50
c -- Void --
  201     0         700 -701 600 -500 -63 50
  301     0         700 -701 600 -500 -63 -50
c -- Stainless Steel --
  202     2      -7.85 701 -702 603 -503 -63 50
  302     2      -7.85 701 -702 603 -503 -63 -50
c -- Aluminum --
  203    11 -2.70 702 -703 603 -503 -63 50
  303    11 -2.70 702 -703 603 -503 -63 -50
c -- Boral --
  204    12   -2.53 703 -704 603 -503 -63 50
  304    12   -2.53 703 -704 603 -503 -63 -50
c -- Stainless Steel --
  205     2      -7.85 704 -705 602 -502 -63 50
  305     2      -7.85 704 -705 602 -502 -63 -50
c -- Boral --
  206    12   -2.53 705 -706 602 -502 -63 50
  306    12   -2.53 705 -706 602 -502 -63 -50
c -- Aluminum --
  207    11 -2.70 706 -707 602 -502 -63 50
  307    11 -2.70 706 -707 602 -502 -63 -50
c -- H2O + Boric Acid --
  208    10 -1.26604 707 -708 601 -500 -63 50
  308    10 -1.26604 707 -708 601 -500 -63 -50
c -- Lead --
```

```
  209     1  -11.35 (708 -709 616 -516 -63 50 )
  309     1  -11.35 (708 -709 616 -516 -63 -50 )
c -- Lead --
  210     1  -11.35 709 -710 616 -516 -63 50
  310     1  -11.35 709 -710 616 -516 -63 -50
c -- H2O + Boric Acid --
  211    10 -1.26604 710 -711 601 -500 50
  311    10 -1.26604 710 -711 601 -500 -50
c -- Polystyrene --
  212     9   -1.06 711 -712 602 -502 50
  312     9   -1.06 711 -712 602 -502 -50
c -- H2O + Boric Acid --
c  213    10 -1.26604 712 -713 601 -500 50
c  313    10 -1.26604 712 -713 601 -500 -50
c ### Shielding: Top (4xx) ###
c -- Core (no fissile content) --
  400     3 -0.998207 207 -500 -62
c -- Steel + Void --
  401     2    -5.9 500 -501 -714
c -- Void --
  402     0         501 -502 -407
  403     0         (407 -714 -509 501 ):(-714 507 506 -509 ):
          (-510 509 -715 507 ):(-715 509 510 -511 507 )
c -- Stainless Steel --
  404     2      -7.85 502 -504 -407
  405     2      -7.85 (-701 714 -508 500 ):(715 -714 509 -508 ):
          (-512 510 511 ):
          (-716 715 509 -511 )
c -- Tungsten --
  406     4   -19.3 504 -505 -407
c -- Stainless Steel --
  407     2      -7.85 505 -506 -407
c -- Void --
c  408     0
c -- Stainless Steel --
  409     2      -7.85 -507 506
c -- Lead --
  410     1  -11.35 513 -514 516
  411     1  -11.35 -517 518 -519
  412     1  -11.35 514 -515 516 -518
c -- Container --
  413     1  -11.35 (713 -717 -64 65 ):(60 -64 -713 ):(-61 65 -713 )
c - Bottom -
  501     2      -7.85 -600 601 -714
```

