HEU TO LEU FUEL CONVERSION REPORT
TO
U.S. NUCLEAR REGULATORY COMMISSION

BY

THE UNIVERSITY OF VIRGINIA

NUCLEAR REACTOR FACILITY
LICENSE NO. R-66
DOCKET NO. 50-62

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List of Commonly Used Acronyms

CAVALIER - Cooperatively Assembled Virginia Low Intensity Educational Reactor

CIF - Cannister Irradiation Facility

EPI RAB - Epi-Thermal Rabbit Facility

HEU - High Enriched Uranium

H.T. - Hot Thimble Facility

HYD RAB - Hydraulic Rabbit Facility

LEU - Low Enriched Uranium

LSSS - Limiting Safety System Setting

MIF - Mineral Irradiation Facility

Reg - Stainless Steel Regulating Rod

SAR - Safety Analysis Report

SHIM - Boron-Stainless Steel Control Rod

THER RAB - Thermal Rabbit Facility

UVAR - University of Virginia Reactor

HEU TO LEU FUEL CONVERSION REPORT

I. Introduction

The Nuclear Regulatory Commission issued a ruling, effective March 27, 1986, that all U.S. non-power reactors convert from HEU fuel to LEU fuel. A Reduced Enrichment for Research and Test Reactors (RERTR) Program was conducted by the Department of Energy at Argonne National Laboratory to coordinate the development of the high density LEU fuel and assist in the development of Safety Analysis Reports for the smaller non-power reactors. Several meetings were held at Argonne in 1987 with the non-power reactor community to discuss the conversion and to set up a conversion schedule for university reactors. EG&G at Idaho was asssigned the coordination of the fuel element redesigns. The fuel elements were manufactured by the Babcock & Wilcox Company in Lynchburg, Virginia.

The University of Virginia was awarded a grant (DE-FG05-88ER75388) by the DOE Idaho Operations Office in 1988 to perform safety analysis studies for the LEU conversion for its 2 MW UVAR and 100 Watt CAVALIER reactors. The University subsequently decided to shut down the CAVALIER reactor. A preliminary SAR on the UVAR, along with Technical Specification changes, was submitted to the NRC in November, 1990. An updated SAR was approved by the NRC in January, 1991.

In September, 1992, representatives from the fuel manufacturer (B&W) and the fuel designer (EG&G, Idaho) came to the UVAR facility to observe trial fittings of new 22 plate LEU mock fuel elements. B&W fabricated two non-fuel bearing elements, a regular 22 plate element and a control rod element. The elements were dimensionally checked against the drawings and test fitted in the UVAR grid plate. The dimensions were acceptable and the elements fit in the grid plate with no problems. The staff made several suggestions for minor construction changes to the end pieces on the elements, which were incorporated into the final design of the actual fuel elements. The "dummy" elements were kept by the facility and are on display for visiting tour groups. The manufacture of the UVAR LEU core was completed in late 1993.

II. Order to Convert

An "Order to Convert", along with Technical Specification changes pertinent to the fuel conversion was issued by the NRC on April 29, 1993. An attachment to the NRC order specified that a maximum limit of 5 kg of U-235 in the form of HEU fuel could be stored at the facility after receipt of LEU fuel until the HEU

fuel was shipped off site. Prior to the time of the conversion order the facility had 6.17 kg of U-235 in the form of HEU fuel so a fuel shipment of 12 fuel elements with a U-235 content of 1.72 kg was made on July 28, 1993 to Savannah River, to reduce the HEU inventory to below the 5 kg limit.
The UVAR reactor operated with HEU fuel until December, 1993 to finish ongoing experiments. The last operation with HEU fuel was on December 22, 1993 and the reactor was then unloaded.

III. Receipt of LEU Fuel

An attachment to the "Order to Convert" modifying License R-66 allows up to 11 kg of U-235 to be possessed by the licensee in the form of LEU fuel. Procedures for the receipt of LEU fuel were developed by the reactor staff and approved by the U.Va. Reactor Safety Committee. On January 11, 1994, the facility received 8.1 kg of LEU fuel from the Babcock & Wilcox Company in the form of 5 control elements, 26 regular elements, and 2 partial elements. The LEU Technical Specifications were put into effect upon receipt of the fuel.

IV. Initial Loading of LEU Fuel

A detailed LEU Test Program developed by the reactor staff was reviewed by the Reactor Safety Committee at four different meetings and approved. The final version of the Test Program was issued on February 15, 1994 (see Appendix 1). The first planned core loading was a 4 x 4 fuel array surrounded by graphite to compare it with a similar HEU configuration operated in 1975.

a) Initial Criticality (LEU-1 Core)

Initial loading of the LEU fuel began on April 19, 1994. Graphite elements were placed in the grid plate surrounding the proposed location of the fuel. A Sb-Be startup source was placed in grid position 14 opposite the installed Source Range fission chamber, located at the top of the graphite element in grid plate position 85. An auxillary fission chamber was placed in grid position 36, with a Pu-Be source opposite the core on top of the graphite element in grid position 42.

The control rods and associated fuel elements were first loaded in the reactor in grid positions 25, 34, 45, and 54. The rod drive mechanisms were attached and checked out for proper operation. Rod drop measurements were made with the following results:

Rod	Response Time (msec)	Drop Time (msec)	Total (msec)
1	14.1	488.9	503
2	34.3	466.7	501
3	34.3	474.7	509

The Regulating Rod is not scrammable.
These measurements were well within the Technical Specification limits of 50 msec (response time) and 700 msec (drop time).

The fuel elements were loaded in the reactor with the control rods positioned at 10 inches. Count rate data was obtained with the rods first at 10 inches and then 26 inches and a reciprocal multiplication curve was plotted. After the addition of the first two elements, in positions 44 and 35, the auxillary fission chamber was discovered not functioning properly. This problem was corrected and the core loading was accomplished with no further problems. When the count rate data indicated that criticality might be achieved with the addition of one more element a partial element was loaded first to check rod positions. Figure 1 shows a plot of the reciprocal multiplication data taken with the auxillary fission chamber.
The reactor first achieved criticality with the four control rod elements and 10 regular elements in the core at 3:38 P.M. on April 20, 1994 with the Regulating Rod and Shim Rods 1 and 2 fully withdrawn and Shim Rod 3 at 22.5 inches. The final configuration (LEU-1) is shown in Figure 2. A 4x4 loading was established with partial fuel elements in grid positions 23 and 26.

The critical rod positions for the LEU-1 configuration were:

Shim Rod 1 @ 12.66 inches   Shim Rod 3 @ 12.71 inches
Shim Rod 2 @ 12.68 inches   Reg. Rod @ 12.54 inches

The rods were then calibrated and yielded the following worths:

Shim Rod 1 = 3.46 %Δk/k   Shim Rod 3 = 2.41 %Δk/k
Shim Rod 2 = 3.86 %Δk/k   Reg. Rod = 0.375 %Δk/k

Integral rod worth curves for LEU-1 are shown in Figures 3 and 4.

The shutdown margin with the highest worth Rod 2 and the non-scrammable Reg Rod fully withdrawn was experimentally determined to be - 1.21 % Δk/k, which is well above the Technical Specification minimum of - 0.4 % Δk/k.
The excess reactivity was experimentally determined to be + 4.66 % Δk/k, which is below the Technical Specification limit of + 5.0 % Δk/k.

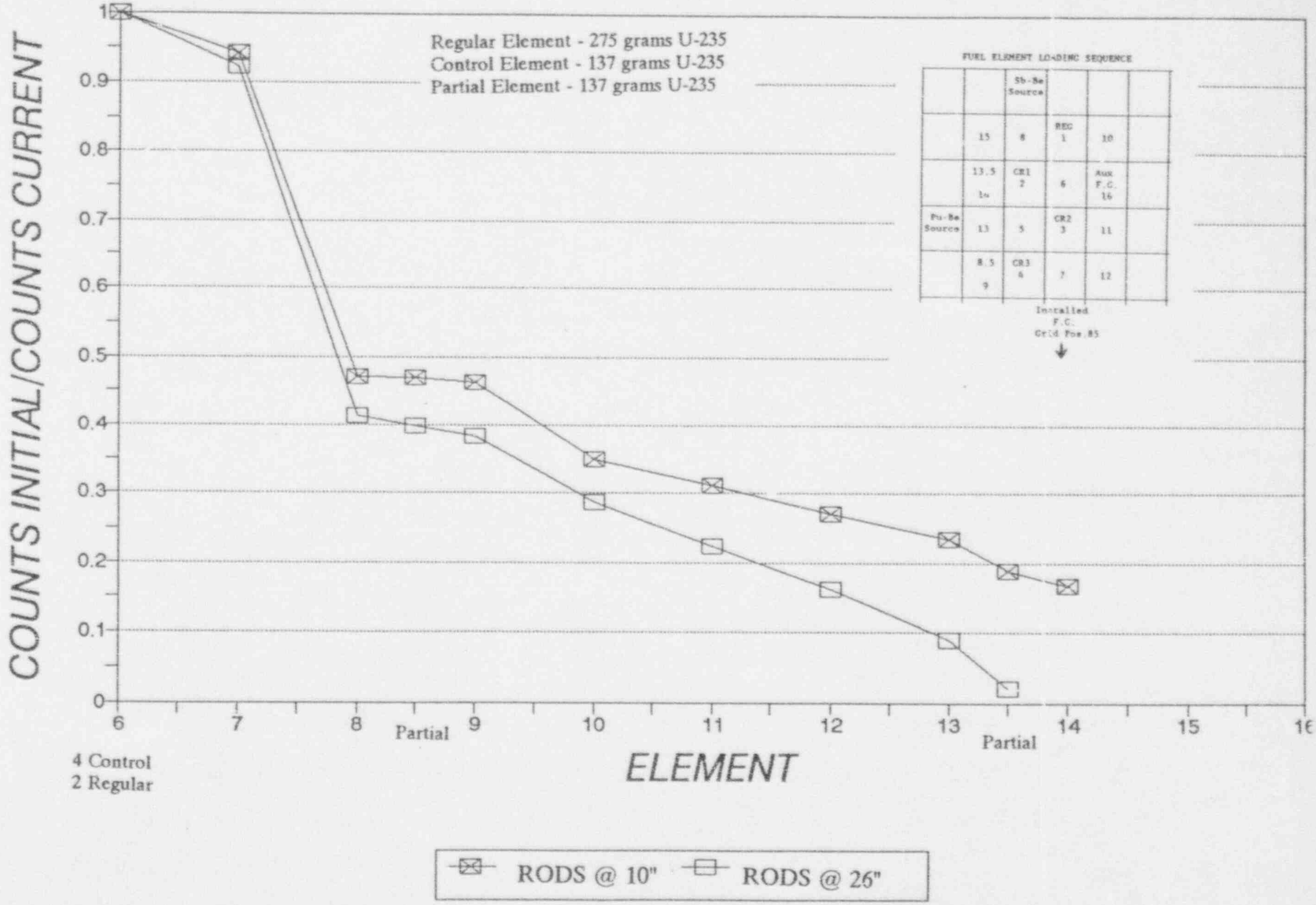

Figure 1. LEU-1, Approach to Critical

CORE LOADING LEU-1 SHUTDOWN MARGIN - 1.21 % delta k/k

Date April 21, 1994 EXCESS REACTIVITY + 4.66 % delta k/k

U-235 3571 GRAMS EXPERIMENT WORTH None % delta k/k

F - Normal Fuel Element
PF - Partial Fuel Element
CR - Control Rod Fuel Element
G - Graphite Element
S - Graphite Source Element
REG - Control Rod Fuel Element with Regulating Rod
P - Grid Plate Plug
HYD RAB - Hydraulic Rabbit
THER RAB - Thermal Pneumatic Rabbit
EPI RAB - Epithermal Pneumatic Rabbit
RB - Radiation Basket

