LA-UR-13-24635
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Intended for: Annual Meeting American Nuclear Society, 2013-06-16/2013-06-20 (Atlanta, Georgia, United States)

Issued: 2013-06-24

MCNP Simulations in Support of the Heat Pipe in Flat-Top Experiment

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INTRODUCTION

A series of MCNP simulations were performed to estimate the excess reactivity of a heat pipe inserted in the glory hole of the Flat-Top assembly. The purpose of the experiment was to demonstrate that a heat pipe coupled to a Sterling engine could generate electricity from a nuclear generated heat source. This experiment demonstrated a new concept for a reliable nuclear reactor for space missions.

The heat source used to generate this electricity originated in the Flat-Top assembly. During certain operations of the Flat-Top assembly, temperature increases are generated in the core, which creates a temperature gradient between the center of the core and the ambient temperature of the room. Typically this excess energy will be removed from the assembly through air convection or heat conduction to the supporting table. However, it is possible to use other means to remove this energy from the assembly, such as through a heat pipe.

A heat pipe is a device that is used to transfer energy from one solid surface to another solid surface, typically with the assistance of a working fluid or coolant. For the heat pipe used in this experiment the working fluid was water. The heat pipe was connected to a Sterling engine and the energy transferred to the Sterling engine was converted to electricity.

To generate the energy needed to provide the temperature increases in the core, the Flat-Top assembly was operated in a supercritical regime. The simulations presented in this summary provided the basis to load the Flat-Top assembly with enough excess reactivity that would produce the energy needed for the experiment but also not exceed the operating reactivity limit of $0.80.

DESCRIPTION OF THE EXPERIMENT AND SIMULATIONS

The Flat-Top assembly consists of a core of fissile material at the center of 19-in OD natural uranium reflector. The driver core for this experiment was an 18-kg sphere of highly enriched uranium (HEU).[1] For this experiment, a heat pipe with approximate dimensions of 0.5-in OD and 45 inches in length was placed through the horizontal 0.5-in diameter glory hole in the HEU core. The heat pipe which extended beyond the stationary natural uranium reflector is shown in Figs. 1 and 2. In order to decrease the heat transfer from the heat pipe to the natural uranium reflector, the natural uranium insert was replaced with a stainless steel insert as shown in Fig. 2.

The heat pipe was fabricated by Advanced Cooling Technologies, Inc. It contained between 0.015 and 0.065 liters of water. The heat pipe was designed so that one end of the heat pipe would remove the heat from the Flat-Top core. The water in the heat pipe would then transfer the heat through the heat pipe and drive the Sterling engine, which would produce electricity. Figure 3 shows three heat pipes that were available for this experiment. One of them was used in this experiment.

Figure 1. Side view of the Flat-Top assembly with the heat pipe. The assembly is shown in the SCRAM position.

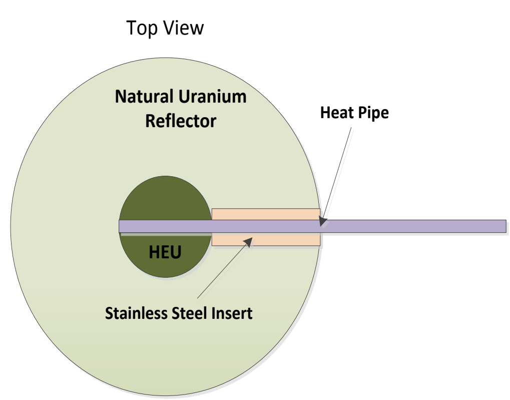


Figure 2. Top view of the Flat-Top assembly showing the heat pipe and the SS insert.

Figure 3. Three heat pipes fabricated by Advanced Cooling Technology, Inc.

Several simulations were performed with MCNP[1] to assess the reactivity worth of placing a heat pipe containing water in the Flat-Top assembly. The MCNP simulations were performed using ENDF/B-VII neutron cross section data. Each simulation had a total of three million histories and the MCNP code was operated in the k-code mode.

RESULTS FROM SIMULATIONS AND EXPERIMENT

The first MCNP simulation was the base case, which represented the Flat-Top assembly as initially configured. From positive reactor period measurements of the initial configuration, the excess reactivity on the Flat-Top assembly was $0.50. The keff for this base case model using MCNP was 1.00004 +/- 0.00038. Future MCNP simulations use this base case keff value to calculate the reactivity worth of making minor modifications to the assembly loading.

The second simulation assumed the inner ½ OD natural uranium rod, which is part of the natural uranium reflector, replaced with water. The simulation yielded a k_{eff} of 0.99999 ± 0.00037. Assuming a β_{eff} of 0.00664 for this assembly, this represents a reactivity worth of -0.0075$ with respect to the base case or +0.4925$ based on the measured excess reactivity of the assembly. Figure 4 shows the configuration that was modeled.

The next simulation assumed the entire glory hole in the core and the ½ OD reflector rod replaced with water. The MCNP simulation yielded a k_{eff} of 0.99438 ± 0.00037 or a reactivity worth of -0.86$ with respect to the base case or -0.36$ based on the measured excess reactivity. Even though water is an excellent moderator, the reactivity worth is negative because fuel in the center of the core which produces fissions is being replaced with water. Figure 5 shows this configuration.

The final configuration modeled was the one shown in Fig. 2. This configuration represented the actual experiment that was going to be placed in the Flat-Top assembly. The heat pipe was modeled with a 0.1-in thick annulus of water and void in the center. The natural uranium insert plug was replaced with a stainless steel insert as seen in Fig. 2. The stainless steel insert was used to reduce the amount of heat transferred to the reflector. The calculation yielded a k_{eff} of 0.99210 ± 0.00029 or a reactivity worth of -1.21$ with respect to the base case or -0.71$ based on the measured excess reactivity.