```
c -- Void --
 502    0        -601 602 -407
 503    0        (-610 -611 ):(611 -715 -608 ):(607 608 -715 ):
        (609 -606 715 -714 ):(-601 606 -714 407 )
c -- Stainless Steel --
 504    2     -7.85 -602 604 -407
 505    2     -7.85 (-612 610 -611 ):(611 -608 715 -716 ):
        (-701 715 608 -609 ):
        (-701 714 609 -600 )
c -- Tungsten --
 506    4   -19.3 -604 605 -407
c -- Stainless Steel --
 507    2     -8 -605 606 -407
c -- Void --
c 508    0
c -- Stainless Steel --
 509    2     -7.85 -607 -606
c -- Lead --
 510    1  -11.35 613 -614 -616
 511    1  -11.35 614 -615 -616
 512    1  -11.35 -517 -618 619
c ### Fill Voids ###
 994    10 -1.26604 (-60 61 -713 )(-60 519 ):(-518 516 515 -713 ):
        (512 -518 -513 511 ):(517 518 -519 -713 ):(-511 -513 716 508 ):
        (716 -516 508 -708 ):(-516 500 710 -711 ):(-516 711 -713 502 ):
        (-619 -713 61 ):(-501 -713 712 601 ):(701 -708 -508 502 ):
        (-502 701 -704 503 ):(-502 707 -708 500 ):(712 -713 501 -502 ):
        (-713 712 -601 616 ):(-711 710 -601 616 ):(-602 616 711 -712 ):
        (710 -713 -208 616 ):(618 -616 61 -713 615 ):(-618 619 517 -713 ):
        (612 618 -613 -611 ):(611 -613 -616 716 ):(616 -608 716 -708 ):
        (-708 701 608 -602 ):(-708 707 602 -601 ):(701 -704 602 -603 )
 995    8 -0.000178 -20 (307 :-308 ) u=6 $UO2 Pin
 996    8 -0.000178 -20 (307 :-308 ) u=4 $Fill Gas: BeO Pin
 997    3 -0.998207 13  u=8 $ Moderator: Distilled Water
 998    4   -19.3 (401 :-402 :403 :-405 :404 :-406 )50 -62 $ W Fill: Driver
        -500 600
 999    1  -11.35 (401 :-402 :403 :-405 :404 :-406 )-50 -62 $ Pb Fill: Rear
        -500 600
c ### Outside Environment ###
1000    13 -0.001205  (717 :64 :-65 ) -800
c ### Graveyard ###
1001    0  800

c ***********************************************************
```

```
c ************************ SURFACES  ***********************
c **********************************************************
  30       cz 100
  40       pz 31.75
  41       pz -31.75
  50       py 0
  51       px 0
  60       pz 100.965  $ Pressure Vessel - Top
  61       pz -100.965  $ Pressure Vessel - Bottom
  62       cz 39.325316  $ Reflector - W/Pb Outer
  63       cz 70.089316  $ Moderator - H2O Outer
  64       pz 103.5497
  65       pz -103.5497
c ### Core Hex ###
 101       px 29
 102       px -29
 103        p 1 1.7320508076 0 58
 104        p -1 1.7320508076 0 58
 105        p 1 1.7320508076 0 -58
 106        p -1 1.7320508076 0 -58
c ### Fuel Element Assembly ###
  10       cz 1.81102  $ Assembly - Fuel Outer
  11       cz 1.83642  $ Assembly - Hastelloy Outer
  12       cz 2.14122  $ Assembly - Insulation Outer
  13       cz 2.1844  $ Assembly - Steel Outer
  14       cz 3  $ Assembly - Surrounding
 201       px 2.2
 202       px -2.2
 203        p 1 1.7320508076 0 4.4
 204        p -1 1.7320508076 0 4.4
 205        p 1 1.7320508076 0 -4.4
 206        p -1 1.7320508076 0 -4.4
 207       pz 40.64
 208       pz -40.64
c ### Fuel Pin ###
  20       cz 0.22987  $ Hastelloy inner radius
  21       cz 0.30607  $ Hastelloy outer radius
 301       px 0.35
 302       px -0.35
 303        p 1 1.7320508076 0 0.7
 304        p -1 1.7320508076 0 0.7
 305        p 1 1.7320508076 0 -0.7
 306        p -1 1.7320508076 0 -0.7
 307       pz 27.94
```