Rod Worths #1 - 3.46 % #2 - 3.86 % #3 - 2.41 % Reg - 0.375 %

G 11	G 12	G 13	S 14	G 15	G 16	G 17	G 18
G 21	G 22	PF VP-002 23	F VS-002 24	F- REG VC-001 25	PF VP-001 26	G 27	G 28
G 31	G 32	F VS-004 33	F-CR1 VC-002 34	F VS-005 35	F VS-003 36	G 37	G 38
G 41	G 42	F VS-007 43	F VS-008 44	F-CR2 VC-003 45	F VS-009 46	G 47	G 48
G 51	G 52	F VS-010 53	F-CR3 VC-004 54	F VS-011 55	F VS-012 56	G 57	G 58
G 61	G 62	G 63	G 64	G 65	G 66	G 67	G 68
G 71	G 72	G 73	G 74	G 75	G 76	G 77	G 78
G 81	G 82	G 83	G 84	G 85	G 86	G 87	G 88

Figure 2. LEU-1 Core Loading Diagram

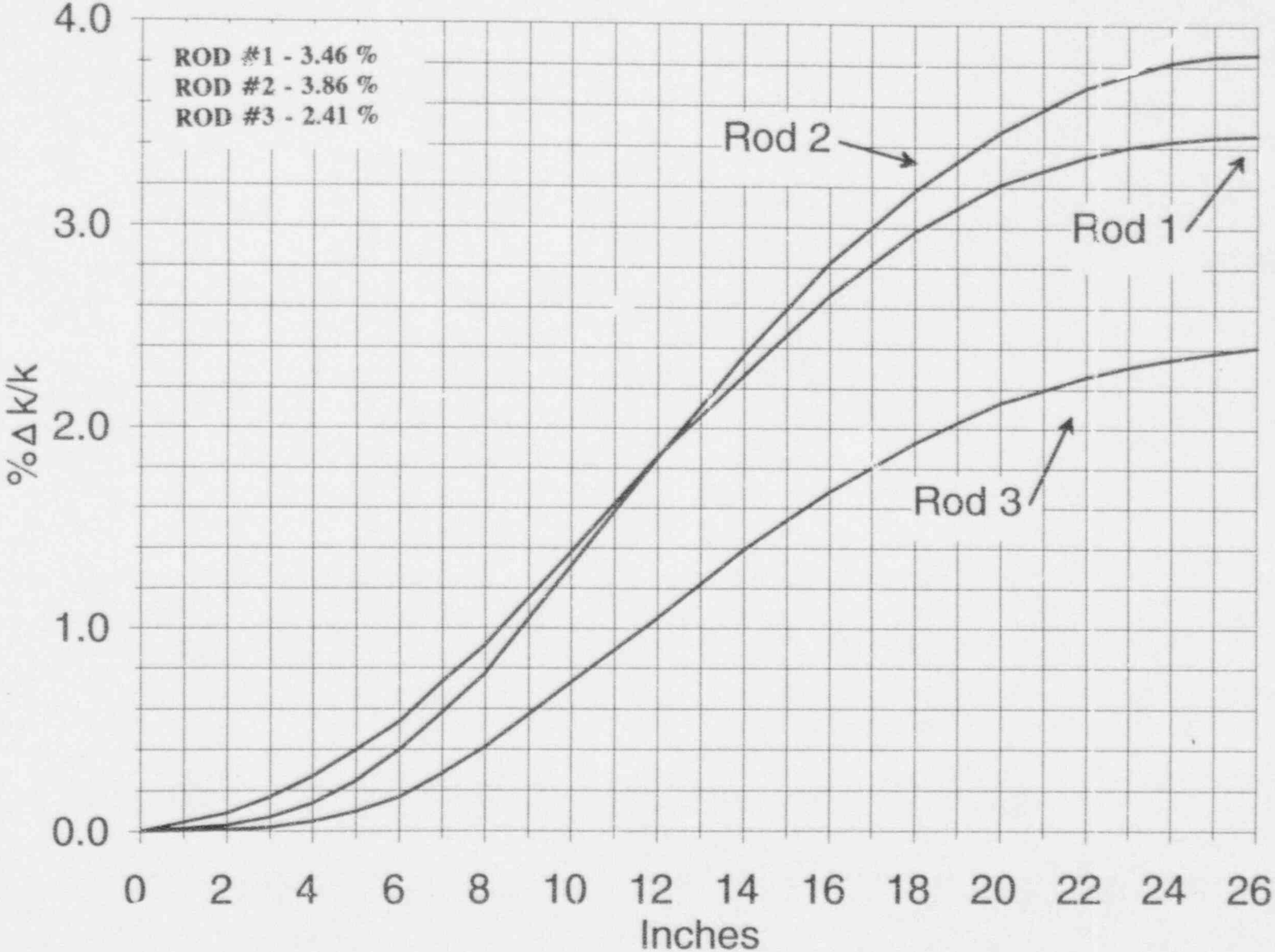

Figure 3. Integral Rod Worth, LEU-1 Shim Rods #1, #2, and #3

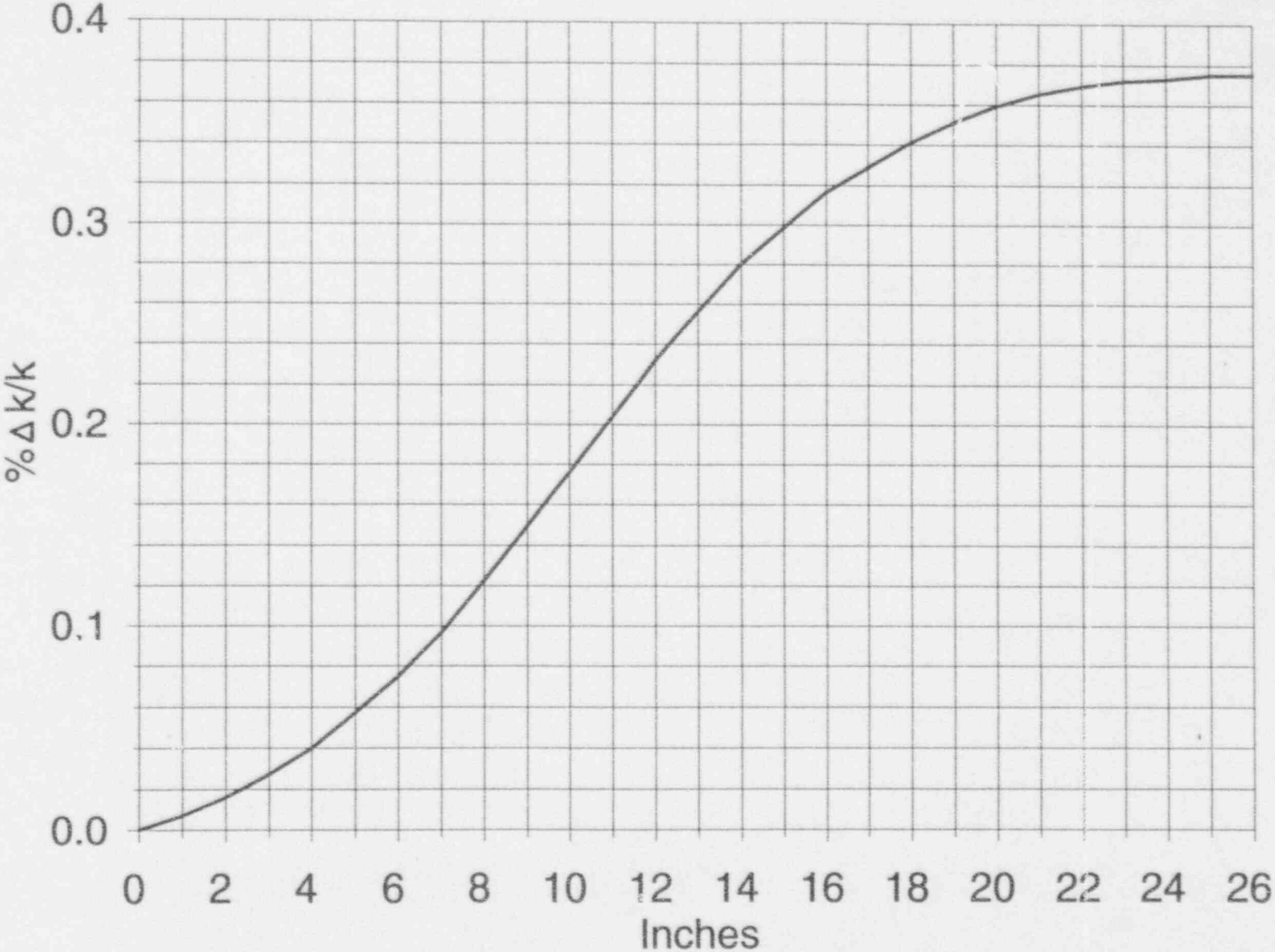

Figure 4. Integral Rod Worth, LEU-1 Regulating Rod

During the final adjustments to the core loading, determinations were made of the reactivity worth of a normal fuel element and a partial fuel element. The results were:

Partial fuel element in grid position 23 = + 1.43 $\%\Delta k/k$, and
Normal fuel element in grid position 23 = + 2.03 $\%\Delta k/k$

b) Flow Coastdown Measurements

Primary flow coastdown measurements were made on April 26, 1994 with the reactor core LEU-1 loaded and the reactor shut down. Figure 5 shows a graph of the measurement and comparison with SAR calculations. The slope of the measured coastdown very closely matches that predicted by the SAR. SAR calculations were performed with the header stuck up.

c) Void Coefficient Measurements

A set of two identical swords (see Figure 6) were constructed of acrylic that had voids built into them that extended uniformly over the length of the active fuel region of the core when inserted into a coolant channel of a fuel element. After measuring the volume of the void in the swords at the pressure associated with the depth of water at the core, one sword had vents cut into it to allow it to flood with water when immersed. These swords were placed in turn into three coolant channels in the LEU-1 core and the critical rod positions were noted for the six conditions (flooded sword in channel x, voided sword in channel x,...). The swords were located in the eighth fuel channel from the east side of the core in the following fuel elements: Element VS-007 in grid position 43, Element VS-008 in grid position 44, and Element VS-010 in grid position 53. To assure accuracy in the rod position measurements, the three shim rods were always placed in the same position after traveling in the same direction in all of the startups in the series performed for this experiment. The regulating rod was always moved in the inward direction for the final criticality adjustment. By paying particular care to the final direction of the rod motion, backlash in the gear train should not affect the rod position indication for a particular rod position. All rod positions were repeatable to within +/- 0.01 inches. The change in regulating rod position between when the flooded sword and the voided sword were in a given channel represents the worth of the void in that channel. To reduce the change in regulating rod position to reactivity, a divided difference interpolation of the regulating rod calibration data was performed.

