AN ABSTRACT OF THE THESIS OF

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Abstract approved:____

Andrew Klein

The NKUA1 is a Small Fission Surface Power (SFSP) space reactor intended for use in upcoming missions to Mars and the moon between the years 2020-2030. The concept of the reactor was created by Dr. Lee Mason and his research team in a joint effort between the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA); complete design of the reactor core was developed by Dr. David Poston at Los Alamos National Laboratories. The Monte Carlo Neutron-Particle (MCNP) Transport code script of the NKUA1 core was used to perform a variety of criticality safety related calculations. The analysis was conducted to compare the effectiveness of control rods versus control drums in providing a safe shutdown configuration. The control drums proved to be more efficient in delivery of negative reactivity, conserved more space than the control rods, and have been found to be highly effective in space reactors. A safety analysis was also performed on the NKUA1 concerning its function in specific accident scenarios. In each accident scenario, the reflector and control drums were removed and the reactor was enclosed in a common naturally occurring material. The reactor was found to be safely shut down in each scenario, with acceptable shutdown margins being greater than \$10.00.

The Control and Safety Analysis of a Small Fission Surface Power Reactor

by

Noel B. Nelson

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Committee Member, representing Nuclear Engineering

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Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Noel B. Nelson, Author

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1 Introduction

The NKUA1 core underwent criticality analysis for two major objectives. First, the old control system (control rods) was compared to the new control system (control drums) in terms of ability to shut down the reactor. Second, a safety analysis was performed to determine the ability of the reactor to shut down during seven prescribed accident scenarios.

2 Survey of Literature

Space reactors have been in use for a number of decades by the National Aeronautics and Space Administration (NASA) and the Russian space program. It is of interest to review the old generation of space reactors before looking at the newer designs. Two space reactors in early space programs were the SNAP10A (USA design) and the TOPAZ reactor (Russian design).

2.1 SNAP 10A

The SNAP 10A was developed in the 1960s and to date is the only U.S. reactor that has been flight tested which took place in 1965[1]. The reactor was graded for a power output of 500 watts electrical, and it had a one year minimum operating lifetime. The reactor contained 37 fuel pins made of a uranium zirconium hydride mixture with some of the pins loaded with a small amount of the burnable poison samarium oxide (Sm_2O_3). The core was designed with a beryllium (Be) reflector around its perimeter with voided cavities for control drums. The void was used to control the reactor by neutron leakage. When the reactor was started the four Be control half-drums were rotated adjacent to the core to reduce the leakage bringing the reactor to a critical state. Afterwards, the reactor was supposed to run at a static steady state power with no need for dynamic control to the end of its lifetime. A rendering of the core of the SNAP 10A core and control system is shown in Figure 1.[2]

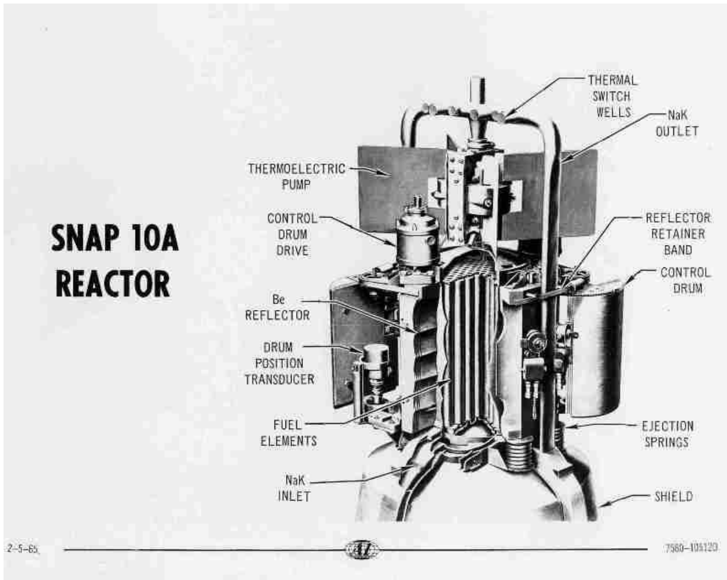

Figure 1: A schematic of the SNAP 10A core with semi-cylindrical control drums and motor systems.[2]

The SNAP 10A was cooled by liquid sodium potassium (NaK). The coolant was circulated in a loop through the core by a thermoelectric powered pump. Power conversion was accomplished by a thermoelectric converter that directly transforms heat into electricity. The process of thermoelectric conversion will be described later, as it is used in the new design for the same purpose. The coolant dumps heat solely to the thermoelectric converters with no apparent heat exchangers used in the coolant loop.[2]

2.2 TOPAZ-2

The TOPAZ reactor series is a bit different from the SNAP 10A reactor. The first TOPAZ was constructed during the 1960s in Soviet Russia.[1] More is known about the TOPAZ-2 reactor design which was sold to the United States in 1989. The TOPAZ-2 reactor had a power output between 4.5 and 5.5 kilowatts electrical and a 3-5 year design operating lifetime.[3]