```
 308        pz -27.94
c ### Reflector ###
c - Radial - 0-180 deg: 1.8" Pb + 2 " W 180-360: 4" Pb
 401        px 34.08
 402        px -34.08
 403         p 1 1.7320508076 0 68.16
 404         p -1 1.7320508076 0 68.16
 405         p 1 1.7320508076 0 -68.16
 406         p -1 1.7320508076 0 -68.16
 407        cz 31.39
c ### Shielding (5xx Top; 6xx Bottom; 7xx P/C direction;
c      8xx non-P/C direction;) ###
c - Top -
 500        pz 30.48
 501        pz 34.29  $ Bottom: Void
 502        pz 36.195  $ Bottom: Steel
 503        pz 29.82
 504        pz 39.055
 505        pz 40.645
 506        pz 41.915
 507       k/z 0 0 46.995 6.25 -1
 508        pz 46.995
 509        pz 44.455
 510        sz 58.825 12.7
 511        pz 58.825
 512        sz 58.825 13.87
 513       trc 0 0 50 0 0 22.796 60.19532 13.716
 514       trc 0 0 50 0 0 22.796 62.73532 16.256
 515       trc 0 0 50 0 0 22.796 65.27532 18.796
 516        pz 50
 517        cz 16.256
 518        pz 72.796
 519        pz 73.431
c - Bottom -
 600        pz -30.48
 601        pz -34.29
 602        pz -36.195
 603        pz -29.82
 604        pz -39.055
 605        pz -40.645
 606        pz -41.915
 607       k/z 0 0 -46.995 6.25 1
 608        pz -46.995
 609        pz -44.455
```

```
  610        sz -58.825 12.7
  611        pz -58.825
  612        sz -58.825 13.87
  613       trc 0 0 -50 0 0 -22.796 60.19532 13.716
  614       trc 0 0 -50 0 0 -22.796 62.73532 16.256
  615       trc 0 0 -50 0 0 -22.796 65.27532 18.796
  616        pz -50
  617        cz -16.256
  618        pz -72.796
  619        pz -73.431
c - Radial -
  700        cz 39.96532
  701        cz 41.45532
  702        cz 42.72532
  703        cz 43.41532
  704        cz 43.68532
  705        cz 48.76532
  706        cz 51.62532
  707        cz 52.57532
  708        cz 60.19532
  709        cz 62.73532
  710        cz 65.27532
  711        cz 71.62532
  712        cz 76.62532
  713        cz 138.3853
  714        cz 35.15
  715        cz 12.7
  716        cz 13.87
  717        cz 140.97
  800        so 20000

mode  n
kcode 10000 1.00 50 250
ksrc  0.150000 0.000000 0.000000
      0.150000 0.000000 -35.000000
      0.150000 0.000000 35.000000
c 10,000 hours operation time + 24hrs + 48hrs + 72hrs
BURN TIME=1 29 60 90 90 95 51.67 1 2 3
      PFRAC=1 1 1 1 1 1 1 0 0 0
      POWER=3
      MAT=5,6
      MATVOL=6.7902E+03,3.3951E+03
c ***********************************************************
c ************************  MAT  ***************************
```

```
c *******************************************************
c ### Lead (rho: 11.35 g/cc) ###
m1    82000.              1
c ### Stainless Steel-304 (rho: -7.85 g/cc) ###
m2    6000.          -0.0008
      14000.          -0.01 24000.          -0.19 25055.          -0.02
      26000.         -0.6842 28000.         -0.095
c ### Water (rho: 0.998207 g/cc)###
m3    1001.        -0.111894  $ H-1
      8016.        -0.888106
c ### Tungsten (rho: 19.3 g/cc) ###
m4    74000.              1  $ W
c ### UC HALEU (rho: 13.63 g/cc) ###
m5    6012.       -0.0918
      92235.      -0.1816 92238.      -0.7266
c ### UC HALEU (rho: 13.63 g/cc) ###
m6    6012.       -0.0918
      92235.      -0.1816 92238.      -0.7266
c ### Hastelloy-X (rho: 8.22 g/cc) ###
m7    24000.         -0.2237
      25000.         -0.0075 26000.         -0.1841 28000.          -0.48
      42000.         -0.0873 74000.         -0.0031 27000.         -0.013
c ### He Fill Gas (rho: 0.000178 g/cc) ###
m8    2000.              1
c ### Thermoflex (rho:0.080 g/cc) ###
m9    13027.         -0.1678
      14000.         -0.3174 5000.          -0.0002 8000.          -0.5113
c ### H2O + 2% Boric Acid (rho: 1.26604 g/cc)###
m10   1001.       -0.1106548
      8016.       -0.8858479 5000.      -0.00349735
c ### Aluminum-6061 (rho: 2.70 g/cc)###
m11   13027.         -0.9675
      24000.         -0.0025 25000.         -0.0015 29000.         -0.005
      26000.         -0.0085 14000.         -0.006
c ### Boral (rho: 2.53 g/cc)
m12   5000.          -0.274
      6000.          -0.076 13027.          -0.65
c ### Air (Dry, Near Sea Level) - PNNL-15870 Material Compendium  ###
m13    6000.        -0.000124
      7014.        -0.755268 8016.        -0.231781 18000.       -0.012827
imp:n   1 73r       0           $ 1, 1001
mt3 lwtr
mt10 lwtr
c *******************************************************
```