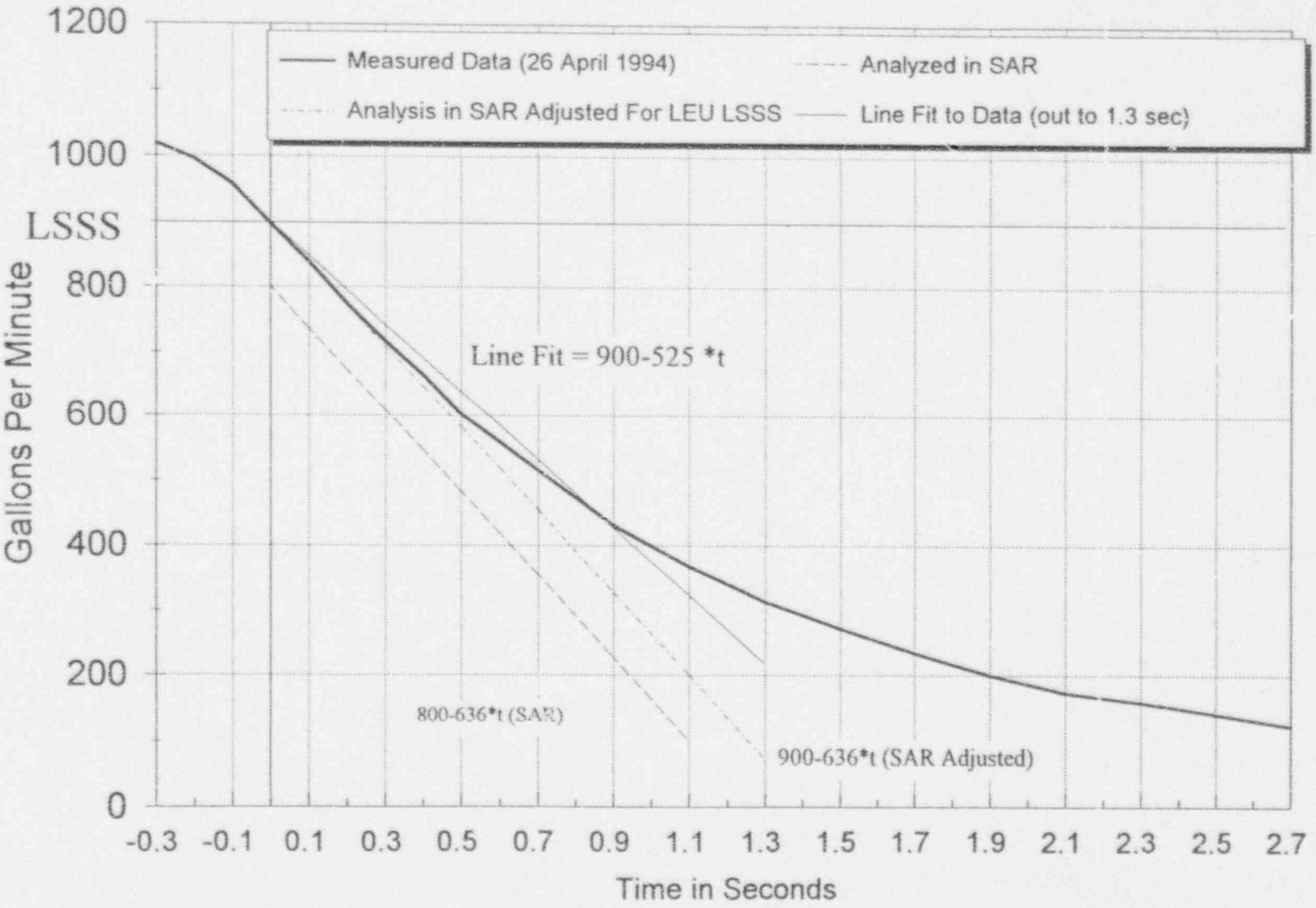

Figure 5. LEU-1 FLOW COASTDOWN, HEADER UP

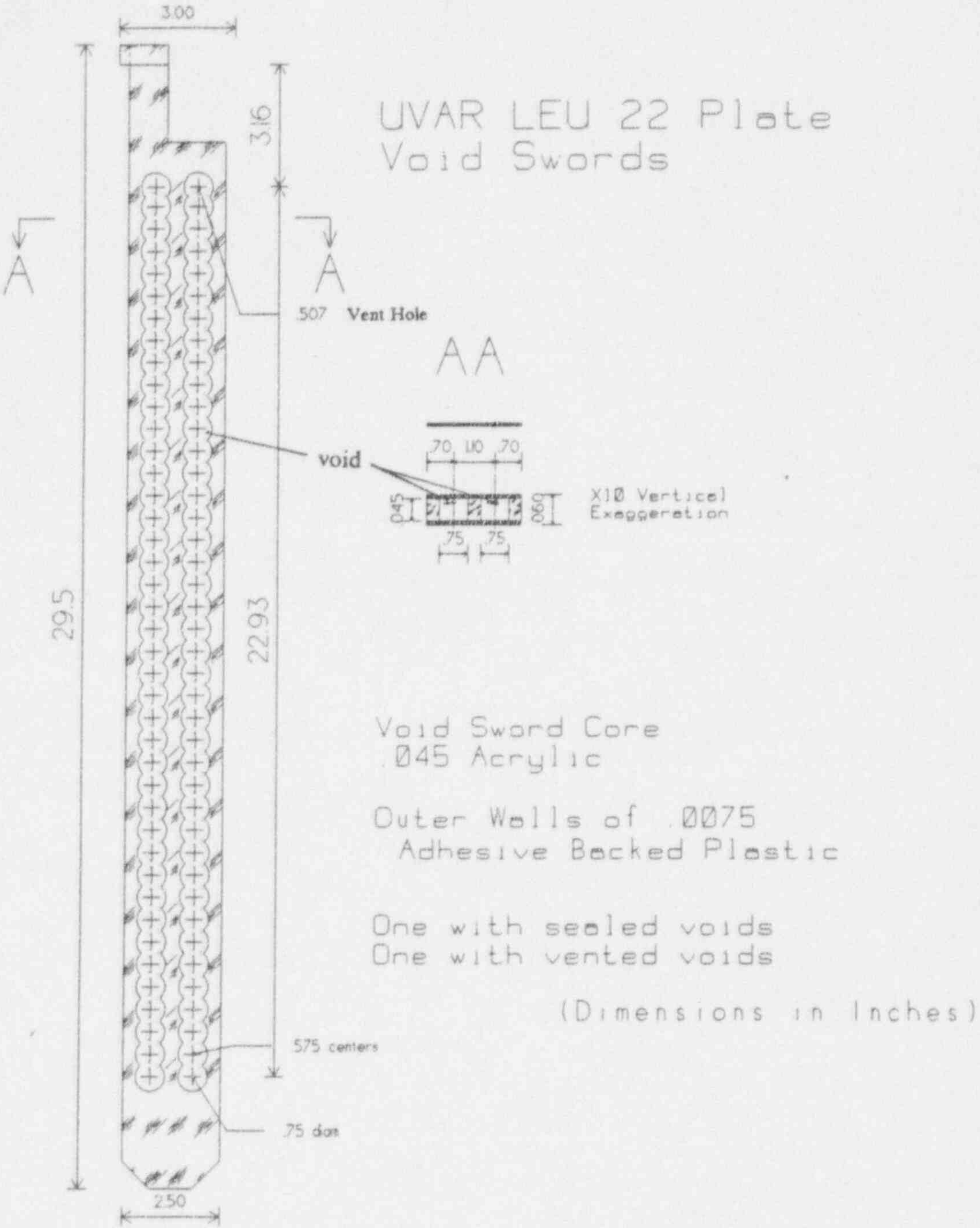

Figure 6. VOID SWORDS

A discussion on the vertical extent of the active core is in order. With the rods at about 12.5 inches from the bottom, the core should not be considered to be a full 24 inches tall. This could be important when considering the volume of the core and the volume of the void in the sword. By designing the swords so that the void was distributed uniformly over the vertical length of the fuel, any arbitrarily chosen height of the core affects the volume of the void to the same extent as the volume of the core.

The calculation of the relative size of the void in the sword to the volume of the core is reduced to a two dimensional problem in the xy plane. To express the size of the void as a percent of voidable volume of the core, the water areas in the xy plane were calculated by defining the total area of the core from the pitch of the grid of holes in the grid plate (4x4 elements) and subtracting out the area occupied by metal. Included in the metal were the side plates, fuel plates, and rod guide plates. Some of the water area thus defined is in the rod channels. The staff does not think the rod channels are voidable. They are defined by solid 0.125 inch aluminum guide plates that are separated from the fuel by coolant channels and are thus not directly heated. There would be no voiding in the rod channels during a nucleate boiling condition and the adjacent cooling channel would have to be essentially empty before the water in the rod channel would start to boil. Therefore, the staff carried through a calculation for the area of the water in the core excluding the rod channels as well as one including the rod channels. Similar calculations for the water area in the xy plane of an individual element were performed, again defining the total area from the pitch of the grid plate. The void in the experiment was then expressed as the ratio of the applicable water area to the effective area of the void in the void sword. The effective area of the void is the measured void volume (at pressure) divided by the length of the void in the sword. This gives the percent of the voidable volume in the core (both with and without the rod channels) or an individual element represented by the actual void in the sword.

By dividing the reactivity measured for the void in the sword at a particular location in the core by the percent voidable area (or volume by considering an arbitrary dimension in z) represented by the sword we get the results in units of % $\Delta k/k$ per % void for the various voidable volumes considered above. The experiment was performed in three distinct locations in the core chosen so that by applying four fold symmetry, a representative value for all of the non-rodded elements in the core was obtained. The regulating rod, being different from the shim rod in composition, prevents full symmetry from being achieved.

The data reported here should not be construed to be valid for uniform voiding of the core or for voiding in the heat generation pattern resulting from boiling (nucleate or bulk boiling) that would occur in an overpower transient. Rather, the results are from an experiment that could be feasibly performed within the

operating restrictions of the UVAR reactor.

The following measurements were made:

	Reg Rod (inches)	Reactivity Worth (% $\Delta k/k$)	Worth of Void (% $\Delta k/k$)
Flood in VS-008	11.78	0.228	
Void in VS-008	12.31	0.242	-0.014
Flood in VS-007	11.88	0.231	
Void in VS-007	12.23	0.240	-0.009
Flood in VS-010	11.65	0.225	
Void in VS-010	12.15	0.238	-0.013
Clean	11.11	0.210	

The results of the void coefficient measurement are as follows:

	VS-008	VS-007	VS-010
(% $\Delta k/k$/%Void Core) With Rod Channels	-.192	-.126	-.178
(% $\Delta k/k$/%Void Core) Without Rod Channels	-.163	-.111	-.155
(% $\Delta k/k$/%Void Element)	-.009	-.006	-.008

The LEU-1 reference reactor core was then unloaded.

V. Loading of Operational Core

a) Initial Criticality (LEU-2 Core)

The control rods were repositioned in the grid plate on April 29, 1994 to establish a configuration for routine operation to accommodate planned experiments. Rod drop measurements were repeated with the following results.

Rod	Response Time (msec)	Drop Time (msec)	Total (msec)
1	13.1	486.9	500
2	28.3	469.7	498
3	20.2	469.7	489.9

The Regulating Rod is not scrammable.
These measurement results were also well below the Technical Specification maximum limits for rod response and drop times (see page 3).

Fuel was added to the core, one element at a time, with the rods held at 10 inches. Reciprocal multiplication data was taken with the rods at 10 inches and 26 inches. Figure 7 shows a plot of the reciprocal multiplication curve and Figure 8 provides an expanded scale for the reciprocal multiplication data corresponding to the last few elements.

Criticality was achieved on May 6, 1994 and the final configuration (LEU-2) was established on May 10, 1994. A diagram of the loading is shown in Figure 9. This loading is a 4 x 5 array of fuel with a partial element in grid position 24. Hot Thimble experiments were loaded in grid positions 53 and 55 and the critical rod positions for this configuration were:

Shim Rod 1 @ 25.65 inches	Shim Rod 3 @ 0.00 inches
Shim Rod 2 @ 12.52 inches	Reg Rod @ 17.60 inches

The rods were then calibrated, yielding the following worths:

Rod 1 = 2.80 $\%\Delta k/k$	Rod 3 = 1.84 $\%\Delta k/k$
Rod 2 = 2.63 $\%\Delta k/k$	Reg Rod = 0.401 $\%\Delta k/k$

Integral rod worth curves for LEU-2 are shown in Figures 10 and 11.
The shutdown margin with Rod 1 and the Regulating Rod fully withdrawn was experimentally determined to be - 1.2 $\%\Delta k/k$, well above the minimum of - 0.4 $\%$ $\Delta k/k$ required by the Technical Specifications.

