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Nuclear Analysis of the UCI TRIGA Reactor

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Nuclear Analysis of the University of California – Irvine TRIGA® Reactor

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COMPUTER PROGRAM

PIN(S)

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LIST OF ABBREVIATIONS/ACRONYMS

APF	Axial Peaking Factor
ARI	All Rods In
ARO	All Rods Out
BOL	Beginning of Life
GA	General Atomics
kW	kilowatt
LEU	Low Enriched Uranium
MCNP	Monte Carlo N-Particle Code
MW	Megawatt
PTS	Pneumatic Transfer System
RPF	Radial Peaking Factor
SAR	Safety Analysis Report
TRIGA®	Training Research Isotope General Atomics
UCI	University of California- Irvine

1 INTRODUCTION

This report provides an overview of the nuclear characteristics of the University of California – Irvine (UCI) TRIGA® Reactor.

2 REACTOR DESCRIPTION

2.1 Reactor Facility

Table 2-1 provides a comparison of the key design safety features of the [redacted], along with a comparison of the key reactor and safety parameters that were calculated for the core. As discussed in Sections 2.2.7 and 2.2.8, there is sufficient shutdown margin combined with a negative power coefficient to show that the UCI reactor facility can be operated safely with [redacted].

The computations produced operational parameters to be compared with the actual measured values from the operations conducted by the UCI staff for the UCI TRIGA® core loaded with [redacted] that GA manufactured. The experimentally measured parameters included the reactivity for the fully loaded core ([redacted]) and the control rod calibration values. In addition, the computations produced results for the prompt, negative temperature coefficient of reactivity (Δk/k-°C) versus reactor fuel temperature that can be compared with current values, as well as the moderator coefficient, void coefficient, and power peaking profiles.

Table 2-1 LEU Design Data, Core Physics, and Safety Parameters

DESIGN DATA	
Number of Fuel Rods	[redacted]
Fuel Type	UZrH
Uranium Enrichment, %	19.79
Zirconium Rod Outer Diameter, mm	[redacted]
Fuel Meat Outer Diameter, mm	
Fuel Meat Length, mm	
Clad Thickness, mm	
Clad Material	
REACTOR PARAMETERS	
Reactor Steady State Operation, kW	250
Cold Clean Excess Reactivity, Δk/kβ ($)	2.82
Measured Cold Clean Excess Reactivity, Δk/kβ ($)	2.66
Prompt Fuel Temperature Coefficient of Reactivity (BOL), Δk/k-°C, 23-1000°C (x 10^{-4})	-0.70 to -1.11
Coolant Void Coefficient, Δk/k-% void, 0 - 10%, (x 10^{-4})	-7.40 to -3.68
Moderator Coefficient, Δk/k -°C, 23-1000°C, (x 10^{-4})	0.884 to 0.396
Maximum Rod Power at 250 kW, kW/element	4.519
Average Rod Power at 250 kW, kW/element	3.125
Prompt Neutron Lifetime, μsec	98.5
Effective Delayed Neutron Fraction	0.0079
ARI cold, clean core, Δk/kβ ($)	-5.88
Shutdown Margin, Δk/kβ ($) (with most reactive rod out)	-2.03
Additional Shutdown case, Δk/kβ ($) (with most reactive rod out and next most reactive rod stuck 50% out)	-1.27

2.2 Reactor Core

This section provides a detailed description of the components and structures in the reactor core. The UCI reactor is a primarily homogeneous, light water moderated and cooled, tank-type reactor fueled with a full core of LEU (19.79% enriched $UZrH_x$) TRIGA® fuel in a cylindrical lattice configuration. The fuel clusters are supported by a 19.05mm thick aluminum grid plate. The UCI core configuration is shown in Figure 2-1; it contains [redacted] each with a central zirconium rod for structural integrity, a fuel-followed shim control rod, a fuel-followed regulating control rod, an air-followed adjustable transient control rod, and an air-followed fast transient rod. A graphite reflector block, located on the periphery of the grid plate, is used for reflection of neutrons.