```
c ************************ PHYS **************************
c ************************************************************
mphys on
F4:n 100
sd4 2.962E5
fm4 2.476E17
e4      1.00E-10 1.00E-09 1.00E-08
        1.00E-07 1.00E-06 1.00E-05
        1.00E-04 1.00E-03 1.00E-02
        1.00E-01 1.00E+00 1.00E+01 2.00E+01
C Neutrons: 3.3 MWth * 3.1E16 fiss/MW * 2.42 n/fiss
C Photons: 3.3 MWth * 3.1E16 fiss/MW * 6.6 y/fiss
C f5z:p 0 3048 0
C FM5 1.023E17
C DE5  log 0.01    0.015   0.02    0.03    0.04    0.05    0.06
c      0.08    0.1     0.15    0.2     0.3     0.4     0.5
c      0.6     0.8     1.0     1.5     2.0     3.0     4.0
c      5.0     6.0     8.0     10.0
C DF5    log 2.78e-6 1.11e-6 5.88e-7 2.56e-7 1.56e-7 1.20e-7 1.11e-7
c      1.20e-7 1.47e-7 2.38e-7 3.45e-7 5.56e-7 7.69e-7 9.09e-7
c      1.14e-6 1.47e-6 1.79e-6 2.44e-6 3.03e-6 4.00e-6 4.76e-6
C      5.56e-6 6.25e-6 7.69e-6 9.09e-6
C F15z:n 0 3048 0
C FM15 1.023E17
C de15     1.00E-09 1.00E-08 2.53E-08 1.00E-07 2.00E-07 5.00E-07 1.00E-06 2.00E-06
c          5.00E-06 1.00E-05 2.00E-05 5.00E-05 1.00E-04 2.00E-04 5.00E-04 1.00E-03
C          0.002 0.005 0.01 0.02 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 0.9 1 1.2
c          2 3 4 5 6 7 8 9 10 12 14 15 16 18 20 30 50 75 100 125 150 175 201
C df15     2.3760E-03 3.2400E-03 3.8160E-03 4.6440E-03 4.8600E-03 4.8960E-03
c          4.7880E-03 4.6440E-03 4.3200E-03 4.0680E-03 3.8160E-03 3.5640E-03
c          3.3840E-03 3.2040E-03 2.9880E-03 2.8440E-03 2.7720E-03 2.8800E-03
c          3.7800E-03 5.9760E-03 8.5320E-03 1.4796E-02 2.1600E-02 3.1680E-02
c          4.7520E-02 6.1200E-02 8.3880E-02 1.1592E-01 1.3500E-01 1.4400E-01
c          1.4976E-01 1.5300E-01 1.5120E-01 1.4832E-01 1.4688E-01 1.4580E-01
c          1.4400E-01 1.4580E-01 1.4724E-01 1.5120E-01 1.5840E-01 1.7280E-01
c          1.8720E-01 1.9440E-01 1.9440E-01 2.0520E-01 2.1600E-01 1.8540E-01
C          1.4400E-01 1.1880E-01 1.0260E-01 9.3600E-02 8.8200E-02 9.0000E-02
C          9.3600E-02
c FMESH104:n  GEOM=CYL ORIGIN=0 0 -103.5497 AXS=0 0 1 VEC=1 0 0
c        IMESH=213.083         IINTS=107
c        JMESH=226             JINTS=113
c        KMESH=1               KINTS=1
c        EMESH=10              EINTS=1
c        OUT=IJ                FACTOR=1.40E13
```