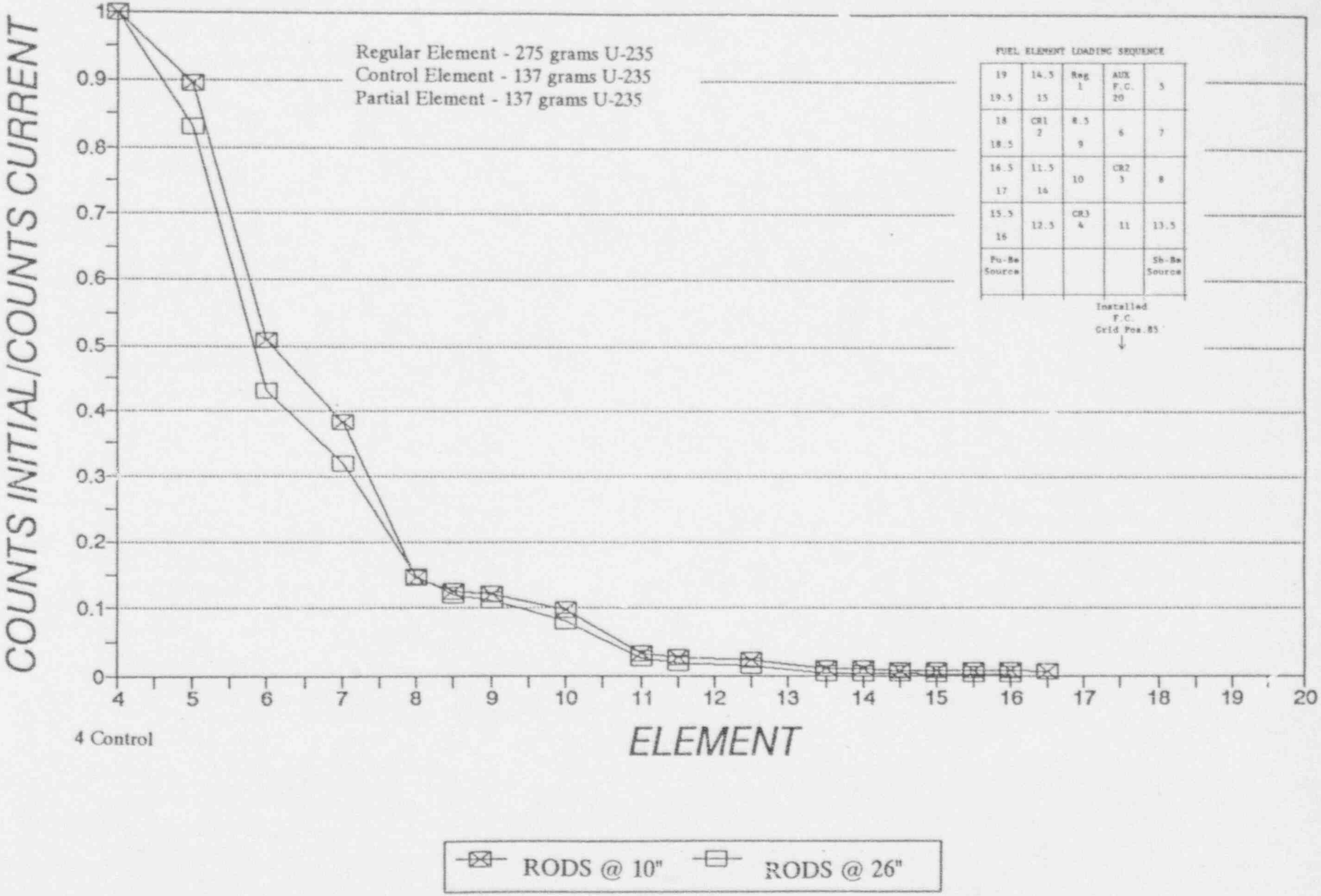

Figure 7. LEU-2 Approach to Critical

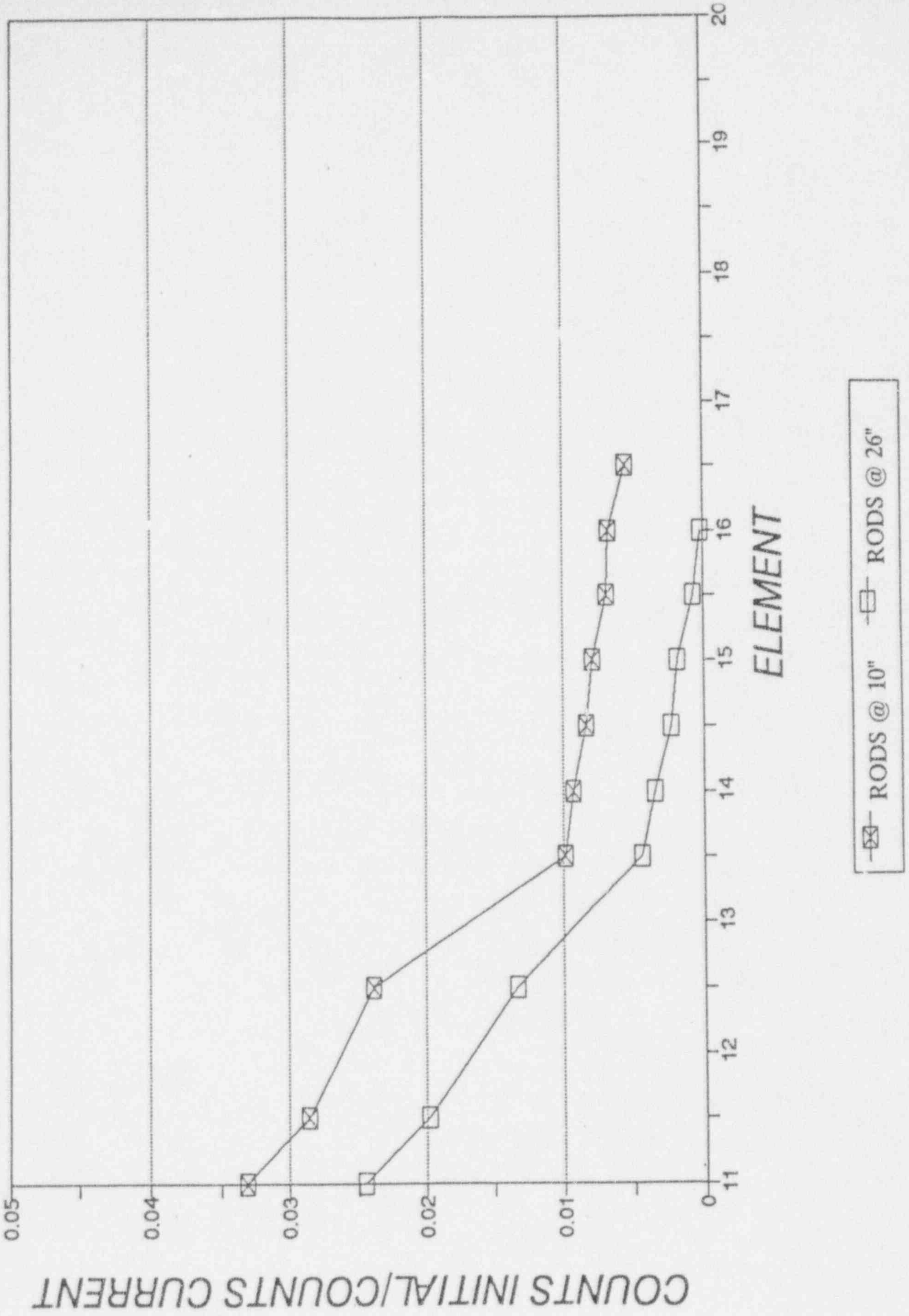

Figure 8. LEU-2 Approach to Critical (Expanded Scale)

CORE LOADING LEU-2 SHUTDOWN MARGIN - 1.2 % delta k/k

Date June 13, 1994 EXCESS REACTIVITY + 3.27 % delta k/k

U-235 4807 GRAMS EXPERIMENT WORTH 1.63 % delta k/k

F - Normal Fuel Element
PF - Partial Fuel Element
CR - Control Rod Fuel Element
G - Graphite Element
S - Graphite Source Element
REG - Control Rod Fuel Element with Regulating Rod
P - Grid Plate Plug
HYD RAB - Hydraulic Rabbit
THER RAB - Thermal Pneumatic Rabbit
EPI RAB - Epithermal Pneumatic Rabbit
RB - Radiation Basket

Rod Worths #1 - 2.80 % #2 - 2.63 % #3 - 1.84 % Reg - 0.401 %

MINERAL IRRADIATION FACILITY

P 11	F VS-015 12	F VS-009 13	F-REG VC-001 14	F VS-013 15	F VS-004 16	CANISTER IRR. FAC. 17	P 18
P 21	F VS-006 22	F-CR1 VC-002 23	PF VP-001 24	F VS-007 25	F VS-008 26	27	P 28
G 31	F VS-001 32	F VS-010 33	F VS-011 34	F-CR2 VC-003 35	F VS-012 36	37	P 38
G 41	F VS-014 42	F VS-003 43	F-CR3 VC-004 44	F VS-002 45	F VS-005 46	47	P 48
G 51	G 52	HT-1 53	G 54	HT-3 55	S 56	57	P 58
G 61	G 62	G 63	EPI RAB 64	G 65	G 66	G 67	G 68
G 71	G 72	THER RAB 73	G 74	G 75	HYD RAB 76	G 77	G 78
G 81	G 82	G 83	G 84	G 85	G 86	G 87	G 88