[redacted]

Figure 2-1 UCI Core Configuration

The core configuration is a circular arrangement of core elements consisting of fuel, control, reflector, and testing elements. The grid-plate consists of 6 circular rings of elements, A for the central ring and G for the outer ring. The individual locations for the elements are numerically ordered in a clockwise direction. The design of the grid-plate will allow it to accept up to a total of [redacted]

2.2.1 Fuel Elements

The LEU (8.5% wt) TRIGA® fuel installed in the UCI core consists of [redacted] Figure 2-2 shows a detailed illustration of the fuel, graphite, and zirconium rod regions. The zirconium rod is manufactured to a diameter of [redacted], but the hole for the zirconium rod has a diameter of [redacted]

[redacted]

Figure 2-2 Fuel Element Details

An aluminum grid plate (19.1 mm thick) is used to support the fuel clusters on the bottom of the reactor. In addition, an aluminum grid plate (16.1 mm thick) is located at the top of the core to provide lateral restraint for the core components. The reactor is controlled by poison rods supported by a bridge mounted at the top of the biological shield.

The core is positioned [redacted] above the bottom of the reactor tank, and it is support by an aluminum core support structure which is bolted to the floor of the reactor tank.

The geometries, materials, and fissile loadings of the current fuel elements are summarized in Table 2-2.

Table 2-2 Description of the Averaged UCI Fuel Elements

Design Data	
Number of Fuel Elements Full Load	 [redacted]
Fuel Type	UZrH
Enrichment, %	19.79
Uranium Density, g/cm^3 Wt-%	 0.59 8.5
^{235}U per Fuel Element, g	[redacted]
Zirconium Rod Outer Diameter, mm.	[redacted]
Fuel Meat Outer Diameter, mm.	[redacted]
Fuel Meat Length, mm.	[redacted]
Cladding Thickness, mm.	[redacted]
Cladding Material	[redacted]

2.2.2 Control Rods

The UCI reactivity control system consists of four standard TRIGA® control rods; one fuel-followed shim rod, one fuel-followed regulating rod, one air-followed adjustable transient rod, and one air-followed fast transient rod as shown in Figure 2-1. All four control rods are supported from the bridge structure at the top of the biological shield.

2.2.3 Neutron Reflector

The primary reflector for UCI reactor consists of nuclear-grade graphite designed in a ring shaped block around the core as shown in Figure 2-1. The graphite block is placed in a leak-tight, welded, aluminum container. It is [redacted] thick radially with an inside diameter of [redacted] and [redacted] high.

2.2.4 Reactor Materials

Table 2-3 presents the material composition of components other than the fuel used in the computational models.

Table 2-3 Material Composition Used in the MCNPX Models

Material	Nuclide[1]	Nuc. Den. (atoms/b-cm)	Physical Density (g/cc)
[redacted] (clad)	Cr-50 Cr-52 Cr-53 Fe-56 Ni-58 Mn-55	0.000778 0.015003 0.001701 0.056730 0.007939 0.001697	7.98
Graphite (reflector in fuel) (reflector blocks)	C	 0.087745 0.078719	 1.75 1.57
Zirconium (rod w/ 60 ppm Hf)	Zr	0.034790	5.27
6061 Al (upper grid plate, lower grid plate, and control rod clad)	Al-27 Fe-56	0.058693 0.000502	2.70
90% B_4C (control rod)	B-10 B-11 C	0.020950 0.084310 0.026320	2.30
Water			1.0
Air			0.000123

2.2.5 Calculation Models; Nuclear Analysis Codes

Three-dimensional calculations are performed using Monte Carlo codes. The Monte Carlo calculations are used to evaluate the facilities around the core and also to compute the worth of core components and different core configurations.

2.2.5.1 MCNPX Monte Carlo Code

Reactor calculations were performed in three dimensions for the initial criticality of the UCI core using the continuous energy Monte Carlo code MCNPX, Version 2.6d for the calculations (Ref. 1). The nuclide cross sections for the core were based on ENDF/B VII.0 data for the final model, included in the library MCNP5 DATA (CCC-710). For the core calculations, most of the nuclide cross sections used ENDF/B VII.0, excluding minor impurities that were not available. The fuel meats were derived from material estimates supplied by UCI, and the fuel meat nuclide densities used in the MCNPX model are shown in Appendix A. Since the fuel meats lack fission

[1] Other isotopes were reviewed in the process, but they were determined to have an insignificant impact on the results.

products the reactivity estimates and shutdown margins will be conservative. The other materials besides the fuel used in the UCI MCNPX models are listed in Table 2-3.

2.2.5.2 Geometrical Models

Each fuel element was explicitly modeled such that 19 cells and 13 surface cards were constructed to properly represent one fuel element. A total of [redacted] and [redacted] were made for the [redacted] for the cold critical case (Ref. 2).