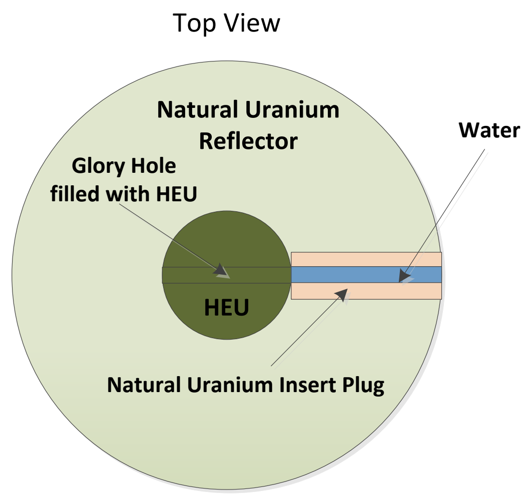


Figure 4. MCNP model of the Flat-Top assembly with water in the reflector.

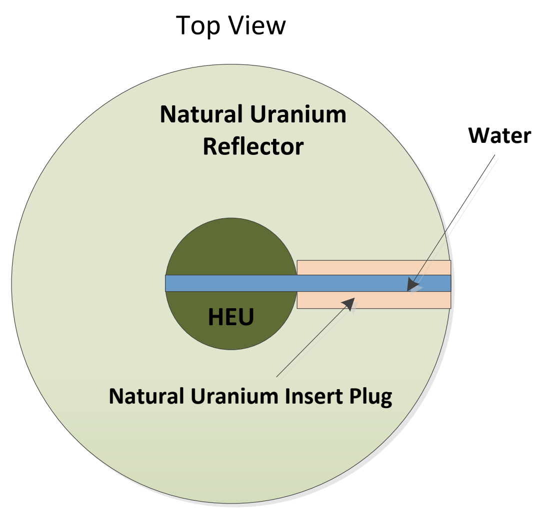


Figure 5. MCNP model used to simulate water in the glory hole and in the reflector.

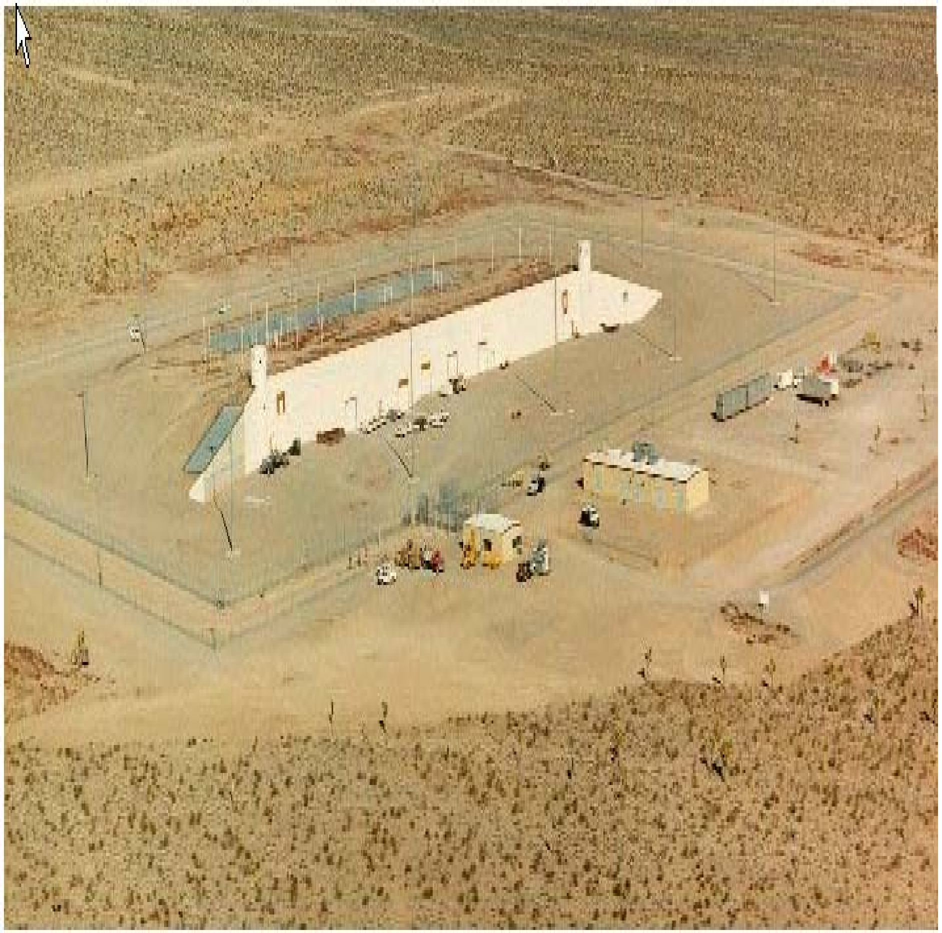
In order to operate the assembly supercritical regime, the operating crew needed to add reactivity to the assembly. It was decided to exchange the split cap for the full HEU cap. This action added 1.52$ of reactivity to the assembly, which meant that according to the MCNP simulation, the assembly was loaded with 0.81$ positive excess reactivity. The uncertainty in the simulation was ± 0.15$ due to the water content in the heat pipe. When the experiment was performed, the measured maximum excess reactivity was 0.67$, which is within the uncertainty of the calculation. Table I summarizes all the simulations that were performed prior to conducting this experiment. Some of them were discussed above.

Table I. Results from MCNP simulations.