Figure 9. LEU-2 Core Loading Diagram

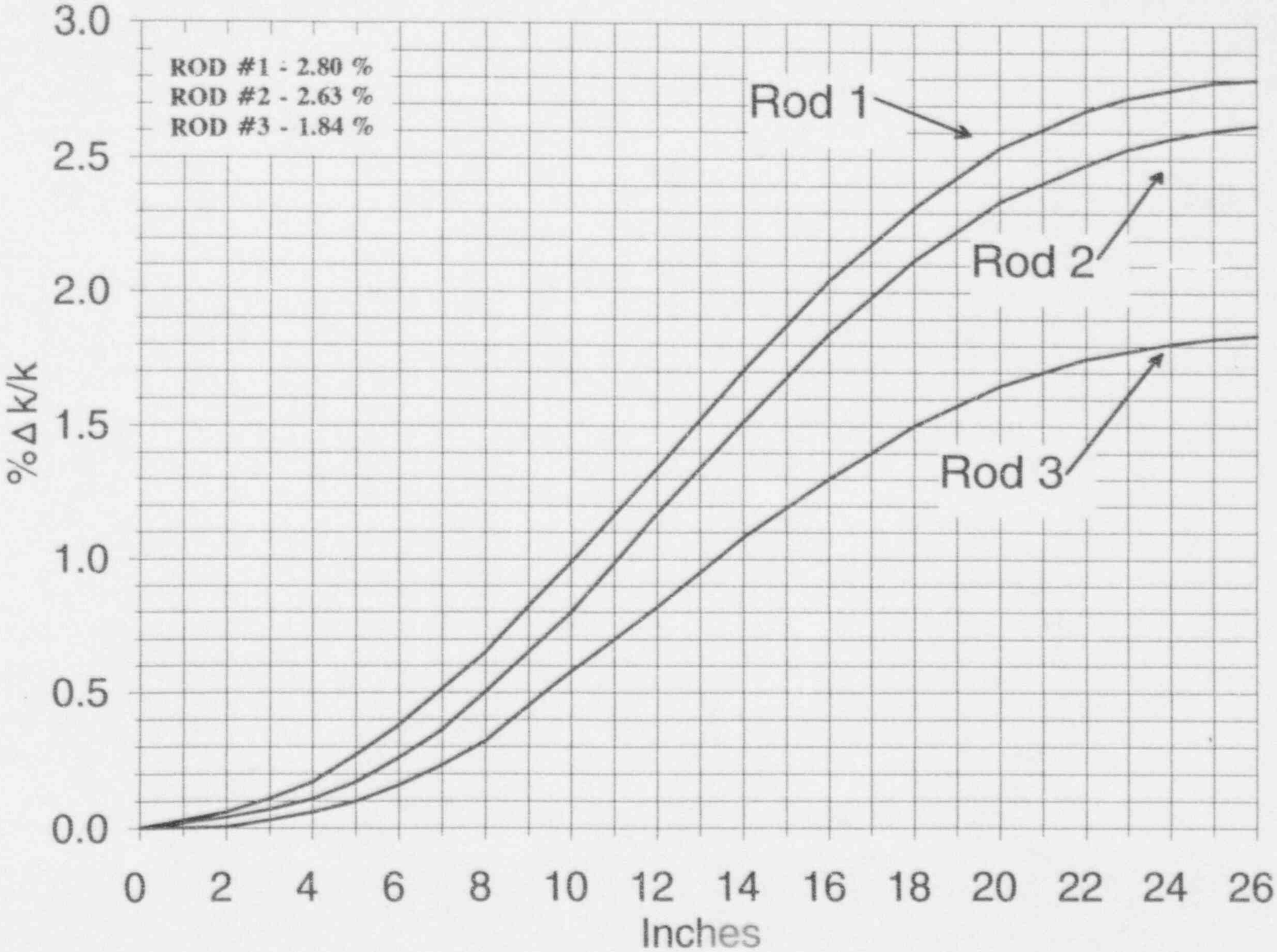

Figure 10. Integral Rod Worth, LEU-2 Shim Rods #1, #2, and #3

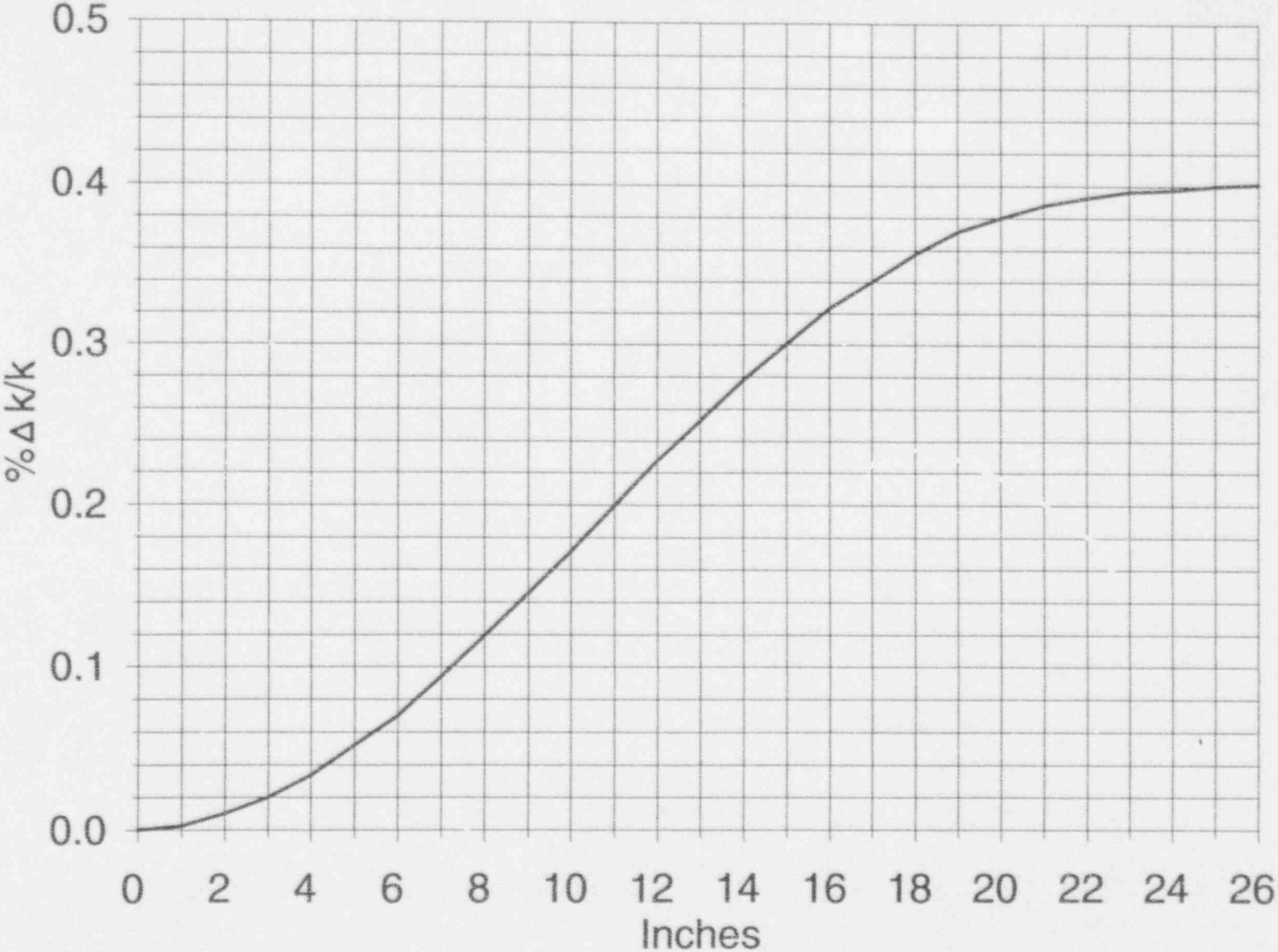

Figure 11. Integral Rod Worth, LEU-2 Regulating Rod

The excess reactivity of LEU-2 was measured experimentally to be + 3.27 % $\Delta k/k$, well below the + 5.0 % $\Delta k/k$ limit required by the Technical Specifications.

b) Experimental Facilities

Before operating at any appreciable power, various experimental facilities were installed in the reactor and the reactivity worth of each facility was determined with the following results:

Experimental Facility	Worth (%$\Delta k/k$)
Epi-Thermal Rabbit, grid position 64	- 0.01
Thermal Rabbit, grid position 73	- 0.01
Hot Thimble #1, with specimens, grid position 53	- 0.28
Hot Thimble #3, without specimens, grid position 55	- 0.54
Canister Irradiation Facility, east side of core	- 0.04

The sum of the absolute worth of the experimental facilities is 0.88 %$\Delta k/k$, well below the 2 %$\Delta k/k$ limit for all experiments required by the Technical Specifications.

c) Approach to Full Power

The initial approach to power with the LEU-2 core was begun on the afternoon of May 12, 1994. The power was leveled out at 200 kW, 500 kW, 1 MW, and finally 2 MW to check instrument response and to perform radiation surveys. Full power of 2 MW was achieved at about 5:20 P.M. Radiation surveys at the reactor bridge and around experimental areas showed no increase in radiation levels as compared to the HEU core.

d) Power Coefficient Measurement

The reactor was taken critical at low power in a xenon-free condition and the critical rod positions were noted. Rod #2 was withdrawn about 0.5 inch to put the reactor on a positive period. Doubling times were measured with a stop watch using the linear instrument. The power was allowed to rise until it leveled off at 870 kW due to negative temperature effects. The average temperature rise across the core was noted. The doubling times were converted to reactivity and matched almost exactly with the reactivity worth of rod #2 when it was withdrawn as determined from the rod worth curve. The power coefficient was experimentally verified to be -0.139 %$\Delta k/k$/MW or in terms of the change in average core temperature - 0.0275 %$\Delta k/k/^oF$. It is noted that this measurement includes several effects such as the fuel doppler, fuel expansion, and moderator temperature coefficients. The moderator temperature coefficient was measured separately.

e) Moderator Temperature Coefficient Measurement

The reactor was operated all day at full power on May 13, 1994 and the pool temperature was 97.9 °F when the reactor was shut down. The cooling systems were secured and the reactor remained shut down for three days to allow Xenon to decay. The reactor was taken critical at low power on May 16, 1994. The pool temperature was 86.9 °F and the ΔT was 0.0 °F. The secondary cooling system was energized and the pool was allowed to cool down. The power level was maintained by adjusting Rod #2. The pool was cooled for 1.5 hours. The Core outlet temperature changed by 11.24 °F. Rod #2 moved from 14.39 inches at the beginning of the test to a final position of 14.16 inches. The reactivity associated with this change was obtained from the rod worth curves and determined to be 0.05 % $\Delta k/k$.

Rod #2 was then moved back to it's original position of 14.39 and doubling times were taken to determine the reactivity associated with the rod movement as a check against the rod curves. The reactivity associated with the doubling times was 0.039 % $\Delta k/k$. Due to incomplete mixing from the cooldown the moderator temperature increased 2.06 °F during this measurement giving a temperature differential 9.18 °F as compared with the original temperature. An average of these measurements yielded a value of - 0.0044 %$\Delta k/k$/°F for the moderator temperature coefficient.

f) Experimental Facilities

Between May 23, 1994 and June 10, 1994, several other experiments were loaded in the reactor, giving the following experiments and experimental facilities now in the reactor.

		Worth (% $\Delta k/k$)
1.	Epi-Thermal Rabbit, grid position 64	- 0.01
2.	Thermal Rabbit, grid position 73	- 0.01
3.	Hot Thimble #1, with specimens, grid position 53	- 0.28
4.	Hot Thimble #3, without specimens, grid position 55	- 0.54
5.	1.2 kg of Fe samples in H.T. #3	+ 0.05
6.	Cannister Irradiation Facility (East side of core)	- 0.04
7.	MIF Stand, front of core on pool floor	0.00
8.	MIF Lead Shield, front of core on MIF stand	+ 0.33
9.	MIF Box, Model 3, #2 (Gas cooled), North side of core	- 0.37

The sum of the absolute worth of the experimental facilities is 1.63 %$\Delta k/k$, which is below the Technical Specification limit of 2.0 % for all experiments..

VI. Comparison Between LEU and HEU Cores

The LEU-1 core was similar to an HEU core operated in 1975. They were both 4x4 configurations surrounded by graphite. Due to the increased U-235 content of the LEU fuel, with changes from 18 to 22 plates per element, partial elements were loaded in grid positions 23 and 26 in the LEU core. Comparisions of the two cores are as follows:

	HEU Core (2.73 kg U-235)	LEU-1 Core (3.57 kg U-235)
Rod Worth (% Δk/k)		
Rod #1	3.56	3.46
Rod #2	3.75	3.86
Rod #3	2.30	2.41
Reg Rod	0.428	0.375
Shutdown Margin (% Δk/k) (Rod #2 and Reg withdrawn)	- 2.7	- 1.21
Excess Reactivity (% Δk/k)	+ 3.35	+ 4.66

The control rod worths that were computed for both the HEU and LEU-1 cores were in good agreement with these measured values.

A comparison of the measurements made with the LEU fuel and predictions in the LEU SAR, and HEU comparisons, where available, are presented below.

The "Power" temperature coefficient was measured during a core-heat-up experiment. It is expressed as the change in Δk/k per average change in core temperature. This is not the same conceptually as the isothermal moderator temperature coefficient, which was measured during a pool-cool-down experiment at low power.

	LEU Core	LEU-SAR	HEU Core
Power Coeff. (% $\Delta k/k/MW$)	- 0.139	NA	NA
"Power" Temperature Coefficient (% $\Delta k/k/°F$)(LEU-2)	-.0275	NA	-.0288
Moderator Temp. Coefficient (% $\Delta k/k/°F$) (LEU-2)	-.0044	-.0082	NA
Void Coefficient (uniform) (% $\Delta k/k/$% void) (LEU-1)	- 0.19	- 0.22	NA

The most significant observation is that the "Power" temperature coefficients for the old HEU and new LEU-2 cores are almost identical, signifying that the safety characteristics of the two cores are essentially the same.

The isothermal moderator temperature coefficient value is clearly different from the "Power" temperature coefficient value, but it was not expected to be comparable. The measured isothermal moderator temperature coefficient is about a factor of 2 smaller than the value calculated for an ideal unrodded LEU core model. Considering experimental uncertainties in the measurement, and the lack of partially inserted control rods in the computational model, the agreement is judged to be acceptable.

The void coefficient measurements lie in the range of the calculated void coefficients. Local experimental differences are expected to be caused by the presence of partially inserted control rods in the core.

VII. Shipment of All HEU Fuel Elements From Facility

All HEU fuel (32 elements) was shipped to Savannah River in the BMI-1 shipping cask in three shipments made on May 4, 1994, June 6, 1994, and July 8, 1994, respectively.

VIII. Pool Water Analysis

During the month after the UVAR reactor had been operated at full power with LEU fuel, daily samples were taken of the reactor pool water and analyzed for specific isotopes. There was no indication of fission product activity in the pool water, attesting to the integrity of the new LEU fuel. The most predominant isotope found in the pool water was Na-24 from the activation of aluminum. This is normally found in the water since Al makes up most of the structural material in and around the reactor. A tabulation of the analysis is shown in Table 1.

Normal weekly pool water samples after operating for over three months have shown no increase in activity in the pool.

IX. Summary

The UVAR has been successfully converted from HEU to LEU fuel. The initial criticality predictions for 4-by-4 and 4-by-5 LEU core configurations were qualitatively correct, leading to a practical LEU-2 core configuration that meets all Technical Specification requirements. The prediction that control rod worths would not be very different between HEU and LEU cores was borne out. Void coefficient measurements agree reasonably well with prior predictions. Temperature coefficient measurements are fairly comparable between HEU and LEU cores. And finally, flow coastdown measurements confirm that adequate cooling is available.

Additional core-specific computational work is in progress to resolve minor uncertainties. Otherwise, the experimental verification tests are essentially finished and the UVAR is back in routine full-time operation.