2.2.6 Critical Core Configuration; Excess Reactivity

2.2.6.1 UCI Full Core; Cold Unrodded

A detailed MCNPX model of the UCI reactor full, cold, unrodded core was made including [redacted] (8.5% wt.) fuel elements, a fuel-followed shim control rod, a fuel-followed regulating control rod, an air-followed adjustable transient control rod, an air-followed fast transient rod, and a graphite block around the core (Ref. 2). Figure 2-3 and Figure 2-4 are the radial and axial plots, respectively, of the MCNP model for the UCI full core cases.

[redacted]

Figure 2-3 Radial Initial Model for Monte Carlo (MCNPX) Transport Calculations Full Core – [redacted]

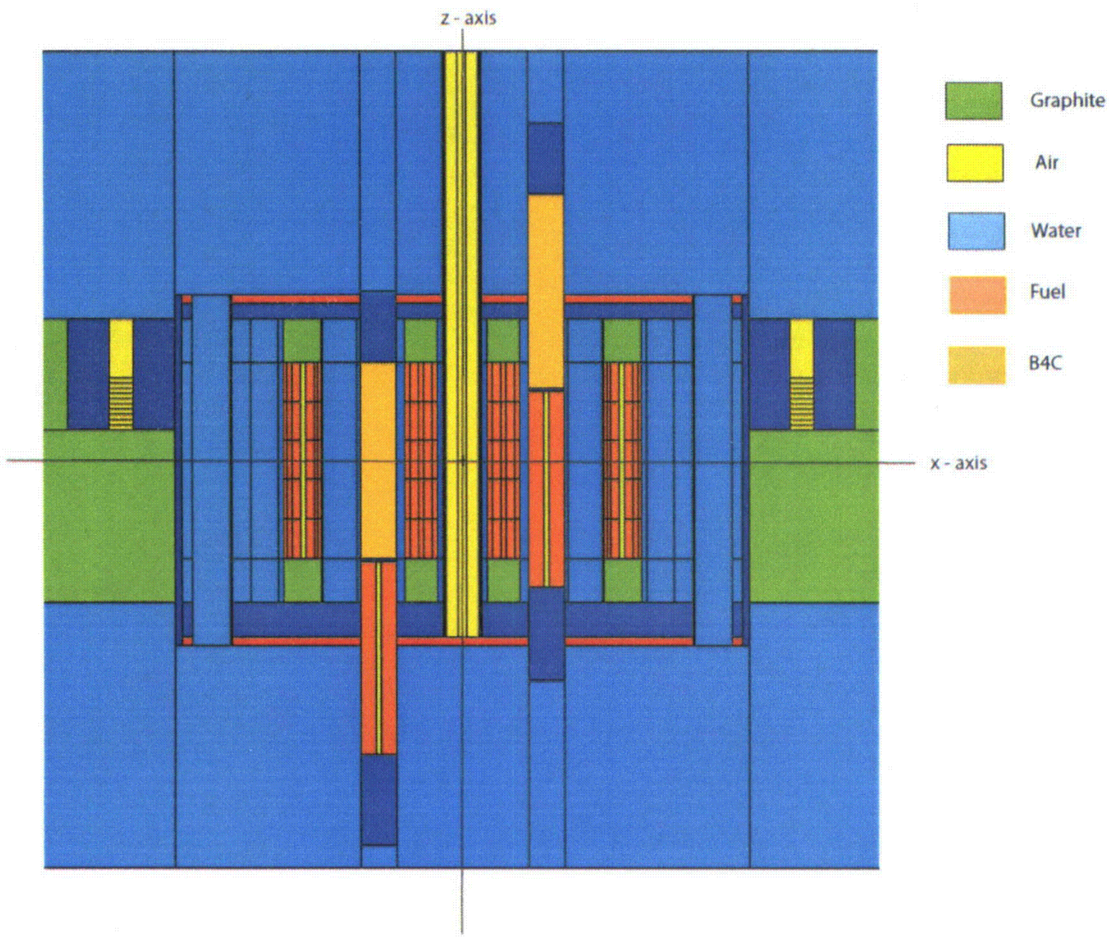

Figure 2-4 Initial Axial Model for Monte Carlo (MCNPX) Transport Calculations Just Critical Full Core – [redacted]

Table 2-4 summarizes the computational analysis for the UCI full core, all rods out, case modeled using MCNPX.

Table 2-4 UCI Unrodded Full Core Results (β_{eff} = 0.0079)

Reactor	k_{eff}	1σ	Reactivity	Measured	No. of Elements
UCI Full Core Cold, Unrodded	keff = 1.0230	$1\sigma = 0.0001$	+$2.82	+$2.66	[redacted]

Since a complete burnup estimate of the fuel was not completed for this analysis, the difference in the modeled fuel elements and actual fuel elements is sufficient to provide a discrepancy of 6%. Thus the unrodded full core results, $2.82, are within a reasonable estimate of the measured value, $2.66.