Description	k_{eff}	*Reactivity Worth($)*	*Total Reactivity($)*
Base case, Flat-Top assembly	1.00004 ± 0.00038	0	+0.50
Inner reflector rod replaced with water.	0.99999 ± 0.00037	-0.0075	+0.4925
Inner reflector rod and glory hole pieces replaced with water.	0.99438 ± 0.00037	-0.86	-0.36
Inner reflector rod and glory hole pieces replaced with water, outer reflector rod replaced with a void.	0.99256 ± 0.00038	-1.13	-0.63
Glory hole pieces, and inner and outer reflector rods replaced with voids.	0.98648 ± 0.00029	-2.07	-1.57
Glory hole pieces and inner reflector rod replaced with a void. Outer reflector rod replaced with polyethylene.	0.98793 ± 0.00028	-1.84	-1.34
No HEU in glory hole.	0.98820 ± 0.00032	-1.80	-1.30
Heat pipe through glory hole and inner reflector rod. Outer reflector rod replaced with stainless steel.	0.99210 ± 0.00029	-1.21	-0.71

REFERENCES

1. R. R Paternoster, et al, "Safety Analysis Report for Pajarito Site (TA-18) and the Los Alamos Critical Experiments Facility (LACEF)," LA-CP-92-235, Los Alamos National Laboratory (May 1992).
2. J. F. Briesmeister, "MCNP – A General Monte Carlo N-Particle Transport Code," LA-12625-M, Los Alamos National Laboratory (March 2000).



MCNP Simulations in Support of the Heat Pipe in Flat-Top Experiment

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Outline

- **Background**
- **Purpose**
- **Description of the Experiment**
- **Description of the Simulations**
- **Conclusions**

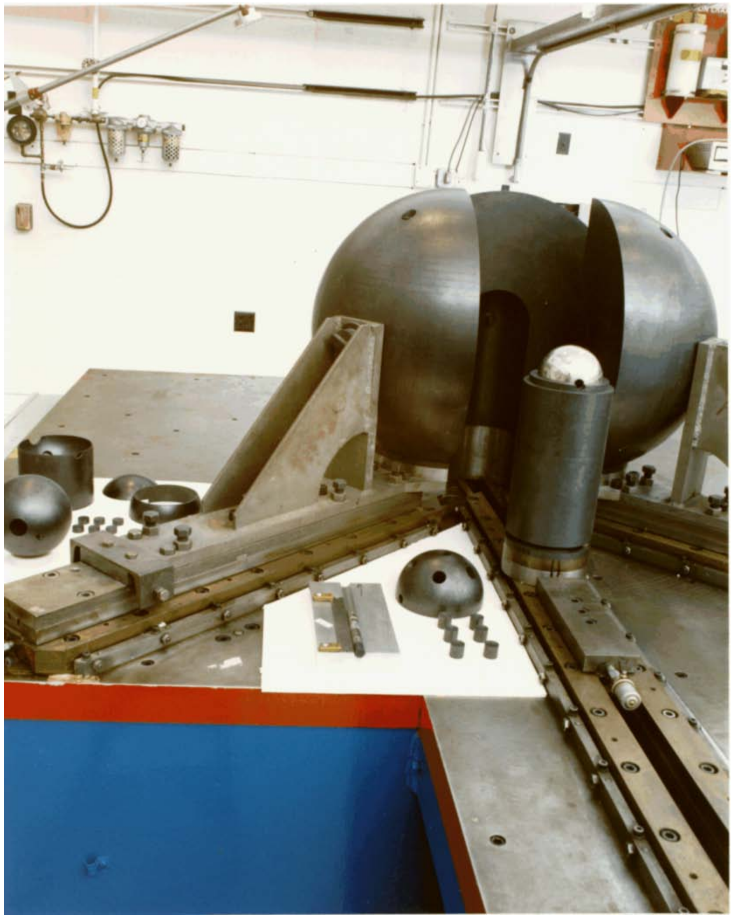
Background

- For many years, NASA has dependably relied on radioisotope thermoelectric generators (RTGs) to power science missions
- David Poston, et al, “A Simple, Low-Power Fission Reactor for Space Exploration Power Systems,” Proceedings of Nuclear and Emerging Technology for Space, February 2013.
- First experiment is performed in September 2012.

Purpose

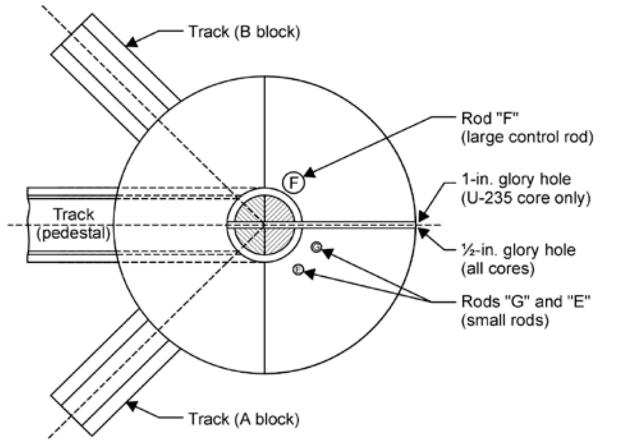
- **MCNP Simulations in Support of the Heat Pipe in Flat-Top Experiment**
  - To demonstrate *that a heat pipe coupled to a Stirling engine could generate electricity from a nuclear generated heat source*
  - The simulations presented in this summary provided the basis to load the Flat-Top assembly with enough excess reactivity that would produce the energy needed for this experiment.