The TOPAZ-2 core was complex. It had an epithermal reactor fueled by uranium and moderated by zirconium hydride (ZrH1.85) similar to the SNAP10A, but the control geometry and the conversion system are very different. The core consisted of 37 thermionic fuel elements (TFE) which were specialized cells containing the fuel and the power conversion system together. Thermionic cells are cylinders with a uranium oxide (UO_2) center (96% enriched in uranium-235 (U-235)), a monocrystal molybdenum (Mo) emitter with a niobium coating for strength, an interelectrode gap, a Mo crystal collector sprayed with an aluminum oxide (Al_2O_3) electrical insulation, and a steel tube for the coolant to collect residual heat. Approximately, fifteen percent of the heat produced by core fissions is converted to electrons by the emitter and collected to be used for power. The residual waste heat is carried by the NaK coolant and is transported by an electromagnetic pump. The heat is then removed via a heat exchanger exposed to the space environment.[3]

The TOPAZ-2 was controlled by a rotating control drum system with full cylinders instead of half drum reflectors used in the SNAP 10A. There were 12 control drums arranged in a circle around the perimeter of the reactor. The drums were cylinders of Be with an 120 degree section of boron carbide (B_4C) absorber. The rotation of the drums controlled the neutron reactions within the core by absorbing fringe neutrons with the B_4C section or by reflecting them with the Be section. A diagram of the TOPAZ-2 core cross-section and a schematic of the TFE are displayed in Figure 2.[3]

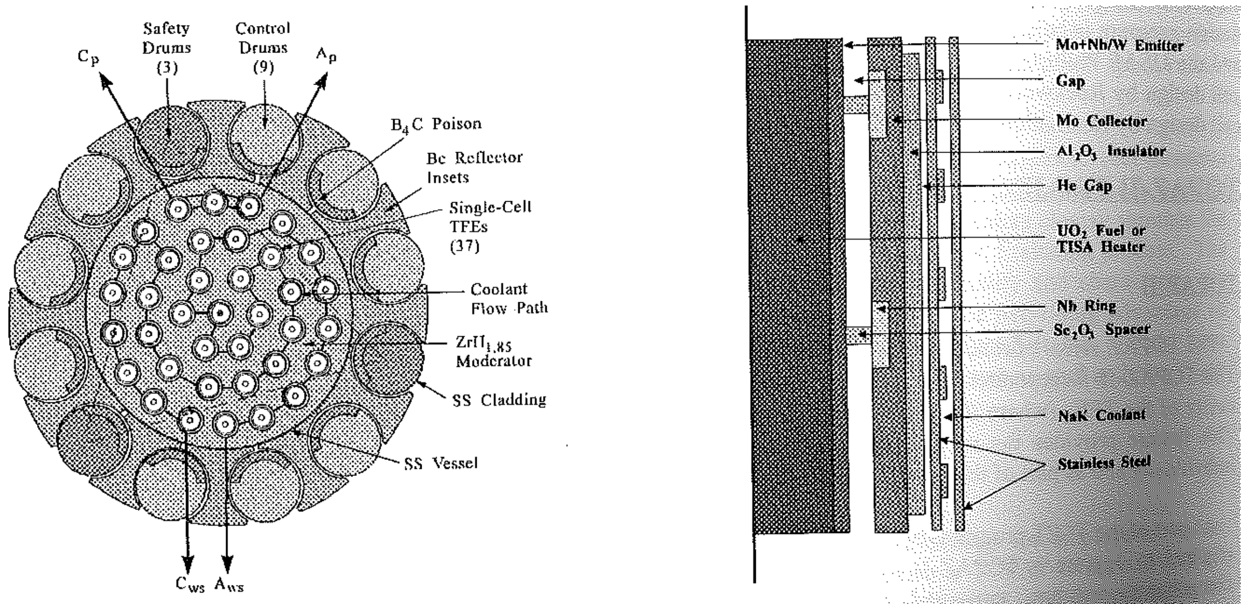

Figure 2: A schematic of the TOPAZ-2 reactor (left) and a diagram of a TFE (right).[3]

3 NKUA1

The new reactor design, the NKUA1 incorporates elements of both reactors. It uses the control drum style of the TOPAZ-2 reactor, thermoelectric power conversion similar to the SNAP 10A, and NaK coolant. However there is no traditional coolant loop as used in the old generation of space reactors. The NKUA1 uses a more recently developed technology called heat pipes to accomplish coolant transport in half the space of the old loop.[3]

The Small Fission Surface Power (SFSP) reactor, designated NKUA1, was designed by Dr. David Poston and his research team at Los Alamos National Laboratory. The reactor was designed originally to power secondary systems on board spacecraft like an Europa Orbiter for upcoming lunar and Mars missions. It is designed to have an output of approximately 1 kilowatt electrical and a 15 year operating lifetime. It is also designed to work in both low gravity (orbit) and higher gravity (planetary) environments. A graphic of the Europa orbiter (shown in Figure 3) displays the basic layout of the spacecraft with the sensitive instruments and the engine at the rear and the nuclear reactor at the tip of the nose.[4]