2.2.7 Worth of Control Rods

2.2.7.1 UCI Full Core Loading; All Control Rods Inserted

The full core loading in the UCI reactor contains [redacted] and includes the aforementioned fuel-followed shim control rod, fuel-followed regulating control rod, air-followed adjustable transient control rod, air-followed fast transient rod, and graphite ring around the core. The MCNPX calculation with all control rods inserted gives a k_{eff} value with one sigma uncertainty:

$$k_{eff} = 0.9376 \pm 0.0001$$

This is equivalent to reactivity shutdown of -\$5.88 (β_{eff} =0.0079), which is calculated as the difference between the ratio of the reactivity for the all rods out case and all rods in case, ARO/ARI, and the core excess (i.e., \$8.70 - \$2.82). As shown in Table 2-5, the four control rods have a combined reactivity worth of \$8.70 when comparing ARO to ARI calculations.

An additional analysis, relative to cold critical, of the individual control rod worths in the UCI core gave values for the shim rod, regulating rod, adjustable transient rod (ATR), and fast transient rod (FTR) respectively \$3.85, \$3.15, \$1.88, and \$0.64 for the shim rod, regulating rod, adjustable transient rod (ATR), and fast transient rod (FTR) respectively. These values sum to \$9.52, which is approximately 9% more than the ARO/ARI calculation. Further, these values relative to critical values are only \$0.45 more (~5%) than the measured control rod worths from the most recent control rod measurement. Table 2-5 summarizes the control rod worth calculations and measurements for the UCI core based upon the model.

Table 2-5 Summary of UCI Control Rod Worths

Control Rod	Calculated Value ARO/ARI	Calculated Value Relative to Critical	Measured Value in LEU Core 5/29/10	Difference
Shim		\$3.85	\$3.60	+6.9%
Regulating		\$3.15	\$2.96	+6.4%
ATR		\$1.88	\$1.81	+3.9%
FTR		\$0.64	\$0.70	-8.6%
TOTAL	\$8.70	\$9.52	\$9.07	+5.0%

2.2.8 Shutdown Margin

As stated in the UCI Technical Specifications (Ref. 3), the reactor shall be placed in the Shutdown Mode unless the reactor can be demonstrated to be subcritical by more than \$0.50 with the following conditions:

a. The most reactive rod fully withdrawn

b. The reactor is experiment free
c. The reactor is xenon free

The MCNPX calculations for a cold, clean core were used to evaluate the individual worth of the four control rods. The maximum worth control rod is the Shim Rod with a calculated worth of \$3.85. The reactor shutdown margin for the Shim Rod withdrawn, a cold excess of \$2.82, and an ARI/ARO of \$8.70 is conservatively estimated to be -\$2.03 (\$2.82 + \$3.85 - \$8.70). In addition, the reactor is required to be subcritical by at least \$1.00 for the ARI case. The calculated ARI reactivity has been calculated to be -\$5.88 (\$2.82 - \$8.70). Therefore, the Shutdown Margin meets the UCI Technical Specification requirements for the current core configuration.

To test for an additional margin of safety, the reactor is shown to be subcritical with the maximum worth rod fully withdrawn and the second most reactive rod withdrawn 50%. The second most reactive rod by calculation is the Regulating Rod with a worth of \$3.15. By adding \$3.85 from the Shim Rod worth and \$1.58 from the Regulating Rod 50% worth, to the ARI reactivity -\$5.88, the reactor is calculated to remain subcritical by \$0.45.

An additional MCNPX model of the UCI cold, clean core was run to verify this additional conservative estimate of the shutdown margin. This run was of the core modeled with the rods in the actual position specified rather than adding individual rod worths to the ARI reactivity case. For this case, the Shim Rod was fully withdrawn, the Regulating Rod was withdrawn 50%, and the ATR and FTR were fully inserted. The modeled k_{eff} with one sigma uncertainty for this shutdown core was:

Shim Rod 100%, Reg. Rod 50%, ATR 0%, FTR 0% withdrawn - $k_{eff} = 0.9901 \pm 0.0001$

This k_{eff} values corresponds to a reactivity of -\$1.27.

2.3 Additional Computed Core Performance Parameters

2.3.1 Effective Delayed Neutron Fraction, β_{eff}

The effective delayed neutron fraction, β_{eff} for UCI was also derived from Monte Carlo calculations of the UCI core with all control rods out.