Flat-Top Assembly

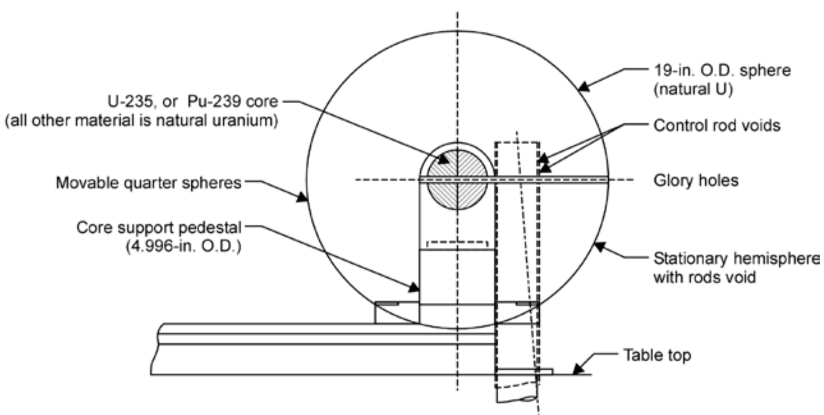


- Simple one-dimensional spherical geometry benchmark assembly that replaced the Topsy assembly at Los Alamos.
- Used originally for critical mass studies for thick uranium reflected systems in spherical geometry.
- 1000 kg natural (0.7 wt.% ^{235}U) uranium reflector
  - 500 kg hemisphere.
  - Two 250 kg quarter-sphere safety blocks.
  - Re-configurable pedestal to accommodate different cores.
- Can operate in "free run" mode up to several kilowatts
  - Temperature increases of up to 300˚C

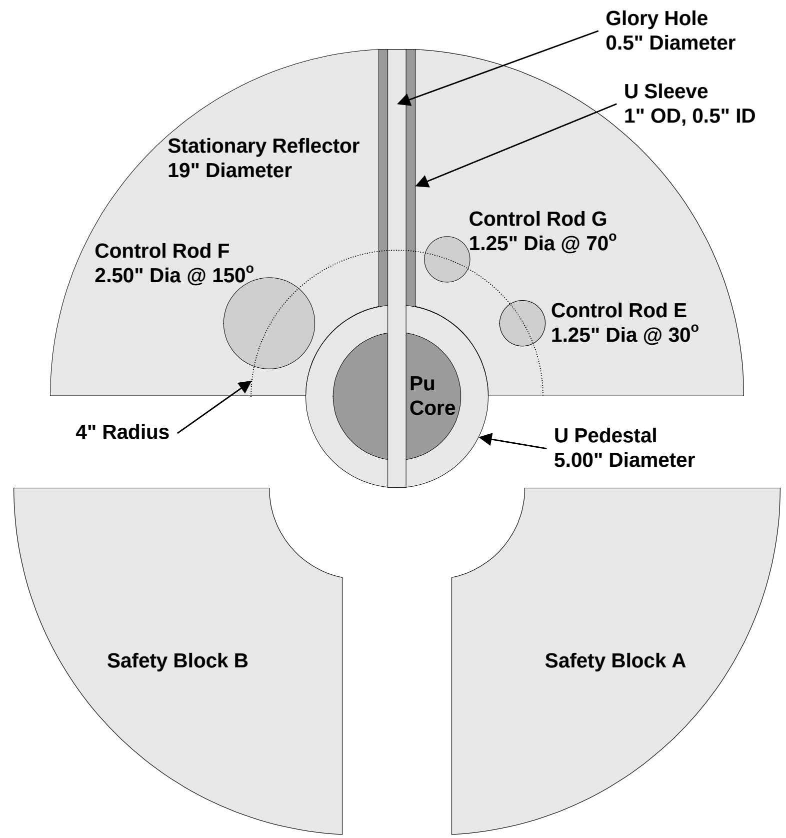
Flattop Core Design



Plan View

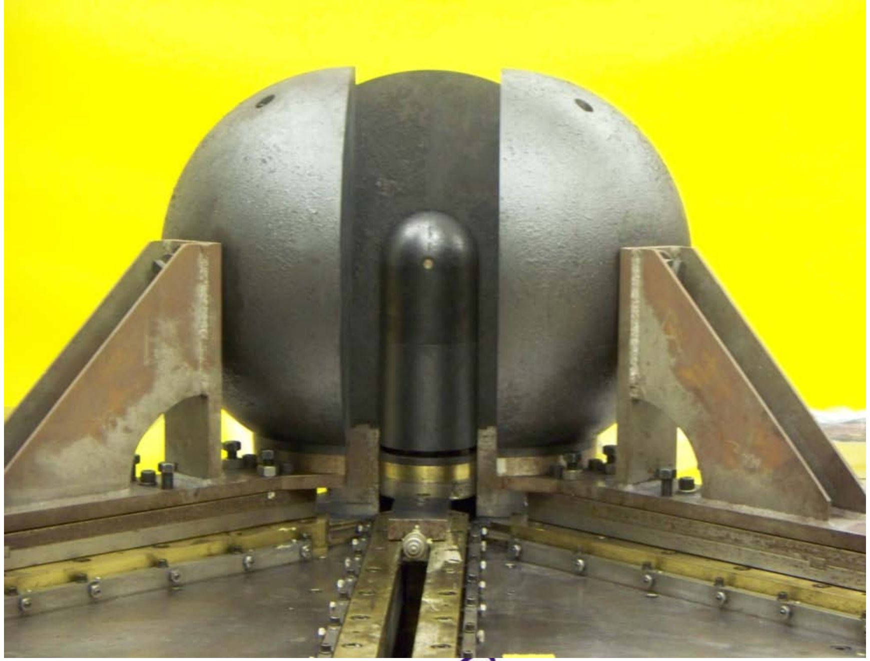


Elevation View



Pu Core: 3.57" Diameter
U Core: 4.77" Diameter
Rod Diameters are 13 mils less than the shown hole sizes