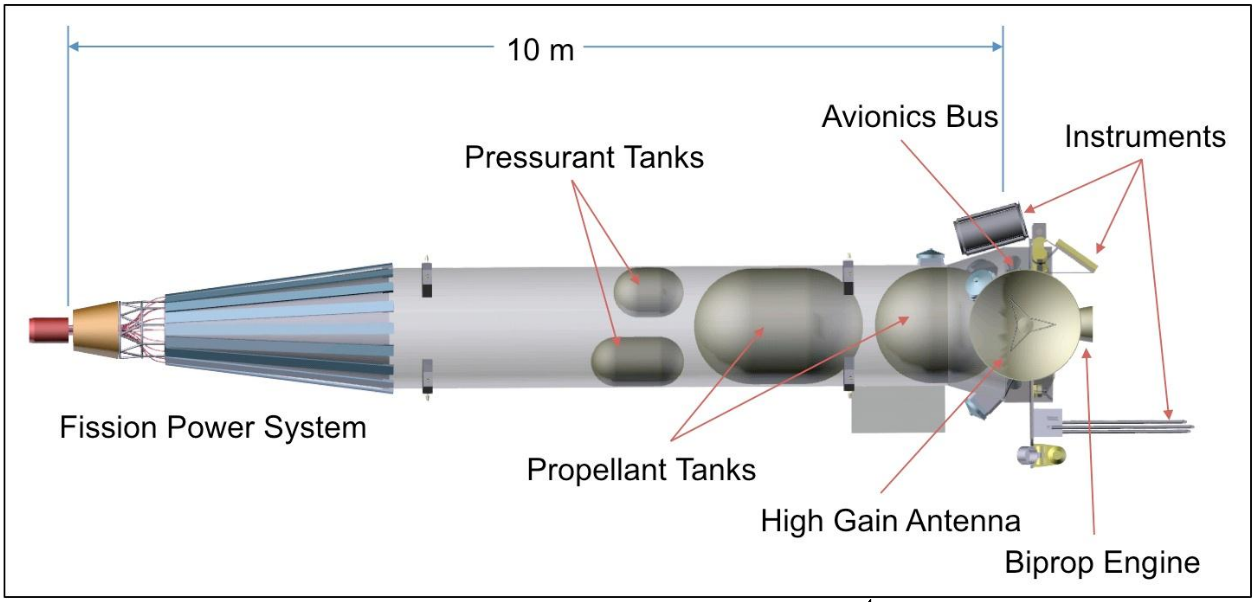

Figure 3: A schematic of a typical Europa Orbiter class spacecraft.[4]

The core of the reactor contains a traditional uranium oxide (UO_2) fuel enriched to 93% U-235. The original design study suggested that the fuel be a uranium molybdenum (UMo) compound fuel of the same enrichment of U-235 for several reasons. First, a report by the International Atomic Energy Agency (IAEA) states that UMo fuel has a higher density of overall Uranium (8 g/cm3) in a tighter crystal structure. The same mass of U-235 to power the core with less volume allowing the reactor to be smaller. (IAEA, 11)[5] Yet, with the same amount of U-235 in the fuel, the core neutron physics should be very similar. Second, the reactor will run at temperatures above 1200 degrees kelvin, which would cause severe thermal stress on the fuel. UMo fuel is much more ductile than UO_2, meaning UMo fuel is less likely to crack during thermal expansion. The prototypic fuel is not yet certified by the Nuclear Regulatory Commission (NRC), but it will likely be certified within the next decade

3.1 Heat Pipes

The reactor is cooled by a system of heat pipes. Heat pipes are generally vacuum sealed pipes with capillary lined walls, filled with a working fluid, and generally have cooling fins attached to one end. The working fluid for the NKUA1 is sodium potassium (NaK). The NKUA1 heat pipes are a modified design that take heat from the heat source, the core, and transfers it to the heat sink, the thermoelectric converters by conduction heat transfer through a saddle system instead of cooling fins. Any residual heat is then radiated to the environment, either to cold space or atmosphere by a radiator plate. A model of the system of heat pipes for the NKUA1 reactor is shown below in figure 4.[4]