The computed values for K_t and K_p are used in the following expression to obtain β_{eff}

$$\beta_{eff} = 1 - [K_p / K_t]$$

where: K_p = core reactivity using prompt fission spectrum

K_t = core reactivity using prompt and delayed fission spectrum

The values of K_p and K_t calculated using MCNPX are:

$$K_p = 0.99228 \pm 0.0001$$

$$K_t = 1.00014 \pm 0.0001$$

Using these values the result for the UCI core is:

$$\beta_{eff} = 0.0079 \quad (1\sigma = 0.0001)$$

2.3.2 Prompt Neutron Life (ℓ)

The prompt neutron lifetime, ℓ, was computed by the 1/v absorber method where a very small amount of boron is distributed homogeneously throughout the system and the resulting change in reactivity is related to the neutron lifetime. The boron cross sections used in the core were generated over a homogenized core spectrum. Boron cross sections used in all other zones were generated over a water spectrum.

The neutron lifetime, ℓ, is defined as follows:

$$\ell = 1/(\delta_o v_o N_B)*(\Delta k_{eff})$$

where N_B = boron density = 6.0180×10^{-7} atoms/b-cm

v_o = 2200 m/sec,

δ_o = 755 barns = δ_a^B at 2200 m/sec

k_{base} = 1.00014

k_{seed} = 0.99029

$\Delta k_{eff} = k_{base} - k_{seed}$ = 0.00985 (the change in reactivity due to the addition of boron)

The result for the prompt neutron life (ℓ) in the BOL UCI core is the following:

$$\ell = 98.5\ \mu sec$$

2.3.3 Prompt Fuel Temperature Coefficient of Reactivity (α_{fuel})

The definition of α_{fuel}, the prompt fuel temperature coefficient of reactivity, is given as

$$\alpha = \frac{d\rho}{dT}$$

where ρ = reactivity

= (k-1)/k

k = multiplication factor

T = reactor temperature (°C)

$$\alpha = \frac{1}{k^2}\frac{dk}{dT}$$

To evaluate ($\Delta\rho$) from reactivity as a function of reactor fuel temperature, the finite differences can be written as follows:

$$\Delta\rho_{1,2} = \frac{k_2 - 1}{k_2} - \frac{k_1 - 1}{k_1}$$

$$= \frac{k_2 - k_1}{k_1 k_2}$$

Thus,

$$\alpha_{1,2} \cong \frac{k_2 - k_1}{k_1 k_2} \times \frac{1}{\Delta T_{1,2}}$$

The data in Table 2-6 were produced by MCNPX for the listed fuel temperatures.

Table 2-6 Reactivity Change with Fuel Temperature, BOL

Avg. Fuel Temperature (°C)	k_{eff}	Δk_{eff}	$\frac{k_2 - k_1}{k_1 k_2}$	$\alpha_{1,2}$ (Δk/k-°C)
20	1.00014			
		0.00746	-0.00751	-7.02E-05
127	0.99268			
		0.02106	-0.02183	-1.09E-04
327	0.97162			
		0.02045	-0.02213	-1.11E-04
527	0.95117			
		0.01752	-0.01973	-9.86E-05
727	0.93365			
		0.01509	-0.01760	-8.80E-05
927	0.91856			

Figure 2-5 is a histogram plot of the computed values for α in Table 2-6 as a function of the reactor core temperature for BOL.