Table 1. UVAR Pool Water Analysis

UVAR Reactor Pool Water Analyses with LEU Fuel (μCi/ml)													
Isotope	Na-24	Mn-54	Mn-56	Mg-27	Cl-38	Cr-51	W-187	Sb-122	Ar-41	Xe-135	Xe-133	I-131	Co-60
½ life	15.0h	312d	2.6h	9.5m	37.3m	27.7d	23.9h	2.7d	1.8h	9.1h	5.3d	8.0d	5.3y
EC **	5.0E-5	3.0E-5	7.0E-5	—	—	5.0E-4	3.0E-5	1.0E-5	—	—	—	1.0E-6	3.0E-6
5/12	1.0E-4		5.5E-6	2.9E-3	1.5E-5				6.1E-4				
5/13	5.5E-4		1.5E-5	1.3E-4	9.7E-6	<4.3E-6	<2.3E-6	<9.1E-7	7.0E-4	<4.7E-7	<1.1E-6	<5.3E-7	<8.3E-7
5/16	2.2E-4		5.7E-6	1.8E-3	1.9E-5	<3.5E-6	<1.9E-6	<7.5E-7	7.2E-4	<3.9E-7	<9.0E-7	<4.3E-7	<5.3E-7
5/17	2.6E-4		5.2E-6	2.9E-3	2.3E-5	<4.2E-6	<2.2E-6	<9.0E-7	6.2E-4	<4.5E-7	<1.0E-6	<5.1E-7	<6.0E-7
5/18	6.4E-4		9.7E-6	4.1E-3	1.8E-5	<5.1E-6	<2.8E-6	<1.1E-6	8.5E-4	<5.6E-7	<1.3E-6	<6.3E-7	<9.1E-7
5/19	3.9E-4		1.1E-6	<1.2E-4	<7.5E-6	<2.8E-6	1.5E-6	5.7E-7	5.6E-5	<3.1E-7	<7.2E-7	<3.5E-7	<6.7E-7
5/20	9.8E-5		<4.2E-7	<4.9E-5	<3.6E-6	1.0E-6	8.9E-7	<3.2E-7	<5.3E-7	<1.6E-7	<4.2E-7	<1.8E-7	<3.5E-7
5/23	1.5E-6	<5.4E-8	<1.1E-7	<1.6E-2	<2.9E-6	2.6E-7	1.8E-7	<6.8E-8	<1.8E-7	<4.7E-8	<1.5E-7	<4.2E-8	<6.2E-8
5/24	9.4E-7	<3.0E-8	<2.5E-7		<4.3E-4	2.0E-7	<1.2E-7	4.8E-8	6.1E-7	<3.9E-8	<9.1E-8	<2.4E-8	3.8E-8
5/25	3.3E-4		6.1E-6	<1.4E-4	<7.1E-6	<3.1E-6	<1.7E-6	<6.8E-7	3.5E-4	<3.5E-7	<8.0E-7	<3.8E-7	<8.4E-7
5/26	6.1E-4		1.8E-5	2.5E-3	1.2E-5	<2.9E-6	1.1E-6	<6.3E-7	8.8E-4	2.6E-7	<7.4E-7	<3.6E-7	<5.9E-7
5/27	5.5E-4	<6.0E-8	8.4E-6	<1.7E-2	<2.2E-5	1.1E-6	1.1E-6	3.0E-7	4.4E-4	2.6E-7	<1.2E-7	<3.4E-8	<4.8E-8
5/31	5.8E-4		1.3E-5	8.8E-4	7.0E-6	<4.5E-6		<9.6E-7	8.0E-4	<5.0E-7	<1.1E-6	<5.5E-7	<8.5E-7
6/1	6.4E-4		2.6E-4	3.3E-3	1.9E-5	<5.2E-6		<1.1E-6	8.3E-4	<5.7E-7	<1.3E-6	<6.4E-7	<9.2E-7
6/2	6.5E-4		1.1E-5	3.5E-4	5.7E-6	<4.7E-6	<2.5E-6	<1.0E-6	7.2E-4	<5.1E-7	<1.2E-6	<5.8E-7	<9.3E-7
6/3	7.4E-4		1.6E-5	5.3E-4	<1.1E-5	<4.9E-6	1.9E-6	<1.1E-6	8.2E-4	<5.4E-7	<1.2E-6	<6.1E-7	<9.7E-7
6/6	9.7E-6	6.7E-8	<3.3E-7		<6.9E-4	6.7E-7	2.1E-7	1.1E-7	<9.2-7	<5.0E-8	<1.1E-7	<3.0E-8	<4.7E-8
6/7	2.7E-6	1.8E-8	<5.5E-7		<2.1E-2	5.5E-7	1.0E-7	8.7E-8	<2.3E-6	<4.3E-8	<7.8E-8	<2.1E-8	<2.9E-8
6/8	5.1E-7	<3.1E-8	<2.2E-7		<2.8E-4	4.6E-7	<1.2E-7	5.7E-8	<6.3E-7	<3.9E-8	<9.1E-8	<2.4E-8	<3.5E-8
6/9	1.1E-7	<2.8E-8	<2.7E-7		<6.6E-4	2.2E-7	<1.1E-7	4.5E-8	<8.1E-7	<3.9E-8	<8.9E-8	<2.3E-8	<3.1E-8
6/10	4.5E-5	<7.6E-7	2.3E-4	2.6E-3	7.7E-6	<4.3E-6	<2.4E-6	<1E-6	2.0E-4	<4.6E-7	<1.1E-6	<5.3E-7	<3.9E-7
Isotope	Na-24	Mn-54	Mn-56	Mg-27	Cl-38	Cr-51	W-187	Sb-122	Ar-41	Xe-135	Xe-133	I-131	Co-60

** Effluent Concentration limit from 10CFR20, App B, Table 2, Column 2, μCi/ml

Attachment 1

LEU FUEL CONVERSION TEST PROGRAM

Low Enriched Uranium Fuel Core Conversion Program

University of Virginia Nuclear Research Reactor

15 February 1994

License No. R - 66

Docket No. 50 - 62

University of Virginia
School of Engineering and Applied Science
Department of Mechanical, Aerospace, and Nuclear Engineering
Nuclear Reactor Facility
Charlottesville, Virginia
22903-2442

Table of Contents

Introduction

This program is the Low Enrichment Uranium (LEU) core conversion program for the University of Virginia Nuclear Reactor Facility mandated by the NRC. The Nuclear Regulatory Commission (NRC) requires ("to the extent that measurements are possible") a number of measurements to verify core operability and safety. In this test program measurements or calculations will be made for the following items:

1. Initial loading measurements;
2. Critical mass;
3. Excess (operational) reactivity;
4. Shut-down margin;
5. Control Rod worths;
6. Partial fuel element worths;
7. Void coefficient;
8. Primary pump flow coast-down;
9. Primary flow;
10. Experimental facility and experiment worths;
11. Temperature and Power coefficients;
12. Reactor power calibration;
13. Reactor pool water fission product activities.

A report will be made, within six months of initial core loading, compiling all data and comparing all results against available HEU core measurements and LEU predictions. The report will also include explanations of any significant differences found during comparisons that could affect both normal operation and possible accidents with the reactor.

The measurement of the effective delayed neutron fraction ($\overline{\beta}_{eff}$) will not be undertaken during the initial conversion period. It is felt that the cost in time and money to undertake this measurement is too great. Extensive computer calculations of $\overline{\beta}_{eff}$ have been made[1]. These calculated values of $\overline{\beta}_{eff}$ show no difference from the HEU $\overline{\beta}_{eff}$ of 0.0074. The $\overline{\beta}_{eff}$ of 0.0074 will be used for the UVAR LEU fuel.

Thermal neutron flux distribution will not be measured since correlations with calculated data could not be made without much more time and experimentation. If interest and funding become available these two measurements may be considered for graduate research.

Relative flux measurements at the experimental facilities will be done after the conversion process only as necessary for specific experimental requirements.

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[1] Freeman, D., Neutronic Analysis for the UVAR Reactor HEU to LEU Conversion Project, Masters Thesis, University of Virginia, January 1990.

Procedures for this program which do not utilize the UVAR Standard Operating Procedures have been written specifically for the test they control. They are approved only for the duration of the conversion program (until the UVAR is returned to normal (unrestricted) operations).

As with all procedures, these are structured and cannot cover all contingencies. The UVAR LEU Conversion Program is an experimental test program and situations may arise where other steps or methods may be more appropriate. Therefore, these procedures may be deviated from by approval of the Facility Director when the deviation does not change the original intent of the existing procedure. Deviations which change procedure intent must have prior approval of the Reactor Safety Committee. All deviations must be documented.

LEU conversion time line

<table>
<tr><th>Time (week)</th><th>Priority 1 item</th><th>Priority 2 item</th><th>Priority 3 item</th></tr>
<tr><td>-2</td><td>1. Construct void swords.</td><td>1. Construct/gather necessary additional electronic equipment.</td><td></td></tr>
<tr><td>-1</td><td>1. Trial fit swords in new fuel.
2. Pressure test void swords.</td><td>1. Op check additional electronic equipment/ready for installation.</td><td>1. Install second fission chamber in core grid plate & source check.</td></tr>
<tr><td>0</td><td>1. Load the referenced/ calculated core.</td><td>1. Obtain subcritical mult. data;
2. Obtain critical mass data;
3. Determine rod worths.</td><td>1. Calculate operational shut-down margin;
2. Calculate excess reactivity.</td></tr>
<tr><td rowspan="2">+1</td><td rowspan="2">Referenced core in place.</td><td>1. Measure partial element reactivity;
2. Measure core flow and flow coast-down.</td><td rowspan="3">1. Calculate partial element worth.</td></tr>
<tr><td rowspan="2">1. Measure void reactivity.</td></tr>
<tr><td rowspan="2">+2</td><td>Referenced core in place.</td></tr>
<tr><td>Establish working core configuration.</td><td>1. Obtain subcritical mult. data;
2. Obtain critical mass data.</td><td></td></tr>
<tr><td>+3</td><td>Working core in place.</td><td>1. Determine rod worths;
2. Load non-fixed experiments;
3. Measure reactivity of non-fixed experiments.</td><td>1. Calculate operational shut-down margin;
2. Calculate excess reactivity.</td></tr>
<tr><td>+4</td><td>1. Ramp to 500 kW.
2. Ramp to 1.0 MW.
3. Ramp to 1.5 MW.
4. Ramp to 2.0 MW.
5. Ramp to 2.0 MW.</td><td>1. Perform power calibrations (each pwr level);
2. Measure power & temperature coefficient reactivity, ramp from 200 kW - 2.0 MW.</td><td>1. Calculate temperature coefficient.</td></tr>
<tr><td>+5</td><td>1. Resume normal operations.</td><td>1. Obtain and analyze pool water samples daily.</td><td>1. Compare & correlate LEU/HEU data as applicable - start writing report.</td></tr>
</table>

Time (week)	Priority 1 item	Priority 2 item	Priority 3 item
+6	Normal operations.	1. Obtain and analyze pool water samples daily.	1. Compare & correlate LEU/HEU data as applicable - continue writing report.
+7	Normal operations.	1. Obtain and analyze pool water samples daily.	
+8	Normal operations.	1. Obtain and analyze pool water samples daily.	

Month 4 - send preliminary report to ReSC (circulate for staff review prior to all submittals)

Month 5.5 - send final report to ReSC and NRC

Prerequisites
for
LEU Conversion

I. Prerequisites Checklist

The steps of this checklist may be completed in any order. It is to be used as a quick indication of which Prerequisite sections have been or have yet to be completed.

____ Void swords have been manufactured and tested as per *Preparations for Void Measurements*, pg. 7,.

Date: ________ by: ______________________________

____ Void Constants are:

$Void_{tp}$ = ________________

Voidable Volume of reactor = ________________

% Void = ________________

Date: ________ by: ______________________________

____ Primary Flow coastdown amplifier has been manufactured and tested as per *Preparations for Coastdown Measurements*, pg. 10.

Date: ________ by: ______________________________

____ Additional source range instrumentation and detector has been tested and is ready for installation and source check.

Date: ________ by: ______________________________

III. Preparations for Void Measurements

A. Construction of Swords and Test Chamber

1. The swords will be made of three layers of plastic with the middle layer cut in a pattern that allows a reasonable compromise between amount of void and support of the voided area. Both swords will be constructed with the same pattern and the flooded sword will have flood and vent holes at the top and bottom to allow water to flood the entire open area in the pattern. At least one of the side layers should be clear plastic so that flooding can be observed when testing the sword. The voided portion of the sword should span the entire length of the fueled region. A sketch that shows the essential features of the swords is given in Figure 1 of the *Procedure for Measuring Void Coefficient with Void Swords* (see page 27).