```
c FMESH204:p GEOM=CYL ORIGIN=0 0 -103.5497 AXS=0 0 1 VEC=1 0 0
c        IMESH=213.083        IINTS=107
c        JMESH=226            JINTS=113
c        KMESH=1              KINTS=1
c        EMESH=10             EINTS=1
c        OUT=IJ               FACTOR=1.02E17
c neutrons
c units: mrem/hr per n/cm^2sec = (pSvcm^2/sec)(3.6e-4)
c de104    1.00E-09 1.00E-08 2.53E-08 1.00E-07 2.00E-07 5.00E-07 1.00E-06 2.00E-06
c          5.00E-06 1.00E-05 2.00E-05 5.00E-05 1.00E-04 2.00E-04 5.00E-04 1.00E-03
c          0.002 0.005 0.01 0.02 0.03 0.05 0.07 0.1 0.15 0.2 0.3 0.5 0.7 0.9 1 1.2
c          2 3 4 5 6 7 8 9 10 12 14 15 16 18 20 30 50 75 100 125 150 175 201
c df104    2.3760E-03 3.2400E-03 3.8160E-03 4.6440E-03 4.8600E-03 4.8960E-03
c          4.7880E-03 4.6440E-03 4.3200E-03 4.0680E-03 3.8160E-03 3.5640E-03
c          3.3840E-03 3.2040E-03 2.9880E-03 2.8440E-03 2.7720E-03 2.8800E-03
c          3.7800E-03 5.9760E-03 8.5320E-03 1.4796E-02 2.1600E-02 3.1680E-02
c          4.7520E-02 6.1200E-02 8.3880E-02 1.1592E-01 1.3500E-01 1.4400E-01
c          1.4976E-01 1.5300E-01 1.5120E-01 1.4832E-01 1.4688E-01 1.4580E-01
c          1.4400E-01 1.4580E-01 1.4724E-01 1.5120E-01 1.5840E-01 1.7280E-01
c          1.8720E-01 1.9440E-01 1.9440E-01 2.0520E-01 2.1600E-01 1.8540E-01
c          1.4400E-01 1.1880E-01 1.0260E-01 9.3600E-02 8.8200E-02 9.0000E-02
c          9.3600E-02
c photons
c units: mrem/hr per n/cm^2sec = (pSvcm^2/sec)(3.6e-4)
c de204    0.0100 0.0125 0.0150 0.0175 0.0200 0.0250 0.0300 0.0400 0.0500
c          0.0600 0.0800 0.1000 0.1250 0.1500 0.2000 0.3000 0.4000 0.5000
c          0.6000 0.8000 1.0000 1.5000 2.0000 3.0000 4.0000 5.0000 6.0000
c          8.0000 10.0000
c df204    2.40732E-05 1.86102E-04 2.96525E-04 3.84480E-04 3.69533E-04
c          3.81615E-04 2.88631E-04 2.30116E-04 2.05350E-04 1.96844E-04
c          2.10320E-04 2.41877E-04 2.96122E-04 3.46533E-04 4.59775E-04
c          6.80119E-04 8.84520E-04 1.07614E-03 1.25346E-03 1.58080E-03
c          1.87794E-03 2.51765E-03 3.07587E-03 4.00512E-03 4.85404E-03
c          5.64282E-03 6.42776E-03 8.03196E-03 9.59904E-03
```

APPENDIX C

MCNP INPUT DECK: SIMPLIFIED HOMOGENOUS MODEL