Heat Pipe in Flat-Top Assembly



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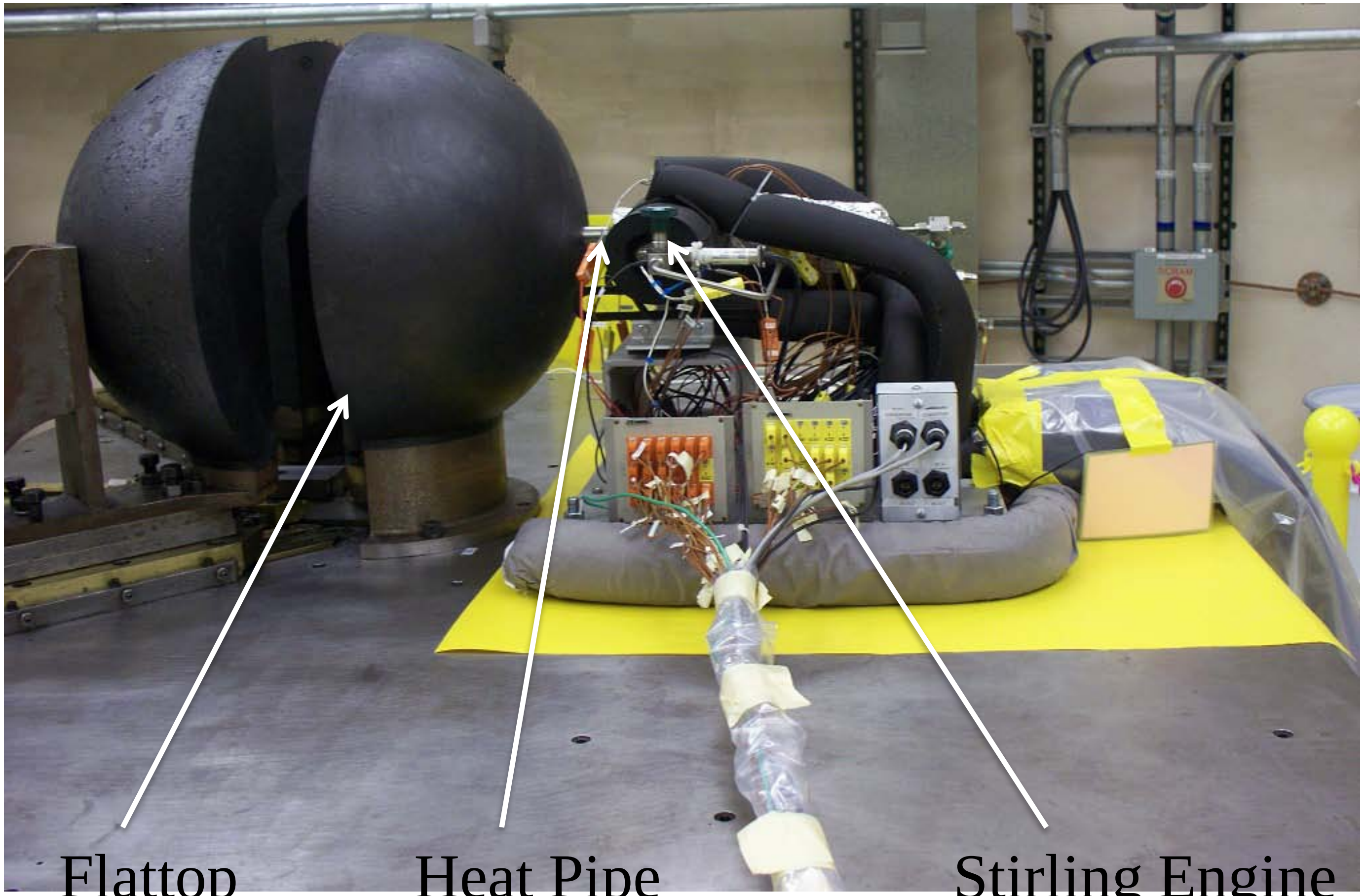
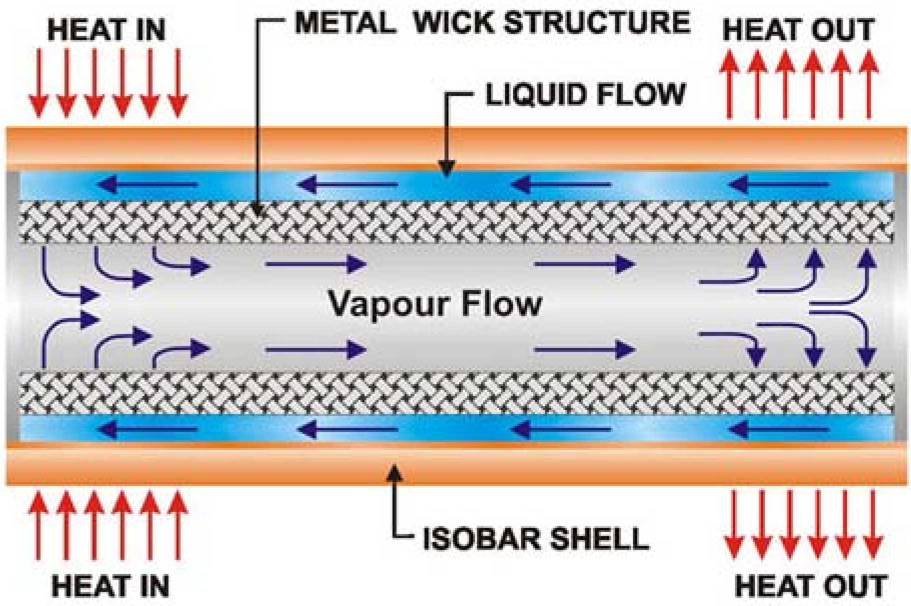
Heat Pipe in Flattop