2. A test chamber consisting of a rigid cylinder capable of holding the entire sword that has a cap with a graduated sight glass penetrating it will be needed. This chamber and cap must be capable of withstanding 10 psi pressure. A sketch of a possible chamber is included as Figure 2 of the *Procedure for Measuring Void Coefficient with Void Swords* (see page 28).

B. Testing the Swords

1. Flooded Sword

Immerse the flooded sword in water and visually check that water fills all of the voids

2. Void Sword

A. Calculate the outline volume of the sword.

B. Measure the density of a sample of the material used to make the sword.

C. Measure the mass of the sword. This will yield the nominal void volume of the sword.

III.B.2. Testing the Void Sword (cont.)

NOTE:

$Void_{zp} = (V_t * \rho_p - M_m) / \rho_p$ where

$Void_{zp}$ =	Void in cc of sword under zero pressure
V_t =	Calculated volume of sword
ρ_p =	Measured density of plastic used for sword
M_m =	Measured mass of sword

D. Measure the actual volume of the void sword when immersed vertically in water by measuring the volume of the displaced water.

NOTE:

$Void_{im} = (V_{im} * \rho_p - M_m) / \rho_p$ where

$Void_{im}$ =	Void in cc of sword under water
V_{im} =	Measured displacement of sword
ρ_p =	Measured density of plastic used for sword
M_m =	Measured mass of sword

E. Measure the change in volume of the chamber when subjected to the hydrostatic pressure of the core.

i. Place the cap on the test chamber and fill the test chamber until there is a reasonable level in the graduated sight glass at its top.

ii. Agitate the test chamber to assure that all of the air has escaped.

iii. Note the level of the graduated sight glass and attach a pressure hose to the top of the cylinder.

iv. Pressurize the cylinder with gas to a pressure of 19'4.5" water head. DO NOT OVER PRESSURIZE. Use appropriate precautions to avoid flying glass.

v. Note the change (drop) in level of the water in the graduated sight glass. This is the change in volume of the chamber as the walls expand (bow) as a result of the gas pressure.

III.B.2. Testing the Void Sword (cont.)

F. Measure the change in displacement of the sword when subjected to the hydrostatic pressure of the core.

i. Place the cap on the test chamber and fill the test chamber until there is a reasonable level in the graduated sight glass at its top.

ii. Agitate the test chamber to assure that all of the air has escaped.

iii. Note the level of the graduated sight glass and attach a pressure hose to the top of the cylinder.

iv. Pressurize the cylinder with gas to a pressure of 19'4.5" water head. DO NOT OVER PRESSURIZE. Use appropriate precautions to avoid flying glass.

v. Note the change (drop) in level of the water in the graduated sight glass. This is the change in volume of the air filled portion of the sword as the sides partially collapse plus that of the chamber expansion.

G. Adjusting the measured void of the sword with the change in displacement due to pressurizing the sword will yield the actual void volume produced by the sword when it is inserted in the core. Record this on pg. 6 of this procedure.

NOTE:

$Void_{fp} = Void_{im} - \Delta V$ where

$Void_{fp}$ = Void in cc of sword under full pressure
$Void_{im}$ = Void in cc of sword under water
ΔV = Drop in level of graduated sight glass when pressurizing test chamber w/sword minus the drop in level when pressurizing test chamber w/o sword.

3. Calculate the voidable portion of the reactor. This is the fuel channels and inter-element gap over the length of the actual fuel. This will yield the percent void represented by the insertion of the voided sword. Record this on pg. 6 of this procedure

NOTE:

$\%Void = Void_{fp} / Voidable\ Volume * 100$

IV. Preparations for Measuring Flow Coast Down Measurement:

Amplifier construction

______ Ensure a simple amplifier such as the one shown in Figure 1 of the *Procedure For Measuring Flow Coast Down*, pg. 21, is constructed to connect the Visicorder to the normal flow instrument current loop. The amplifier may be built on a bread board.

Procedure
for
Establishing LEU Core 1

LEU Core 1 Procedure

I. Description:

4 x 4 - graphite reflected (to the extent possible). Referenced to High Enrichment Uranium (HEU) Texas element core 4 x 4 - graphite reflected. (see Attachment 1 for core loading map, page 16).

II. Preliminary:

_____ A. HEU fuel removed from core as per SOP 5.4.2.B, grid plate bare with exception of source/source holder, graphite reflectors, plugs, and detectors.

_____ B. Auxiliary source range detector installed.

_____ C. Control rod inspection completed satisfactorily in accordance with (IAW) SOP 7.5.

_____ D. Limit maximum power level to 10^6 cps on main source range with fission chamber completely inserted (approximately 250 watts).

III. Loading:

NOTE
Ensure the Daily Checklist is completed prior to the first reactor startup each day that the reactor is to be taken critical from a secured condition.

A. Initial and date each major component of the checklist (part B), listed below, as the step is completed.

B. Load LEU fuel IAW SOP 5.4 and Attachment 1 (core 1 loading map, page 16).

_____ 1. Desired graphite reflectors and plugs in place.

_____ 2. Control rods installed IAW SOP 5.4.2.D.

_____ 3. Control rod drop times completed satisfactorily IAW SOP 7.3.

_____ 4. Subcritical multiplication (1/M) data obtained.

III.B. Loading (cont.)

_____ 5. Completely banked initial critical rod configuration rod heights obtained (for critical mass measurement, see Attachment 2, page 17).

_____ 6. Core loaded to desired configuration.

_____ 7. Integral & differential rod worths obtained IAW SOP 7.4.

_____ 8. Core excess reactivity calculated IAW SOP 5.5.

Excess reactivity is _____________ % $\Delta k/k$ (< 5.0 % $\Delta k/k$).

_____ 9. Core shutdown margin calculated IAW SOP 5.5.

Shutdown margin is ______ % $\Delta k/k$ (> 0.4 % $\Delta k/k$).

IV. Partial Element Worth Measurement:

NOTE
Ensure the Daily Checklist is completed prior to the first reactor startup each day that the reactor is to be taken critical from a secured condition.

A. Bring the reactor critical, at power less than 10^6 cps, IAW SOP 5.1

_____ 1. Measure banked critical rod heights

Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

_____ 2. Note pool temperature: (_______ ° F)

_____ 3. Shut down the reactor.

B. Remove the designated fuel element IAW SOP 5.4.2.C.3.

IV. Partial Element Worth Measurement (cont.)

C. Add the designated partial fuel element IAW SOP 5.4.2.C.2.

D. Bring the reactor critical, at power less than 10^6 cps, IAW SOP 5.1.

_____ 1. Measure critical rod heights:

Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____.

_____ 2. Note pool temperature: (________ ∘ F).

_____ 3. Shut down the reactor.

E. Return core to initial reference core configuration (see pg. 16) IAW SOP 5.4.2.C.

V. Primary Pump Flow Coast Down Measurements

A. Initial Conditions

_____ 1. The reactor is shut down.

_____ 2. The ampiifier has been installed on the flow instrument IAW the *Procedure for Measuring Flow Coast Down*, pg. 19.

B. Perform flow coast down measurements IAW the *Procedure for Measuring Flow Coast Down*, pg. 19.

_____ 1. The Flow Coast-down measurement is complete.

_____ 2. The amplifier installed for the measurement has been removed from the flow instrument.

_____ 3. The flow instrument has been returned to normal operation.

VI. Void Measurements

NOTE

Ensure the Daily Checklist is completed prior to the first reactor startup each day that the reactor is to be taken critical from a secured condition.

A. Limit maximum power level to 10^6 cps on main source range with fission chamber completely inserted (approximately 250 watts).

B. Record critical rod height positions in provided data table (pg. 25).

C. Measure the Void coefficient IAW the *Procedure for Measuring Void Coefficient with Void Swords*, pg. 23.

_____ Void measurements completed.

Attachment 1: Core 1 map

Core Loading: LEU - 1; Date: __________; U - 235: 3846 Grams;

F	Normal Fuel Element	**P**	Grid Plate Plug
PF	Partial Fuel Element	**HYD RAB**	Hydraulic Rabbit
CR	Control Rod Fuel Element	**THER RAB**	Thermal Pneumatic Rabbit
G	Graphite Element	**EPI RAB**	Epithermal Pneumatic Rabbit
S	Graphite Source Element	**RB**	Radiation Basket
REG	Control Rod Fuel Element with Regulating Rod		

North ⇑

G 11	G 12	G 13	S 14	G 15	G 16	G 17	G 18
G 21	G 22	F VS-001 23	F VS-002 24	F-REG VC 001 25	F VS-003 26	G 27	G 28
G 31	G 32	F VS-004 33	F-CR1 VC-002 34	F VS-005 35	F VS-006 36	G 37	G 38
G 41	G 42	F VS-007 43	F VS-008 44	F-CR2 VC-003 45	F VS-009 46	G 47	G 48
G 51	G 52	F VS-010 53	F-CR3 VC-004 54	F VS-011 55	F VS-012 56	G 57	G 58
G 61	G 62	G 63	G 64	G 65	G 66	G 67	G 68
G 71	G 72	G 73	G 74	G 75	G 76	G 77	G 78
G 81	G 82	G 83	G 84	G 85	G 86	G 87	G 88

Loading Approved By: ______________________ Date: ____________

Attachment 2: Worksheet for calculating Critical Mass

List each fuel element placed in core and associated U-235 content (in grams)

Element	Mass	Σ Mass	Banked Rod heights	Banked Height %	C/C_o mass prediction	est. Critical Mass
VC-001						
VC-002						
VC-003						
VC-004						

Banked Height % = Banked rod height/26

Estimated Critical Mass = Σ Mass of the n-1 elements + [mass of the n[th] element * banked rod height %] (note: valid only when criticality is achieved.

Procedure
for
Measuring Flow Coast Down

Procedure For
Measuring Flow Coast Down

I. Prerequisite

The UVAR must be shut-down to perform this measurement.

II. Set Up/Calibration

A. Ensure a simple amplifier such as the one shown in Figure 1 (page 21) has been constructed.

B. De-energize the 35 volt power supply for the flow instrument and install the amplifier into the GROUNDED END of the current loop as shown in Figure 1 (page 21). Re-energize the 35 volt power supply.

C. Connect the amplifier to one channel of the Visicorder and check that the Visicorder is working. This will be the Flow Channel of the Visicorder.

D. Thoroughly vent the differential pressure cell and apply a differential pressure corresponding to 100% flow using the manometer bottles in a manner similar to that used in the normal calibration of the flow meter.

E. Set one of the unused galvanometers of the Visicorder to coincide with the position of the Flow Channel. This will record a line at 100% throughout the measurement.

F. Connect the Header up position indicator to the unused galvanometer of the Visicorder, check that indication is given when header position is changed.

G. Apply a zero differential pressure to the cell and set the other unused galvanometer to correspond with the Flow Channel. This will record a line at zero throughout the measurement.

H. If the distance from the zero line to the 100% line is not appropriate adjust the voltage on the collector of the transistor of the amplifier depicted in Figure 1.

I. Run the Visicorder at a slow speed while setting the bottles to zero, 1/4, 1/2, 3/4 and full scale. Pause for several centimeters of paper travel at each point to make a permanent record of the relationship of Visicorder position and differential pressure. Annotate the chart for future reference. The head of water for these points are given in SOP 7.7.

J. Isolate the manometer bottles and place the differential pressure cell in service.

III. Measurement

A. Establish the nominal flow condition for the coast down measurement. This will normally be with the header up, both primary isolation valves fully open, and all positions in the grid plate filled.