```
ML-1 Model: Homogenized Core - ENDF/VII
c *** MCNP6.2 Model developed by B. Passons, Texas A&M University ***
c ***********************************************************
c ************************* CELLS ***************************
c ***********************************************************
   1    1  -1.0556 -1 2 -3
   2    0        1 :-2 :3

c ********************************************************
c ********************** SURFACES  **********************
c ********************************************************
   1       pz 27.94
   2       pz -27.94
   3       cz 27.94

c ********************************************************
c ********************** MAT/PHYS  **********************
c ********************************************************
mode  n
kcode 10000 1.000000 50 500
ksrc  0.000000 0.000000 0.000000
m1       8016.70c  -0.48760
         92235.70c -0.42670
         92238.70c -0.03212
         1001.70c  -0.05358
mt1 lwtr
imp:n   1          0           $ 1, 2
f4:n 1
e4   1.00E-10 1.00E-09 1.00E-08
    1.00E-07 1.00E-06 1.00E-05
    1.00E-04 1.00E-03 1.00E-02
    1.00E-01 1.00E+00 1.00E+01 2.00E+01
fm4 2.5823E17 $ P_th(3.4) x 3.1E16 x 2.45 = 2.5823E+17 n/s flux multiplier
```

APPENDIX D

PYTHON SCRIPT: MAPPING ENERGY AND CENSUS DATA

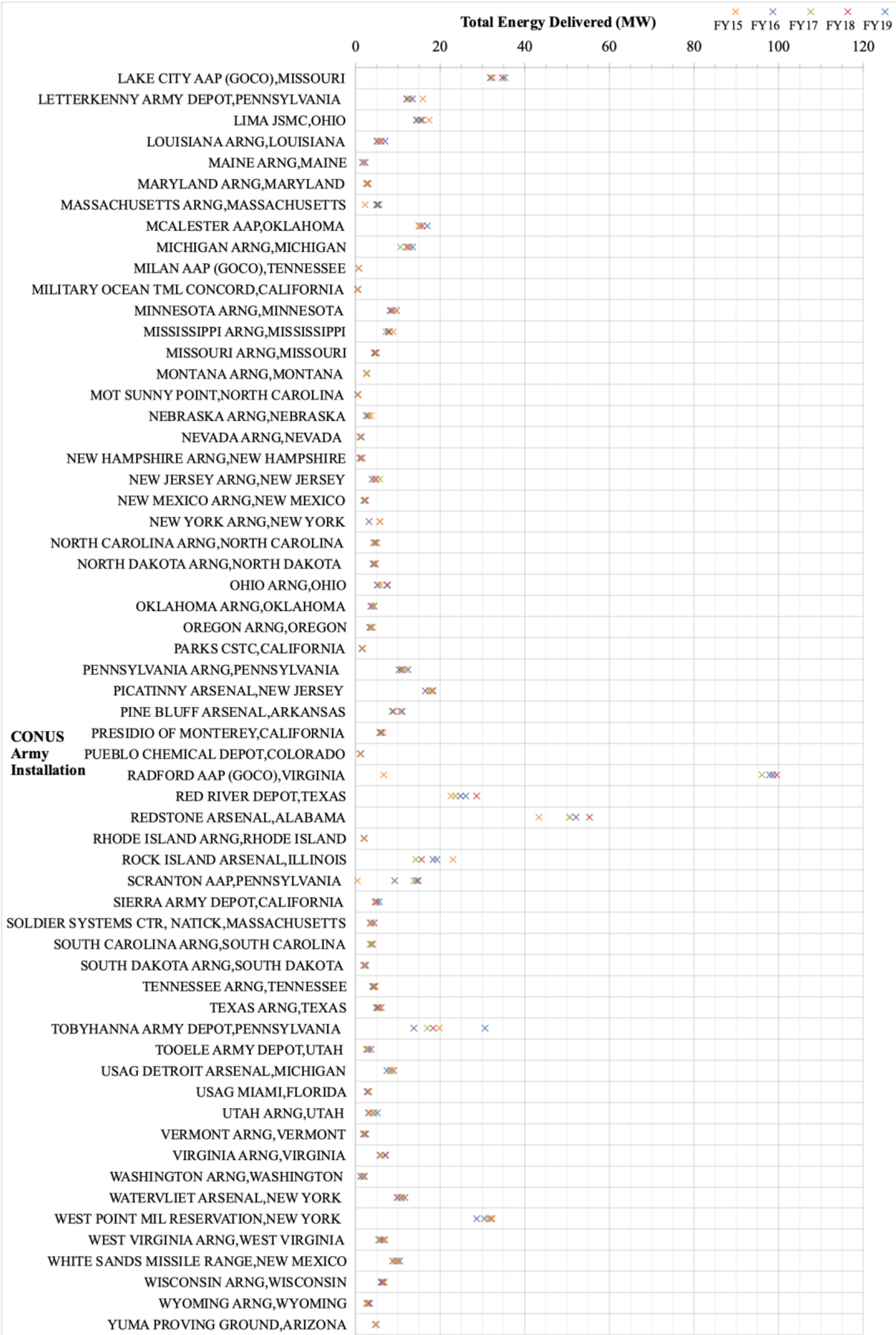
```
# Import dependencies
import sys
from osgeo import ogr
from shapely.wkb import loads
from shapely.geometry import *
from random import uniform
import pyarrow.parquet as pq
import pandas as pd
import numpy as np
import geopandas as gpd
import matplotlib.pyplot as plt
import geoviews as gv
import geoviews.tile_sources as gvts
from geoviews import dim, opts
import datashader as ds, datashader.transfer_functions as tf, numpy as np
from datashader import spatial
gv.extension('bokeh')