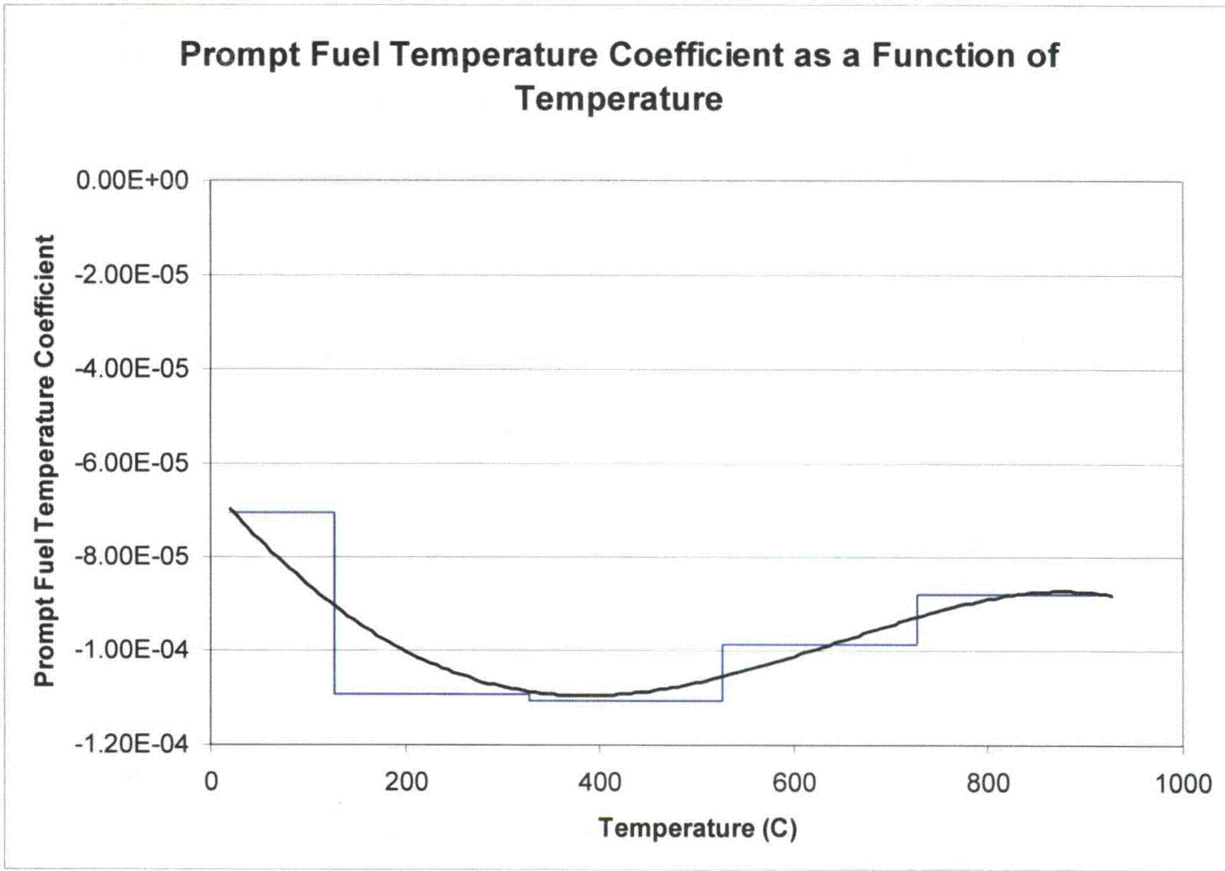

Figure 2-5 Prompt Fuel Temperature Coefficient for TRIGA® LEU (8.5% wt.) Fuel, BOL

2.3.4 Void Coefficient, (α_{void})

The void coefficient was calculated for 1%, 5%, and 10% and the results are plotted in Figure 2-6. The void coefficient for the UCI reactor ranges from -7.40×10^{-4} for 0% void to -3.68×10^{-4} with 10% void. The overall estimated worth calculates out to be roughly -$0.06 per 1% water void.