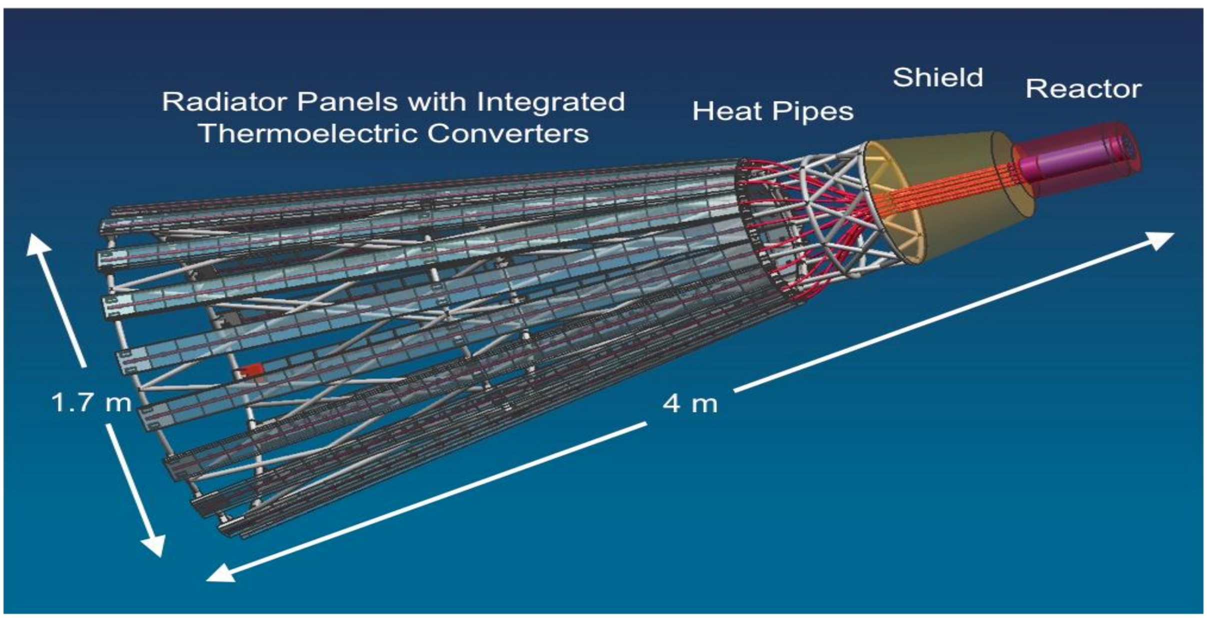

Figure 4: A schematic of the SFSP reactor (NKUA1) and its major components.[4]

In general, heat pipe systems work by a systematic form of convective heat transfer. The heat source evaporates the working fluid and it transfers heat across the fluid down the pipe to the heat sink. After heat is removed from the fluid, the cooled liquid returns to the heat source by using the capillary structures on the pipe walls called the wick. This movement through the narrow wick grooves is called capillary action. By capillary action, the effects of low gravity are countered making the heat pipe system efficient in space environments. Figure 5 shows the heat transfer process of a common heat pipe device.[6]

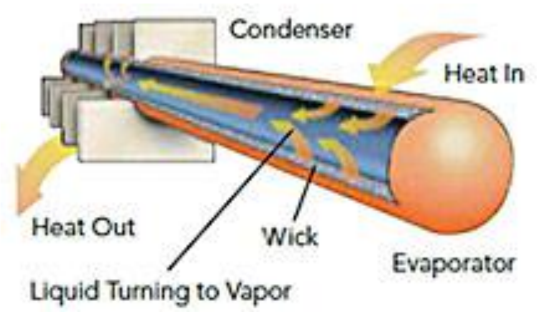

Figure 5: a schematic of a heat pipe[7]

3.2 Thermoelectric Conversion

As can be seen in Figure 4, the generation of electrical power for the NKUA1 is accomplished by thermoelectric power converters. Thermoelectric converters (TEC) work by use of two different semiconducting plates between a heat source and sink. The high temperature heat pipes provide the source while the sink is a radiator plate that dissipates waste heat. The temperature differential across the two semiconducting plates produces a direct current (DC) to power systems on board the spacecraft.[7] This technology is well suited to low gravity environments and has been in use since the 1960s for radioisotope thermoelectric generators (RTG).[1] A sketch of the TEC technology projected for use with the NKUA1 is shown below in Figure 6.

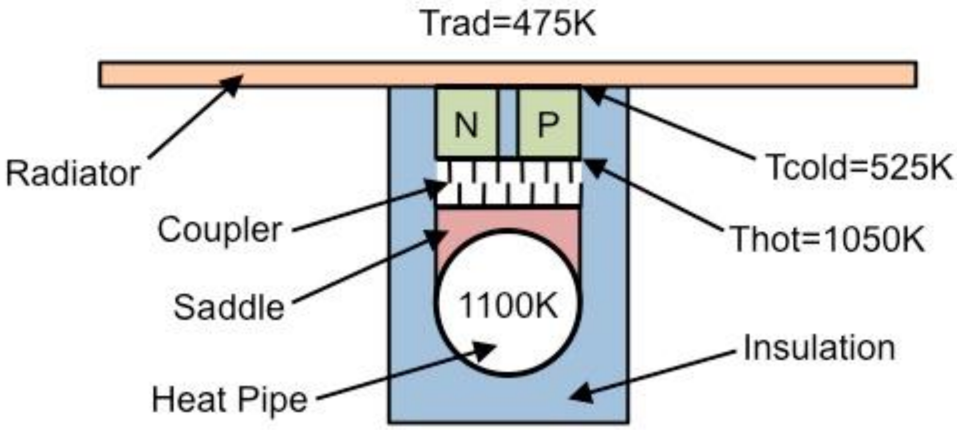

Figure 6: A schematic of the thermoelectric converter and the projected temperatures of the major components.[4]

3.3 Core Geometry and Control Components

The reactor core of the NKUA1 is the focus of this paper in order to perform critical safety criticality analyses for proper shutdown and control of the reactor. The NKUA1 has 163 fuel pins or small cylindrical fuel rods of about 0.6 cm diameter and and a height of 48 cm. There are three beryllium reflectors: two axial (bottom and top) and a radial reflector along the perimeter of the fuel. Before describing the control mechanisms of the reactor, it is important to note that there have been modifications to the original reactor control design.

The old control design suggested by Lee Mason et al. consisted of two components: a large control rod in the center of the reactor and a sliding poison shell around the perimeter of the reactor. The two components were to be made of B_4C, but the sliding sleeve called the "safety sleeve" was intended to be the component with the highest dollar value of negative reactivity. (Mason)[4] Reactivity is the deviation of the core multiplication factor from its critical value k=1." For example, an absorber like boron carbide creates negative reactivity when the absorber is inserted (less neutrons cause fissions making $k<1$) and positive reactivity when it is removed (more neutrons cause fissions making $k>1$). (D+H)[8]

The safety sleeve would have introduced the highest amount of negative reactivity of the old control concepts, so it would have been used for major reactor transient situations, such as reactor startup, shutdown, and certain accident scenarios requiring a SCRAM or immediate shutdown. The central control rod was designed to control the reactor during operation and account for burnup (loss of fuel from use), and changing power requirements. A sketch of the old core design and its safety components is shown in Figure 7. All together the control system is efficient, and it is partially compared to the new design in this paper.