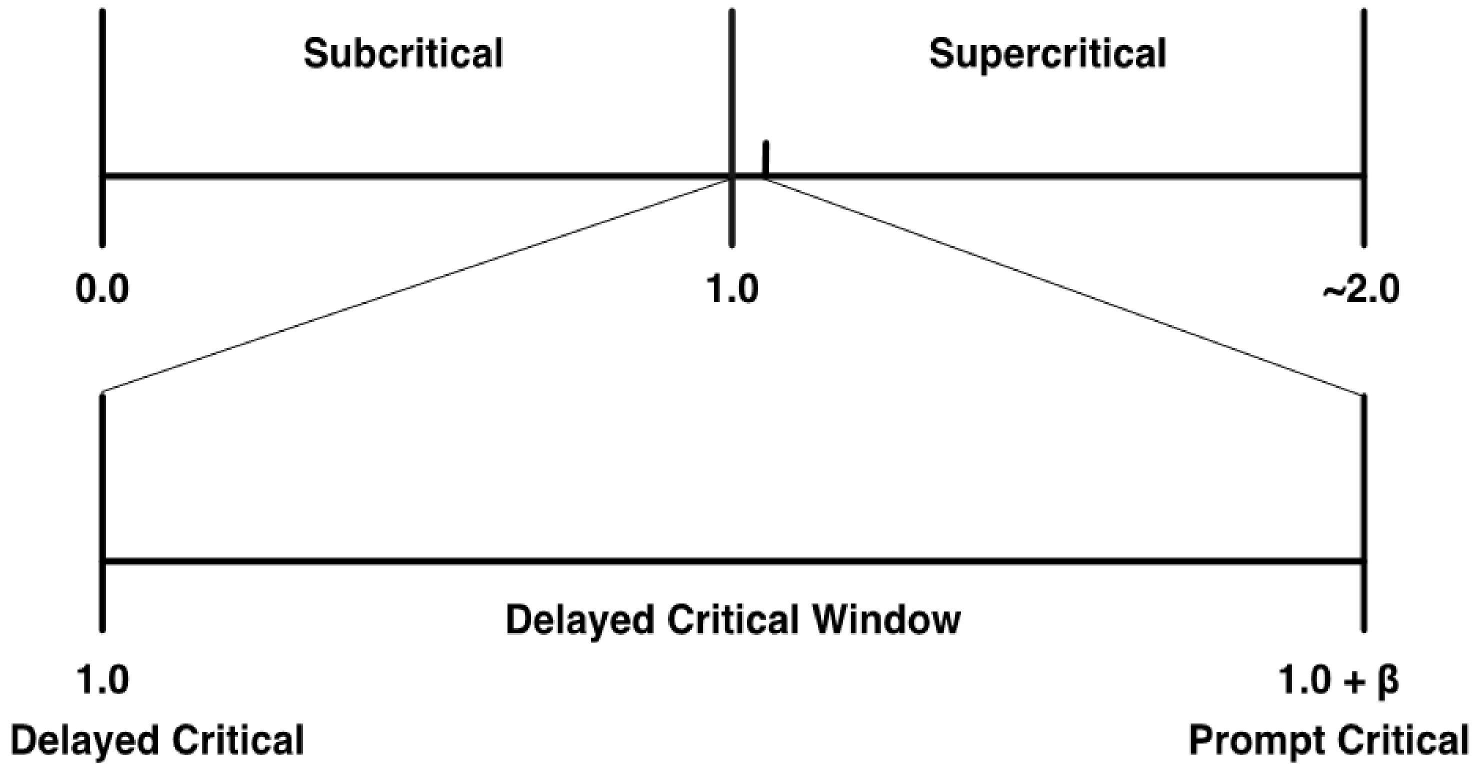
Heat Pipes

- Fabricated by Advanced Cooling Technology, Inc.
- Contained between 0.015 and 0.065 liters of water
- Approximate dimensions: 0.5-in OD and 45 inches in length
- Heat pipe is a device that is used to transfer energy from one solid surface to another

Heat Pipes


HEAT IN
METAL WICK STRUCTURE
HEAT OUT
LIQUID FLOW
Vapour Flow
ISOBAR SHELL
HEAT IN
HEAT OUT

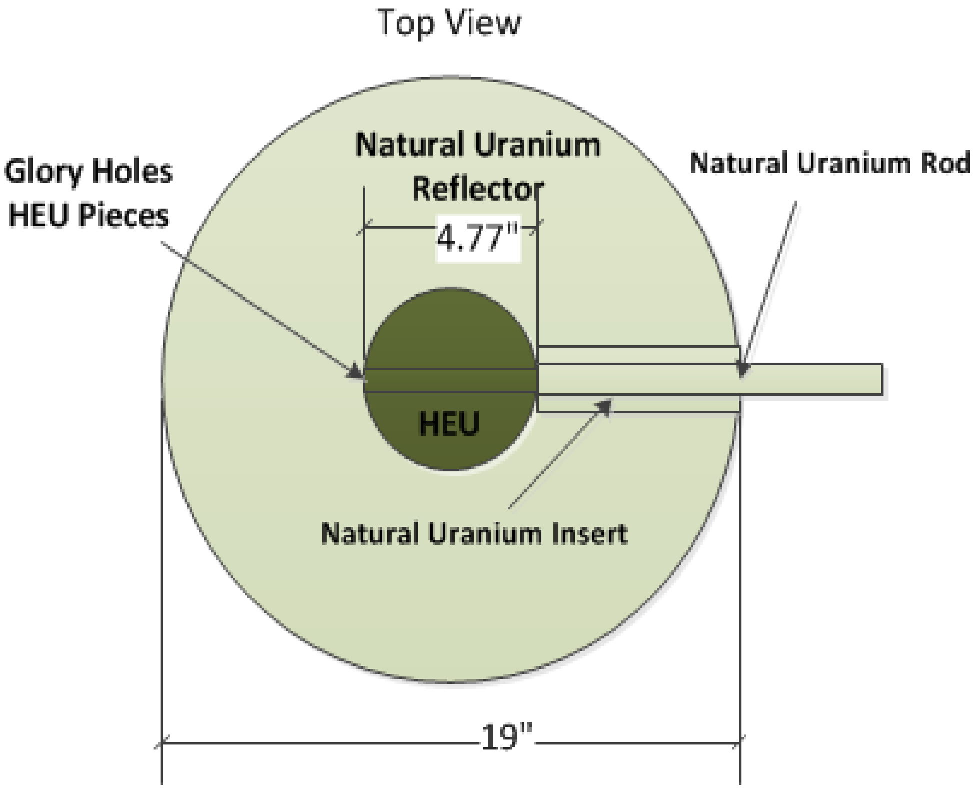
Behavior of Critical Systems



MCNP Simulations

- **The MCNP simulations were performed using ENDF/B-VII neutron cross section data**
- **Each simulation had a total of three million histories. The first 50 generations were skipped**
- **The MCNP code was operated in the k-code mode**