# Convert installation, state to geocoordinates (lat,long)
from opencage.geocoder import OpenCageGeocode

# Free API key goes here:
key = "****************************"
geocoder = OpenCageGeocode(key)

locations_df = pd.read_excel(r'./Desktop/Energy Requirements.xlsx')

locations = locations_df["location"].values.tolist()

latitudes = []
longitudes = []

for location in locations:
	result = geocoder.geocode(location, no_annotations="1")

	if result and len(result):
		longitude = result[0]['geometry']['lng']
		latitude = result[0]['geometry']['lat']
	else:
		longitude = "N/A"
```

```
            latitude = "N/A"

        latitudes.append(latitude)
        longitudes.append(longitude)

locations_df["latitudes"] = latitudes
locations_df["longitudes"] = longitudes

locations_df.to_excel(r'./Desktop/Research/Geocoded Energy Requirements.xlsx')

# Import census data
df=pq.read_table('./Desktop/Research/census_data.parquet/ab2ea7a1a07e499bb0bba81e
7f9dd98.parquet').to_pandas()
# Installation information
locations = pd.read_excel(r'./Desktop/610/Geocoded Energy Requirements.xlsx')
locations_gv_points = gv.Points(locations, ['longitudes', 'latitudes'],
                    ['installation','state','area',
                    'energy_mw','energy_Bbtu','location','color'])
from bokeh.models import HoverTool
tooltips = [('Location', '@location'),
        ('FY19 Energy Requirements', '@energy_Bbtu{0.00 a}Bbtu'),
        ('Converted Energy Requirements', '@energy_mw{0.00 a}MW'),
        ('Installation', '@installation'),
        ('State', '@state'),
        ('Longitude', '$x'),
        ('Latitude', '$y'),
        ]
hover = HoverTool(tooltips=tooltips)
print(locations)

#Setup plot
energy_plot = (gvts.CartoLight * locations_gv_points).opts(
   opts.Points(width=1200, height=700, alpha=0.3,
          xaxis=None, yaxis=None,
          size=('energy')))
from bokeh.models import HoverTool
tooltips = [('Location', '@location'),
        ('FY19 Energy Requirements', '@energy_Bbtu{0.00 a}Bbtu'),
        ('Converted Energy Requirements', '@energy_mw{0.00 a}MW'),
        ('Installation', '@installation'),
        ('State', '@state'),
        ('Longitude', '$x'),
        ('Latitude', '$y'),
        ]
```