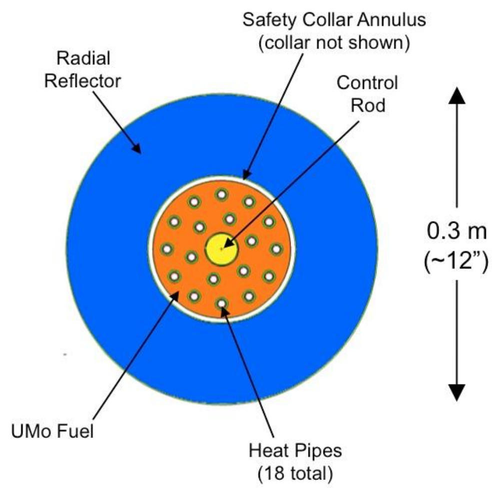

Figure 7: A diagram of the NKUA1 core, old design.[4]

A relatively compact design that later proved to be more efficient was created by Dr. Poston and his research team. The design is composed of six control drums embedded into the radial reflector grid. The drums are cylinders of beryllium approximately 17 cm in diameter and 48 cm long with a crescent sliver of B_4C covering one side of the control rod. A diagram of the design composed from the MCNP code in VISED is displayed in Figure 8.

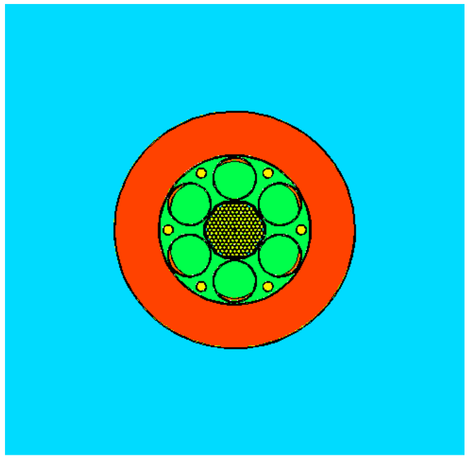

Figure 8: A diagram of the NKUA1 reactor core, new design (generated by VISED)

The control drums are powered by small motors and rotate, thereby allowing portions of the poison face to be exposed to neutrons exiting the core. The control drums cover both small transients (power levels and burnup), and large transients (shutdown, startup, and accidents) accomplishing the goals of the two components in the old design with one component. Space is conserved by removing one component, and more so by the positioning of the control drums within the radial reflector.

In a larger space reactor of similar design, Dr. Poston chose rotating control drums over a sliding poison sleeve. Control drums were chosen for two reasons: heritage and reactivity feedback. The rotating control drum system has been in use longer than the sliding poison sleeve. The poison sleeve is more vulnerable to thermal stresses than the drums. As the poison (B_4C) heats up, it loses density, allowing more neutrons to reach the reflector and return to the system raising power.[9]

3.4 MCNP Background

Several tests of the NKUA1 reactor control system were conducted using a code called the Monte Carlo Neutron Particle Transport code (MCNP). The code was developed in 1973 as an all-purpose particle transport code for neutrons, photons, electrons, and coupled combinations of the three. Since then four new versions of the code have been developed; MCNP5 was the version used in this study. MCNP works by defining geometry in terms of cells and surfaces. Surfaces designate boundaries, while cells define the volumes between surfaces.

MCNP is a stochastic code that keeps track of a number of particles determined by the user through each interaction with the atoms of materials defined in cells until the particle either escapes from the system or is absorbed. Probabilities of interactions are determined by the scientific standard cross-sections defined in the Evaluated Nuclear Database Files (ENDF) created by Brookhaven National Laboratory. The types of possible particle interactions are then determined according to the respective material cross-sections and are chosen by a random number generator.

The code is useful for many applications including dosimetry and radiological medical science as well as nuclear reactor design. MCNP is best known for its efficiency in neutron applications. In the case of reactor design, the code can be used to calculate the criticality of a reactor with a given geometry. That type of calculation is called k-code. MCNP calculations were used in this study to determine the state of the NKUA1 reactor under the conditions prescribed in the materials and methods section and perform criticality tests during seven accident scenarios, particularly crash scenarios.

MCNP works by keeping track of the number of neutrons produced by fission, the number absorbed that produce fissions, and the number that are lost from the problem including those that either leak out of the system or are absorbed without fissioning. Keff is essentially an estimation of the “mean number of fission neutrons produced in one generation per fission neutron started.” A keff value less than one means the system is subcritical and subsequent neutron populations are decreasing. A keff value of one is a critical system where the neutron population is sustained. A keff value greater than one defines a supercritical system in which the neutron population is increasing every generation.