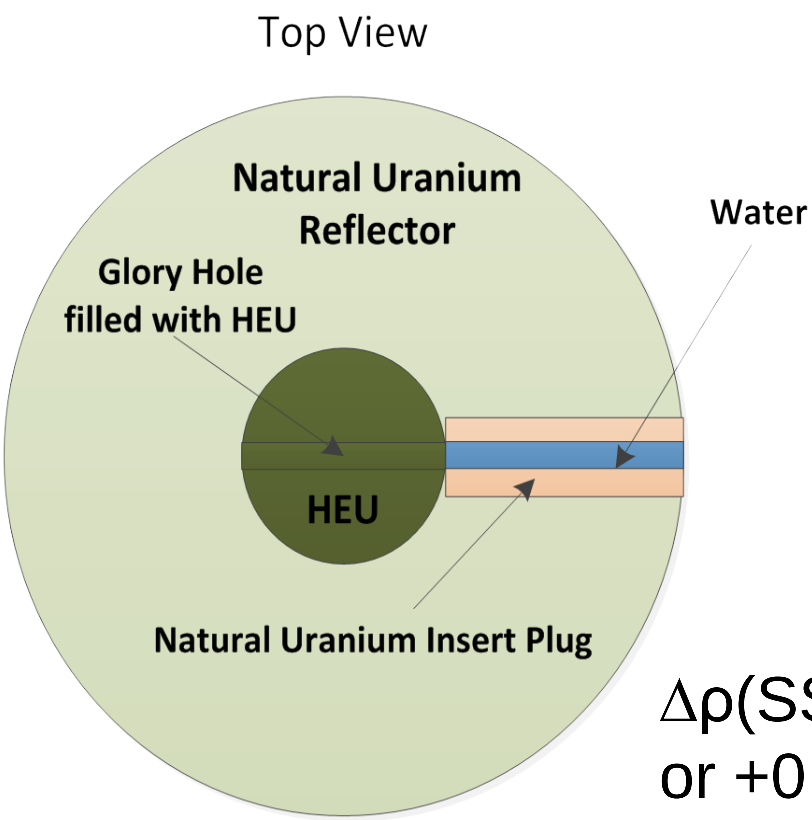
Base Case (First MCNP Simulation)



k_{eff}= 1.00004 $\pm$ 0.00038

This base case simulation represents 0.50$ $\pm$ 0.01

Second MCNP Simulation (NU rod replaced with water)



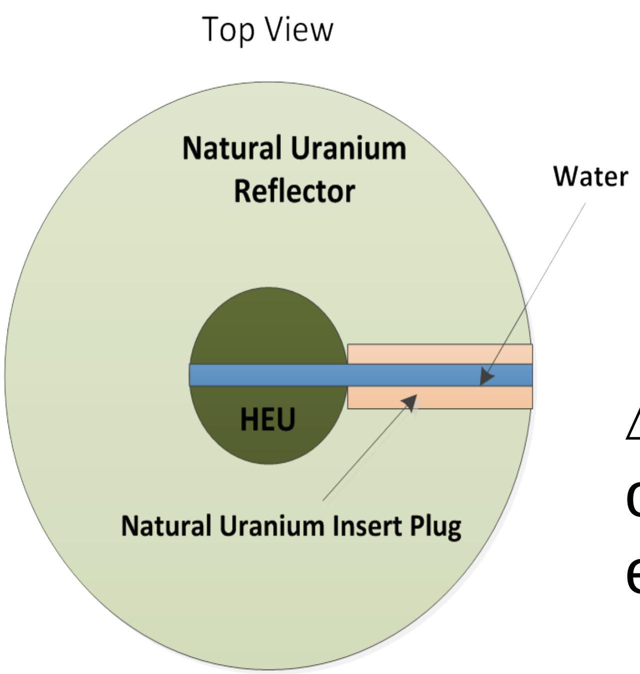
$k_{eff} = 0.99999 \pm 0.00037$

Assuming a β_{eff} of 0.00664

$\Delta\rho(\$) = (k_2 - k_1)/(\beta_{eff}\, k_1 * k_2)$

$\Delta\rho$(SS – Base Case) = -0.0075\$ $\pm$ 0.08 or +0.4925\$ $\pm$ 0.08 based on the measured excess reactivity of the assembly