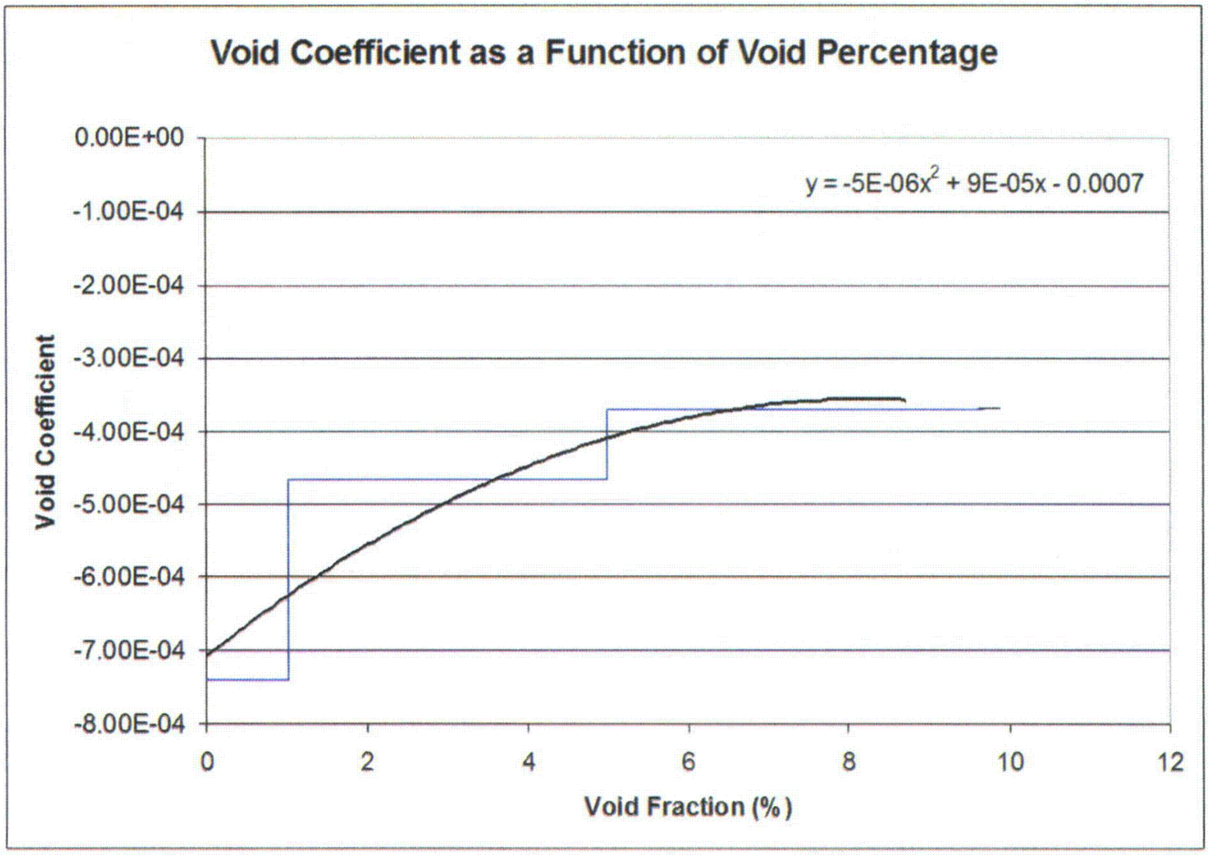

Figure 2-6: Reactivity Worth as a Function of Percent Coolant Void Fraction

2.3.5 Moderator Coefficient, (α_{mod})

The moderator coefficient, α_{mod}, was calculated using MCNPX through a series of cases with the moderator (both water and graphite) having a temperature of 297K, 400K, 600K, 800K, and 1000K; the results are plotted in Figure 2-7.