```
hover = HoverTool(tooltips=tooltips)
energy_plot = (gvts.CartoLight * locations_gv_points).opts(
   opts.Points(width=1200, height=700, alpha=0.3,
            color=dim('color'), hover_line_color='black',
            line_color='black', xaxis=None, yaxis=None,
            tools=[hover],size=np.sqrt(dim('energy_mw'))*5,
            hover_fill_color=None, hover_fill_alpha=0.5))
# Display plot
pop_energy = dynspread(datashade(points, cmap=cm(Greys9,0.2),
element_type=gv.Image))
gts.EsriImagery() *population*locations_gv_points*
gts.StamenLabels().options(level="annotation")
```

APPENDIX E

PLOTS: CONUS ARMY INSTALLATION ENERGY CONSUMPTION DATA



Total Energy Delivered (MW)
FY15
FY16
FY17
FY18
FY19
0
20
40
60
80
100
120
CONUS Army Installation
LAKE CITY AAP (GOCO),MISSOURI
LETTERKENNY ARMY DEPOT,PENNSYLVANIA
LIMA JSMC,OHIO
LOUISIANA ARNG,LOUISIANA
MAINE ARNG,MAINE
MARYLAND ARNG,MARYLAND
MASSACHUSETTS ARNG,MASSACHUSETTS
MCALESTER AAP,OKLAHOMA
MICHIGAN ARNG,MICHIGAN
MILAN AAP (GOCO),TENNESSEE
MILITARY OCEAN TML CONCORD,CALIFORNIA
MINNESOTA ARNG,MINNESOTA
MISSISSIPPI ARNG,MISSISSIPPI
MISSOURI ARNG,MISSOURI
MONTANA ARNG,MONTANA
MOT SUNNY POINT,NORTH CAROLINA
NEBRASKA ARNG,NEBRASKA
NEVADA ARNG,NEVADA
NEW HAMPSHIRE ARNG,NEW HAMPSHIRE
NEW JERSEY ARNG,NEW JERSEY
NEW MEXICO ARNG,NEW MEXICO
NEW YORK ARNG,NEW YORK
NORTH CAROLINA ARNG,NORTH CAROLINA
NORTH DAKOTA ARNG,NORTH DAKOTA
OHIO ARNG,OHIO
OKLAHOMA ARNG,OKLAHOMA
OREGON ARNG,OREGON
PARKS CSTC,CALIFORNIA
PENNSYLVANIA ARNG,PENNSYLVANIA
PICATINNY ARSENAL,NEW JERSEY
PINE BLUFF ARSENAL,ARKANSAS
PRESIDIO OF MONTEREY,CALIFORNIA
PUEBLO CHEMICAL DEPOT,COLORADO
RADFORD AAP (GOCO),VIRGINIA
RED RIVER DEPOT,TEXAS
REDSTONE ARSENAL,ALABAMA
RHODE ISLAND ARNG,RHODE ISLAND
ROCK ISLAND ARSENAL,ILLINOIS
SCRANTON AAP,PENNSYLVANIA
SIERRA ARMY DEPOT,CALIFORNIA
SOLDIER SYSTEMS CTR, NATICK,MASSACHUSETTS
SOUTH CAROLINA ARNG,SOUTH CAROLINA
SOUTH DAKOTA ARNG,SOUTH DAKOTA
TENNESSEE ARNG,TENNESSEE
TEXAS ARNG,TEXAS
TOBYHANNA ARMY DEPOT,PENNSYLVANIA
TOOELE ARMY DEPOT,UTAH
USAG DETROIT ARSENAL,MICHIGAN
USAG MIAMI,FLORIDA
UTAH ARNG,UTAH
VERMONT ARNG,VERMONT
VIRGINIA ARNG,VIRGINIA
WASHINGTON ARNG,WASHINGTON
WATERVLIET ARSENAL,NEW YORK
WEST POINT MIL RESERVATION,NEW YORK
WEST VIRGINIA ARNG,WEST VIRGINIA
WHITE SANDS MISSILE RANGE,NEW MEXICO
WISCONSIN ARNG,WISCONSIN
WYOMING ARNG,WYOMING
YUMA PROVING GROUND,ARIZONA