Next MCNP Simulation (Entire GH and NU rod replaced with water

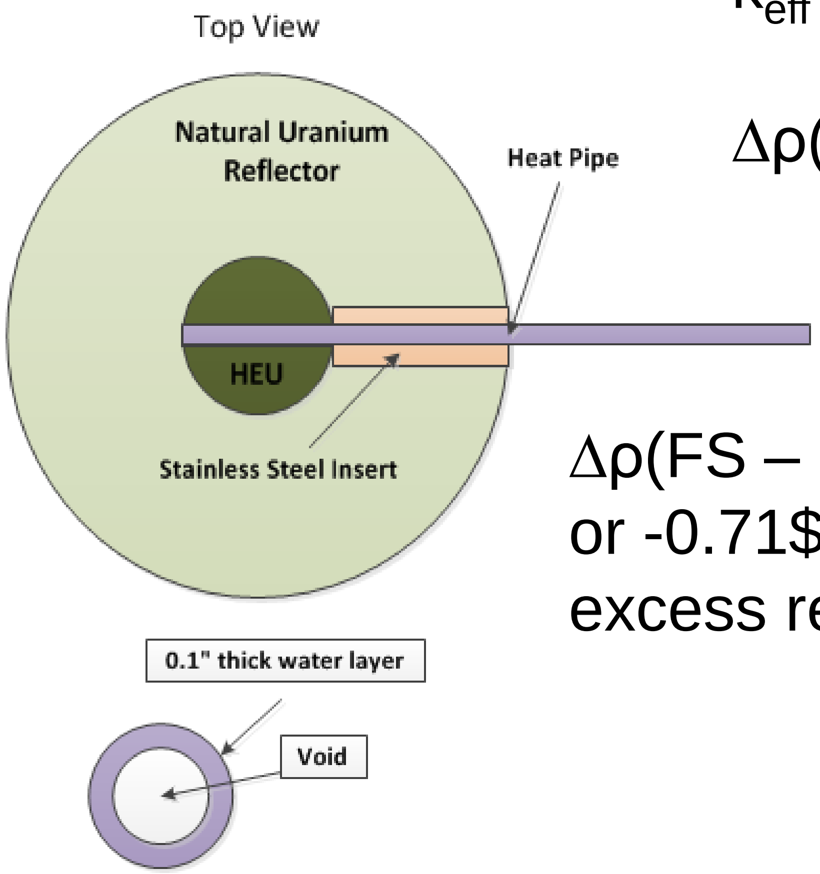


$k_{eff} = 0.99438 \pm 0.00037$

$\Delta\rho(\$) = (k_2 - k_1)/(\beta_{eff}\, k_1 * k_2)$

$\Delta\rho$(TS – Base Case) = -0.86$ $\pm$ 0.08 or +0.36$ $\pm$ 0.08 based on the measured excess reactivity of the assembly

Next MCNP Simulation (Heat Pipe in the GH)

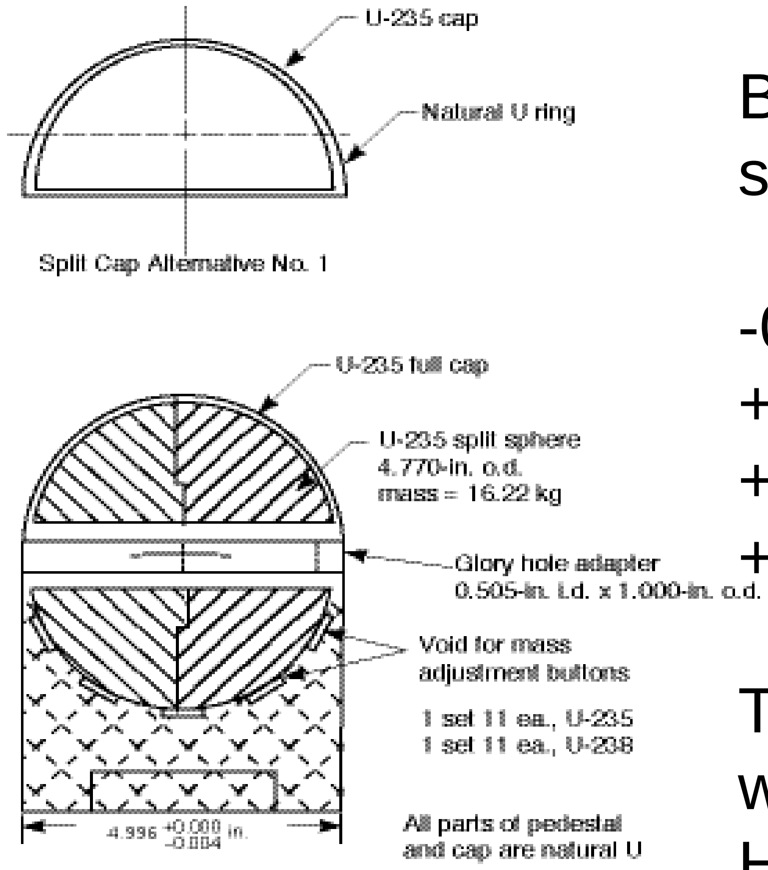


$k_{eff} = 0.99210 \pm 0.00029$

$\Delta\rho(\$) = (k_2 - k_1)/(\beta_{eff}\, k_1 * k_2)$

$\Delta\rho$(FS – Base Case) = -1.21$ $\pm$ 0.07 or -0.71$ $\pm$ 0.07 based on the measured excess reactivity of the assembly

Split cap vs Full HEU Cap



Based on the previous simulation

-0.71$ ± 0.07 (hp with Split Cap)
+1.52$ ± 0.01 (hp with Full Cap)
+0.81$ ± 0.07
+0.81$ ± 0.15 (hp water content)

The measure excess reactivity with heat pipe in place and Full HEU cap was
0.67$ ± 0.01

Temperature Coefficient of Reactivity

$$\frac{\Delta\rho}{\Delta T}(¢/°C)$$

Negative – temperature reactivity quench
Positive – autocatalytic or divergent reaction

Assembly	Approx. Temp. Coeff.
Godiva IV, Big Ten, Flattop U	-0.3 (¢/°C)
Flattop delta phase Pu	-0.2(¢/°C)
SHEBA U(5) solution	-4.0 to -10.0 (¢/°C)
CNPS(U(20)O_2-C matrix	-1.2 (¢/°C)

Contributions from expansion, Doppler shifts, geometry changes

$$\Delta T = \frac{\Delta\rho}{\Delta\rho/\Delta T} = \frac{0.67\$}{0.003\$/°C} = 223.3°C$$

Conclusions

- Simulations agreed quite well with the experimental value of reactivity

- The experiment was planned, designed and executed in a three months

- The experiment was successful in producing electricity by using the heat pipe to transfer the heat from the core to the Stirling engine