That neutron generation is counted as a keff cycle in MCNP. A user desired number of keff cycles are then calculated and averaged at the end by first half of the cycles, second half, and final result (average of the first and second halves). With those averages a confidence interval is drafted from the standard deviations of all the keff cycles. The final result value and confidence interval was used for all tests in this study.[10]

4 Materials and Methods

After receiving the reactor Monte Carlo N-Particle Transport Code (MCNP) input file (called NKUA1) from Dr. David Poston of Los Alamos National Laboratory, the criticality (k-code) reactor code was tested with an initial run. Before the initial run, a number of cross-sections had to be converted from specialized 30c cross-sections to normal isotope cross-sections available to the code library. After the appropriate cross-section conversions, Dr. Poston's code ran successfully producing a supercritical multiplication factor (k-value).

The reason for the supercritical k-value was caused by the control drums being rotated all the way inward. This is not a configuration that would be found in true operation. A central control rod was planned for the NKUA1 in the original NASA and DOE reports, so one was designed for comparison against the new control drum system. A control rod was designed by duplicating fuel rod specifications and replacing the inner gap, fuel sleeve, and fuel pellet with B_4C. A number of control rod configurations (shown in Figures 9-14) were tested until a safe k-value was produced. Next, the reflector's efficiency was tested by replacing the control drum reflectors with void yielding a new k-value. This was done to test the reactor design response to the absorber poison on the alternate sides of the reflectors which approximates the rotation of the drums to shut-down safe position.

```
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 4 4 4 4 4 4 9 9
9 9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 4 5 4 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9 9
9 9 4 4 4 4 4 4 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
```

Figure 9: One Central Rod control rod configuration (CRC)
5=control rod, 4=fuel rod, and 9=void

```
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 4 4 4 4 4 4 9 9
9 9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 4 5 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 5 4 5 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 5 4 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9 9
9 9 4 4 4 4 4 4 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
```

Figure 10: Four Rods in 1st Ring CRC
5=control rod, 4=fuel rod, and 9=void

```
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 4 4 4 4 4 4 9 9
9 9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 4 4 4 4 4 5 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 4 5 4 5 4 5 4 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 5 4 4 4 4 4 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9 9
9 9 4 4 4 4 4 4 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
```

Figure 11: One Central Rod
and Four Rods in 2nd Ring CRC
5=control rod, 4=fuel rod, and 9=void

```
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 4 4 4 4 4 4 9 9
9 9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 4 4 4 4 5 4 4 4 4 4 4 4 9
9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 5 4 4 5 4 4 5 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9
9 4 4 4 4 4 4 4 5 4 4 4 4 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9 9
9 9 4 4 4 4 4 4 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
```

Figure 12: One Central Rod
and Four Rods in 3rd Ring CRC
5=control rod, 4=fuel rod, and 9=void

```
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 4 4 4 4 4 4 9 9
9 9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 5 5 5 4 4 4 4 4 4 9
9 9 4 4 4 4 4 5 5 5 4 4 4 4 4 9 9
9 4 4 4 4 4 4 5 5 5 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9 9
9 9 4 4 4 4 4 4 4 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
```

Figure 13: Nine Rod Solid Box CRC
5=control rod, 4=fuel rod, and 9=void

```
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 4 4 4 4 4 4 9 9
9 9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 9 4 4 4 4 4 4 4 4 4 4 9
9 9 9 9 9 4 4 4 5 4 4 4 4 4 4 4 9
9 9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 9 4 4 4 4 4 4 4 4 4 4 4 4 4 9
9 9 4 4 4 4 4 5 5 5 4 4 4 4 4 4 9
9 9 4 4 5 4 4 5 5 5 4 4 5 4 4 9 9
9 4 4 4 4 4 4 5 5 5 4 4 4 4 4 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9
9 4 4 4 4 4 4 4 4 4 4 4 4 9 9 9 9
9 4 4 4 4 4 4 4 5 4 4 4 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9
9 4 4 4 4 4 4 4 4 4 9 9 9 9 9 9 9
9 9 4 4 4 4 4 4 4 9 9 9 9 9 9 9 9
9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9
```

Figure 14: Nine Rod Solid Box and Four Rods in 3rd Ring CRC
5=control rod, 4=fuel rod, and 9=void

Finally, seven accident scenarios were simulated in the k-code to test the safe operation of NKUA1 during a failed launch or a crash landing in various environments. In all of the scenarios, it was assumed that the reflectors would fall off (a standard space reactor "failsafe response") and be replaced by environmental materials. Also, it was assumed that the reactor would be covered in a sphere with a thickness of twenty mean free path lengths of the environmental substance to ensure that the full effects of neutron reflection in that material were observed. The required sphere thickness under this assumption was calculated using equations (1-6) for all seven accident scenarios. Furthermore, the sphere radius was calculated and input into the code by adding the longer axial length of the reactor cylinder (426 cm) to the sphere thickness as shown by equation (7).

$$\bar{A} = \sum_{i=1}^{n} af_i A_i \quad (1)$$

$$N_{mix} = \frac{\rho_{mix} \cdot A_v}{\bar{A}} \quad (2)$$

$$N_i = af_i \cdot N_{mix} \quad (3)$$

$$\Sigma_i = N_i \cdot \sigma_i \quad (4)$$

$$\Sigma_t = \sum_{i=1}^{n} \Sigma_i \quad (5)$$

$$t_{sphere} = \frac{20}{\Sigma_t} \quad (6)$$

$$r_{sphere} = t_{sphere} + Z_{bound} \quad (7)$$

The seven accident scenarios considered are burials of the reactor system in the following substances: freshwater, wet sand, seawater, wet sand and seawater mixture, dry sand, lunar regolith (soil), and Martian soil. The sphere thicknesses input into the code are tabulated for each case in Table 1.