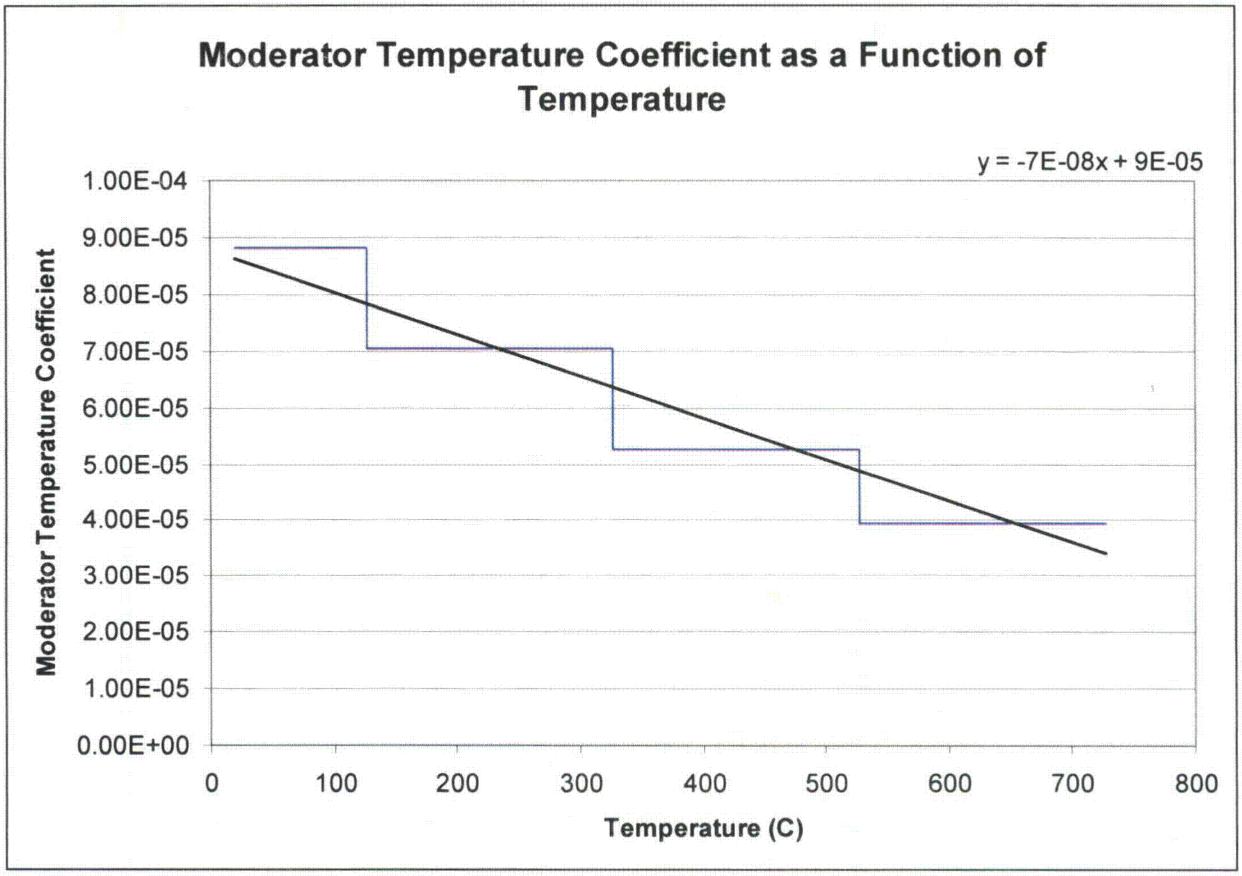

Figure 2-7: Moderator Temperature Coefficient as a Function of Temperature

2.3.6 Power Peaking Results

Power peaking in the BOL core is analyzed on the basis of the following component values:

1. $\overline{P}_{rod} / \overline{P}_{core}$: rod power factor, the power generation in a fuel rod (element) relative to the core averaged rod power generation.

2. $(\hat{P} / \overline{P})_{axial}$: axial peak-to-average power ratio within a fuel rod (element).

3. $(\hat{P}_{rod} / \overline{P}_{rod})_{radial}$: rod peaking factor, the peak-to-average power in a radial plane within a fuel rod (element).

Since maximum fuel temperature is the limiting operational parameter for the core, the peaking factor of greatest importance for steady-state operation is $\overline{P}_{rod} / \overline{P}_{core}$. The maximum value of this factor for the hottest rod, the hot-rod factor, [$(\overline{P}_{rod} / \overline{P}_{core})_{max}$ = hot-rod factor], determines the power generation in the hottest fuel element. The hot rod power factor is calculated to be 1.446, which can be found in fuel element C6. When combined with the axial power distribution, the hot-rod factor is used in the thermal analysis for determination of the maximum fuel temperature. The axial power peaking factor, $(\hat{P}/\overline{P})_{axial}$, is calculated to be 1.352, and at BOL it is relatively independent of fuel temperatures or radial position in the core. The radial power distribution within the element has only a small effect on the peak temperature, but it is also used in the steady-state thermal analysis.

The rod peaking factor, $(\hat{P}_{rod}/\overline{P}_{rod})_{\text{radial}}$, is of importance in the transient analysis for calculating maximum fuel temperatures in the time range where the heat transfer is not yet significant, and was calculated to not exceed 1.717. It is used in the safety analysis to calculate the peak fuel temperature under adiabatic conditions, where temperature distribution is the same as power distribution.

The reactor radial power peaking map for the UCI core is shown in Figure 2-8.

[redacted]

Figure 2-8 Hot Critical - Core Power Map

3 SUMMARY

Based on the nuclear analysis performed the UCI TRIGA® reactor is considered to be safely operating under steady-state conditions. The UCI full, cold, unrodded core has an excess reactivity of $2.82; the reactivity of the core for the ARI case shows that the core is subcritical by $5.88. The Shutdown Margin for the most reactive rod withdrawn from the core shows that the reactor is subcritical by $2.03. Also, it has been demonstrated that the reactor has both a negative void coefficient and negative prompt, fuel temperature coefficient, which provide for a controllable reactor. In addition, the highest rod factor shows a peak value of 1.446, which leads to a maximum power per fuel rod of 4.519 kW. Hence, it has been demonstrated through thorough analysis that the neutronic behavior of the UCI reactor meets the necessary operating requirements.

4 REFERENCES

1. "MCNPX 2.6D Code Verification Report," General Atomics, April 2008
2. Chiu, H., "Support Calculations for the Nuclear Analysis of the UCI TRIGA® Reactor," General Atomics, GA 911197, November 2010
3. UCI Technical Specification, July 2010

APPENDIX A: FUEL ROD NUMBER DENSITIES

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