Table 1: Sphere thicknesses for each accident scenario.

Accident Scenario	Mixture Density, g/cm^3 (ρ_{mix})	Sphere Thickness, cm (t_{sphere})
Freshwater	1	5.8
Wet Sand	2.056	3.98
Seawater	1.023	5.72
Wet Sand and Seawater	2.064	5.72*
Dry Sand	1.69	112
Lunar Regolith	1.65	150*
Martian Soil	1.8*	150*

*Note: wet sand and seawater were kept the same as pure sea water's thickness to save time and be conservative. Also, the Martian soil and lunar regolith sphere thicknesses were estimated off of dry sand's thickness with a margin of about 40cm added to it to be conservative because there were too many components to make a formal calculation.

5 Results

MCNP k-code was used to calculate multiplication factors for all six of the control rod configurations shown in figures 9-14. The first ten cycles of each simulation were discarded as inactive cycles to allow for greater stability in the neutron populations and reduce variance in the statistics. The average keff and standard deviations in the first four configurations were calculated outside the program because the program was interrupted at eleven cycles. The code was interrupted because it was obvious by inspection of the displayed keff that the reactor was still supercritical. The fifth and sixth configurations ran all 110 cycles. Of those, the active cycles were averaged and a standard deviation calculated for uncertainty by the MCNP code.

The average keff value wass subtracted from a keff value of one (critical) to calculate the shutdown margin. Then, this value was divided by the kinetics model delayed neutron fraction, beta, for Uranium-235 (BETA=0.0065) to produce shutdown margins in the standard unit of reactivity, dollar units. The delayed neutron fraction (beta) is the ratio of delayed neutrons emitted from fission daughter products undergoing neutron decay to those emitted promptly from fission reactions. Shutdown margin represents the ability of a transient like a control rod insertion to shutdown the reactor, and therefore only produces values when keff values are less than one. Because the first few configurations did not produce keff values less than one, the positive distance above one was calculated as excess reactivity instead of shutdown margin. The cold clean core startup reactor reference value and the reactivity data for all six control rod configurations can be found in Table 2. The control rod configurations are shown in Figures 9 through 14.

Table 2: Reactivity data from MCNP simulations for each control rod configuration.

Control Rod Config.	keff	Shutdown Margin ($)	Excess Reactivity ($)
Cold Clean Core	1.06389±0.00071	0	9.83
1 Central Rod	1.04870±0.0073	0	7.49
4 Rods in 1st Ring	1.01878±0.0086	0	2.89
1 Central Rod and 4 Rods in 2nd Ring	1.00870±0.0094	0	1.34
1 Central Rod and 4 Rods in 3rd Ring	1.00803±0.0096	0	1.24
9 Rod Solid Box	0.97763±0.00065	-3.44	0
9 Rod Solid Box + 4 Rods in 3rd Ring	0.93636±0.00067	-9.79	0
Reflector Voided	0.75792±0.00058	-37.24	0

After an adequate control rod configuration was found such that the reactor was subcritical, safety analysis of the design was conducted by running the seven crash test scenarios with the assumptions described earlier in the materials and methods section. Because the control rods were less effective than the control drums, no control rods were inserted. Instead, the ejection safety feature of the control drums was carried out. All cycles were carried out for each test, and the same process for obtaining the data in Table 2 was repeated to transform the average keff data into change in reactivity values for all seven accidents in Table 3.

Table 3: Reactivity data from MCNP simulations for each accident scenario.

accident #	Type	keff	Shutdown Margin ($)
REF	Poison segments exposed	0.75792±0.00058	-37.24
1	Freshwater	0.87701±0.00079	-18.92
2	Wet Sand	0.92816±0.00083	-11.05
3	Seawater	0.85430±0.00069	-22.42
4	Wet Sand and Seawater	0.92056±0.00073	-12.22
5	Dry Sand	0.82908±0.00065	-26.30
6	Lunar Regolith	0.81532±0.00056	-28.41
7	Martian Soil	0.83001±0.00061	-26.15

The NKUA1 reactor passed all the accident scenarios with keff values below 0.95 and shutdown margins above $10.00 representing successful reactor shutdown in each case. The reactor is safe under all foreseeable launch failure accident scenarios.

6 Discussion

The original DOE and NASA design report specified that the reactor required a central control rod and a sliding poison (neutron absorber) sleeve. The new design suggested by Dr. Poston used a rotating control drum system embedded in the radial reflector for control. The new control system was tested by filling the control drum reflectors with empty space leaving the poison crescent of the drums exposed to neutrons leaving the fuel. Essentially this represented the control drum poison crescent being rotated inwards to the shutdown position. The 110 cycles of MCNP produced a final subcritical keff value of 0.75792±0.00058 and resulted in simulating a successful shutdown.

It should be noted that the cold clean core configuration had $9.83 of excess reactivity. That configuration consisted of the control drum poison crescents rotated completely out, therefore only beryllium reflecting material was facing the core. This excess reactivity demonstrates that control drums were never meant to be utilized solely for shutdown and startup. They could be used for fine tuning the reactivity for the reactor during operation. As a result the control drums would never be fully rotated to the inside without at least a small part of the poison facing the core.

A control rod system was designed for comparison against the new control drum system. The control rod system was designed with the supercritical baseline for simplicity rather than redefining the control drum geometry or removing it. First a central control rod was inserted (configuration 1) with the reflectors turned all the way inwards (representing a static reflector) to test shutdown margin. It was not enough to shut down the reactor or make it subcritical, so the number of control rods was increased in subsequent configurations. The first four configurations: One Central Rod and the increasing perimeter ring formations of the four additional rods, proved to be insufficient to shut down the reactor as well. Refer to the Materials and Methods section for more details of the control rod configurations.

In configuration five, a three by three array of control rods in the center position, produced a shutdown margin of $3.44. This was a sufficient amount of reactivity to shut down the reactor in theory, but in application it is better to have a larger margin for error. Also, the shutdown margin is scarcely larger than one control rod worth (~$2.25) which means that if a control rod failed to insert, the reactor may not shut down. Finally, with four more rods inserted in configuration six, a reasonable shutdown margin of $9.79 was produced. The control rods were much less effective in this case as evidenced by the need for fourteen rods to accomplish a fourth of the shutdown margin created by the control drums. It is likely that in the original design, the poison sleeve would have contained most of the reactivity needed to shut down and start up the reactor. Also, control rods are bulky and take up more space than control drums because they require extra axial length for fuel followers or the sacrifice of fuel space radially. Overall the rotating control drums on the perimeter were much more effective than the control rods inserted in the center of the reactor.

In all of the accident scenarios, the loss of the control drums and reflector was more than enough to shut down the reactor. The resulting keff values were all below 0.93, and the reactor will remain subcritical beyond the margin of doubt. This means that in all conceivable crash scenarios, even if the reflectors and drums fall apart or are ejected in a crash where reactor salvage is unlikely, the reactor will shut down. The only scenario that would require any manual human intervention would be if more than half of the control drums became stuck and did not fall off. Even so, control drum ejection would still be an option if repairs could not be made.

Interestingly, all of the cases resulted in keff values below 0.9, except for the wet sand and wet sand and sea water mixture cases which produced the highest keff values above 0.92. Wet sand seems to be an excellent moderator and reflector for neutrons. Upon viewing the cross-section tables of Duderstadt and Hamilton, it can be found that the water in the sand makes a good neutron moderator and a fair reflector with a high scattering cross-section and a low absorption cross-section.[8] The quartz sand crystals themselves have a lower cross-section than water, but it is much higher than its absorption cross-section.[11]

Perhaps the increased reflection properties come from the increased density of the mixture. As sand gains moisture it increases in density and clumps together. A higher density means higher neutron scattering probabilities, a higher macroscopic cross section, and resulting in a better reflecting material. The relationship of increasing density of sand with moisture content continues, until there is more water than sand. Then the sand crystals begin to disperse, as evidenced by case four, which produced a lower reactivity. The combination of water with silicon dioxide (sand) makes a much more powerful reflector than when the sand is dry. Neither the sand nor water (fresh or sea) by themselves make particularly good reflectors as seen by the keff values for the accident cases in Table 3.

7 Conclusion and Suggestions for Additional Work

The control rod system of the old NKUA1 design was compared against the new control drum design. The old design was to be used in combination with a perimeter sliding poison sleeve with a very large central control rod. The control rod was used more for power regulation during operation and the sleeve was to be used for startup and shutdown of the reactor. This was proven true as the largest control rod configuration, the Nine Rod Solid Box and Four Rods in the Third Ring configuration (13 rods total), held only a fourth of the negative reactivity contained in the control drum system. After verification of the new control drum design, a safety analysis was performed concerning launch accident scenarios. The reactor core would lose its reflector and control drums in each case and be covered in a naturally occurring material, such as sand or seawater. In all seven accident scenarios, the reactor shutdown successfully with safe shutdown margins greater than $10.00. The NKUA1 reactor will be safe in all foreseeable crash test scenarios provided the control drums and reflectors fall off.

There is still plenty of work to be done on the NKUA1 before it is launched into space. Time did not permit it, but a safety analysis on stuck control drums should be done. This would verify how many control drums could get stuck while maintaining the ability to shut down the reactor safely. A heat and thermal analysis should be performed on the heat pipes and thermoelectric converters to verify power output and operating temperatures. Finally, test facilities can be designed and built for the reactor to collect physical data and compare it with the code calculations.

8 References

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9 Nomenclature

Ai- the atomic weight of the constituent element i (measured in Atomic Mass Units, AMU)

Afi- the atom fraction of the constituent element i (%)

$\bar{A}$- the average atomic weight of the compound or mixture (AMU)

Nmix- number density of the mixture or compound (atoms/cm^3)

ρmix- the density of the mixture or compound (g/cm^3)

Av- Avogadro's number defined as 6.022E23 (atoms/mole)

Ni- the number density of the constituent element

Σ_i- the macroscopic cross section of a constituent element i (cm^{-1})

σ_i- the microscopic neutron cross-section of a constituent element I (barns or 1E-24 cm^{-2})

Σ_t- the total macroscopic neutron cross-section of the mixture or compound (cm^{-1})

t_{sphere}- the thickness of the sphere surrounding the reactor

r_{sphere}- the radius of the sphere surrounding the reactor

Z_{bound}- the outermost axial boundary of the reactor