B. Set the Visicorder for 25 inches pe: second and check that it is working properly.

C. Start the Visicorder and turn off the primary pump. Stop the Visicorder soon after flow indications fall to zero.

IV. Disassembly

A. De-energize the 35 volt power supply for the flow instrument.

B. Disconnect the amplifier from the channel of the Visicorder.

C. Remove the amplifier from the GROUNDED END of the current loop as shown in Figure 1 (page 21).

D. Re-energize the 35 volt power supply.

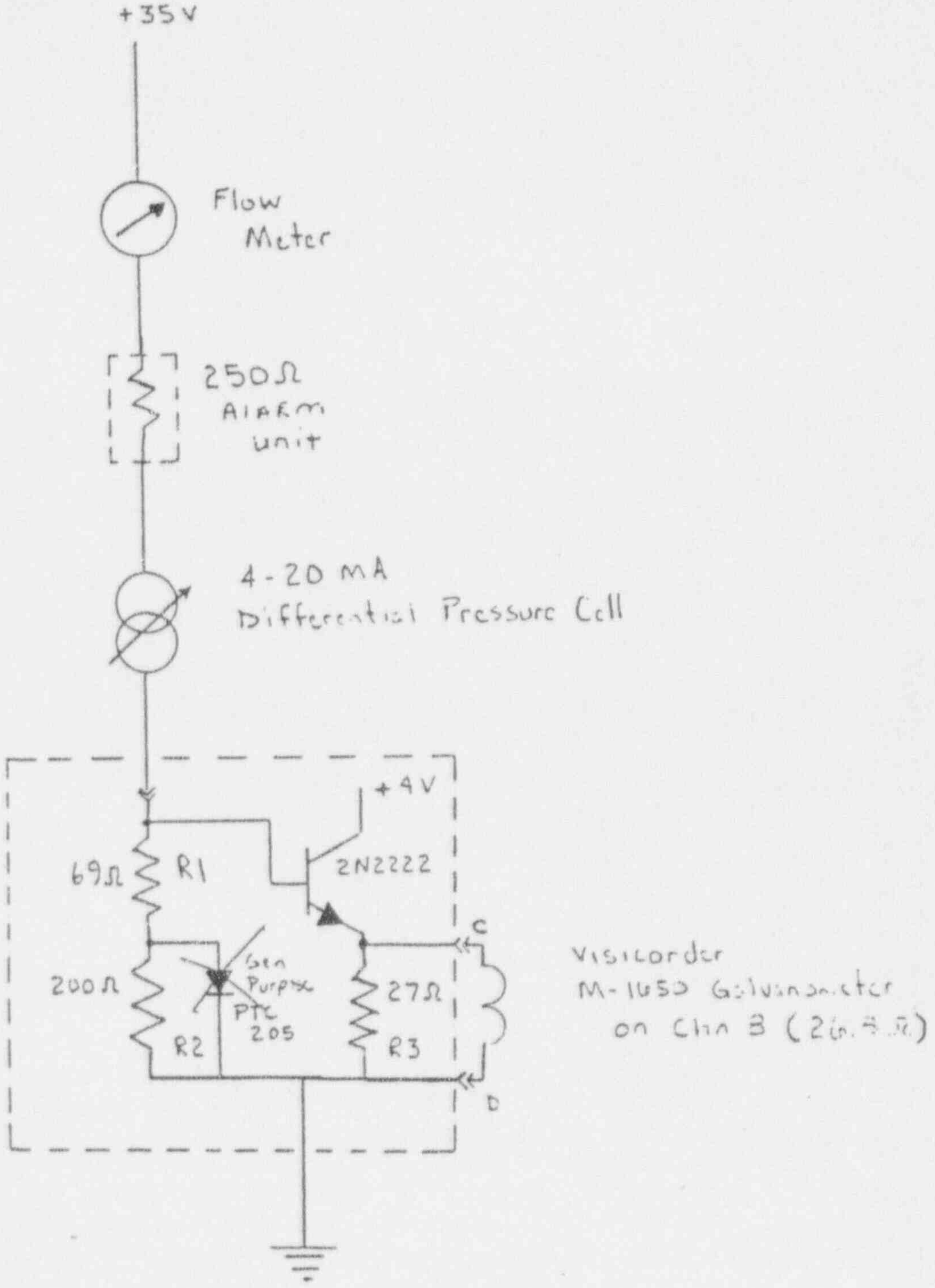
V. Data Reduction

A. Measure the relationship between differential pressure and position on the Visicorder trace with a scale (ruler) and the trace from step II.H. The actual flow rate is proportional to the square root of the differential pressure. Thus, for example, the position 3/4 of the way from the Zero Line to the 100% Line is 86.6% of full flow. Full flow on the indicator is normally set to 1200 gpm so this point would correspond to 1040 gpm.

B. Mark the trace at several convenient flow rates such as 1000, 900, 800, ..., 100 gpm. One of these marks should be at the Limiting Safety System Setting (LSSS) for primary flow.

C. Using the LSSS as the zero time point, plot the flow rate vs. time for the transient. This is the flow coast down curve to compare with the one in the Safety Analysis Report (SAR). A favorable flow coast down condition is one where this line is always above the line in the SAR.

Figure 1: Amplifier



Procedure
for
Measuring Void Coefficient with Void Swords

Procedure For
Measuring Void Coefficient with Void Swords

I. Introduction

This procedure utilizes a pair of swords of identical construction with the exception that one of them is flooded while the other is sealed to contain air. It is the difference in reactivity between the flooded volume of one sword and the air filled volume of the other sword that constitutes an individual void coefficient measurement. Several of these measurements must be performed at representative locations throughout the core to get a core average void coefficient.

It may not be possible to manipulate the swords into the core from the bridge in which case the fuel elements will have to be brought close to the surface to insert the swords. The fuel elements may be removed with the control rods either inserted or at ten inches but the rods must be at ten inches when replacing the fuel element, see SOP 5.4.2. parts B and C. If the elements are brought near the surface, monitor the dose rate carefully as the element is brought up. An element can be quite radioactive when pulled from a core that has recently been operating for just a short time at low power.

The procedures in SOP 5.4.2.c. are to be followed for any fuel manipulations. SOP 5.1.A, 5.1.B, or 5.1.C. are to be followed for bringing the reactor critical for each measurement. SOP 2.F. is to be followed when bringing either the sword or fuel element near the surface.

II. Equipment Setup

A. Obtain the $Void_{tp}$ value calculated in the prerequisite section: *Preparations for void measurements* (tabulated on pg. 6).

B. Obtain the voidable portion of the reactor calculated in the prerequisite section: *Preparations for void measurements* (tabulated on pg. 6).

C. Determine the percent void represented by the insertion of the voided sword calculated in the prerequisite section: *Preparations for void measurements* (tabulated on pg. 6).

III. Individual Measurement.

A. Position the rods either at the bottom or banked at 10 inches.

III. B. Insert the Flooded Sword into a channel of a normal fuel element noting the position of the sword in the element and the element in the core. If the fuel element was removed for this operation, reinsert the fuel element with the rods at 10 inches.

C. Take the reactor critical at low power with the control rods banked and note the rod positions on the Void Coefficent Measurement Data Table pg 25.

D. Position the rods either at the bottom or banked at 10 inches.

E. Remove the Flooded Sword and insert the Voided Sword in the same location. If the fuel element was removed for this operation, reinsert the fuel element with the rods at 10 inches.

F. Take the reactor Critical with 3 of the four rods in the same position as in step C and the remaining rod (the regulating rod if the reactivity change is very small) at the position required for criticality. Note the rod positions on the Void Coefficent Measurement Data Table pg 25.

G. The Void Coefficient for that position is the change in reactivity from the change in rod position divided by the voidable volume represented by the sword.

H. Position the rods either on the bottom of the core or banked at 10 inches

I. Remove the Voided Sword from the element. If the fuel element was removed for this operation, reinsert the fuel element with the rods at 10 inches.

J. Repeat steps A through I for several representative positions in the core.

Void Coefficient Measurement
Data Table

Voidable Volume of reactor = ________________

$Void_{fp}$ = ________________ % Void = ________________

Element # & sword postion	Pool temp	Rod Positions - flooded sword				Rod Position - dry sword			
		Rod 1	Rod 2	Rod 3	Reg	Rod 1	Rod 2	Rod 3	Reg

IV. Data Considerations

From section III, local void coefficients are measured in several locations in the core. To get an idea of the void coefficient at other locations, the core's symmetry will be used. The core established from core 1 map (page 16), can be made approximately symmetric by establishing a critical banked rod height on rods 1 and 2, with the Regulating rod and rod 3 in their full out positions.

Other reactor facilities have gone to great lengths to determine the volume of the void and voidable volume below the rods and used that number when calculating the void coefficient. By making the void length identical to the fuel length and having the void in the sword aligned with the fuel, the active length of the core will always match the active void volume and no adjustment will be needed.

There is no technical specification limit on void coefficient nor a prescribed manner of reporting it.

Figure 1: The essential features of the swords

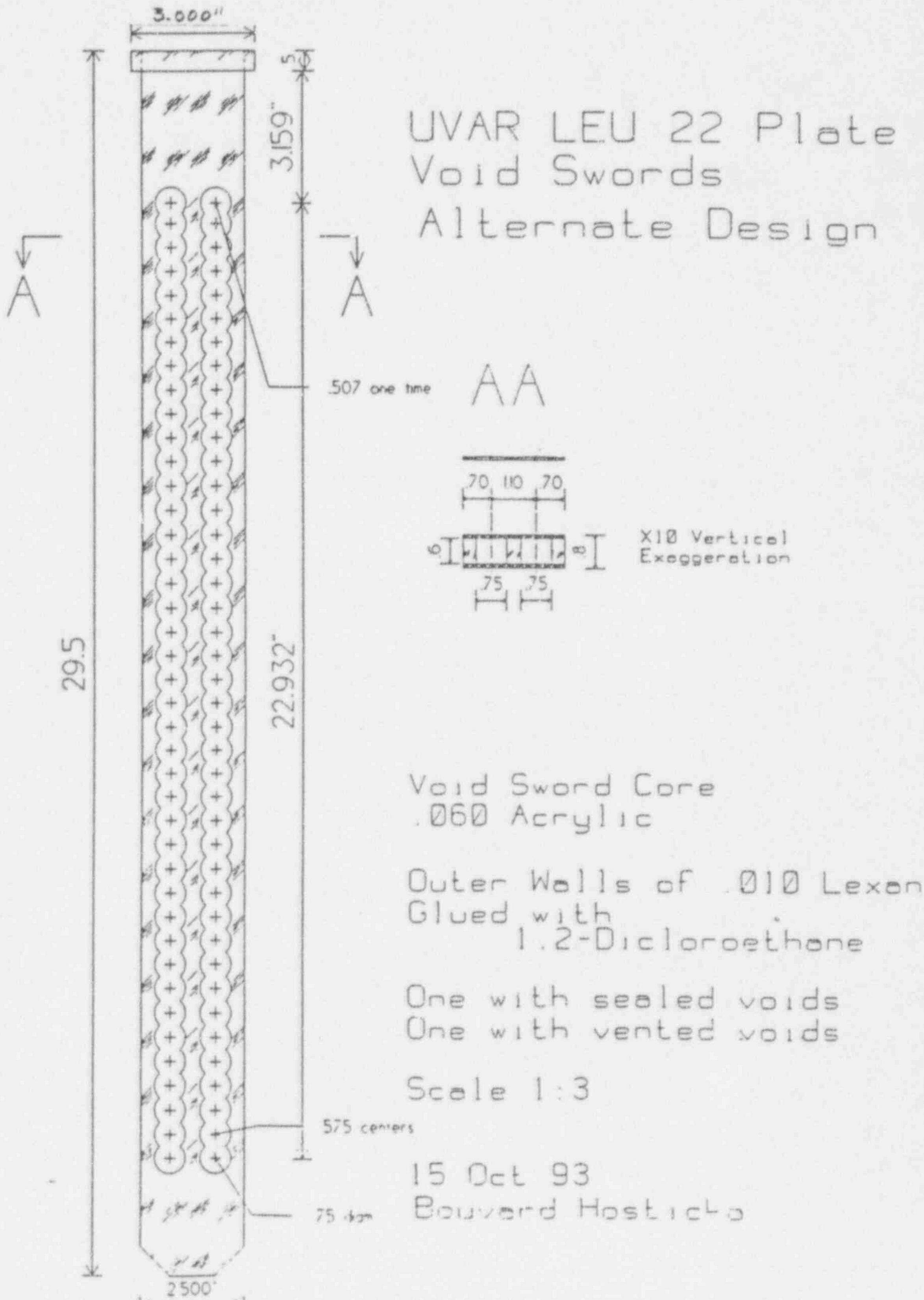
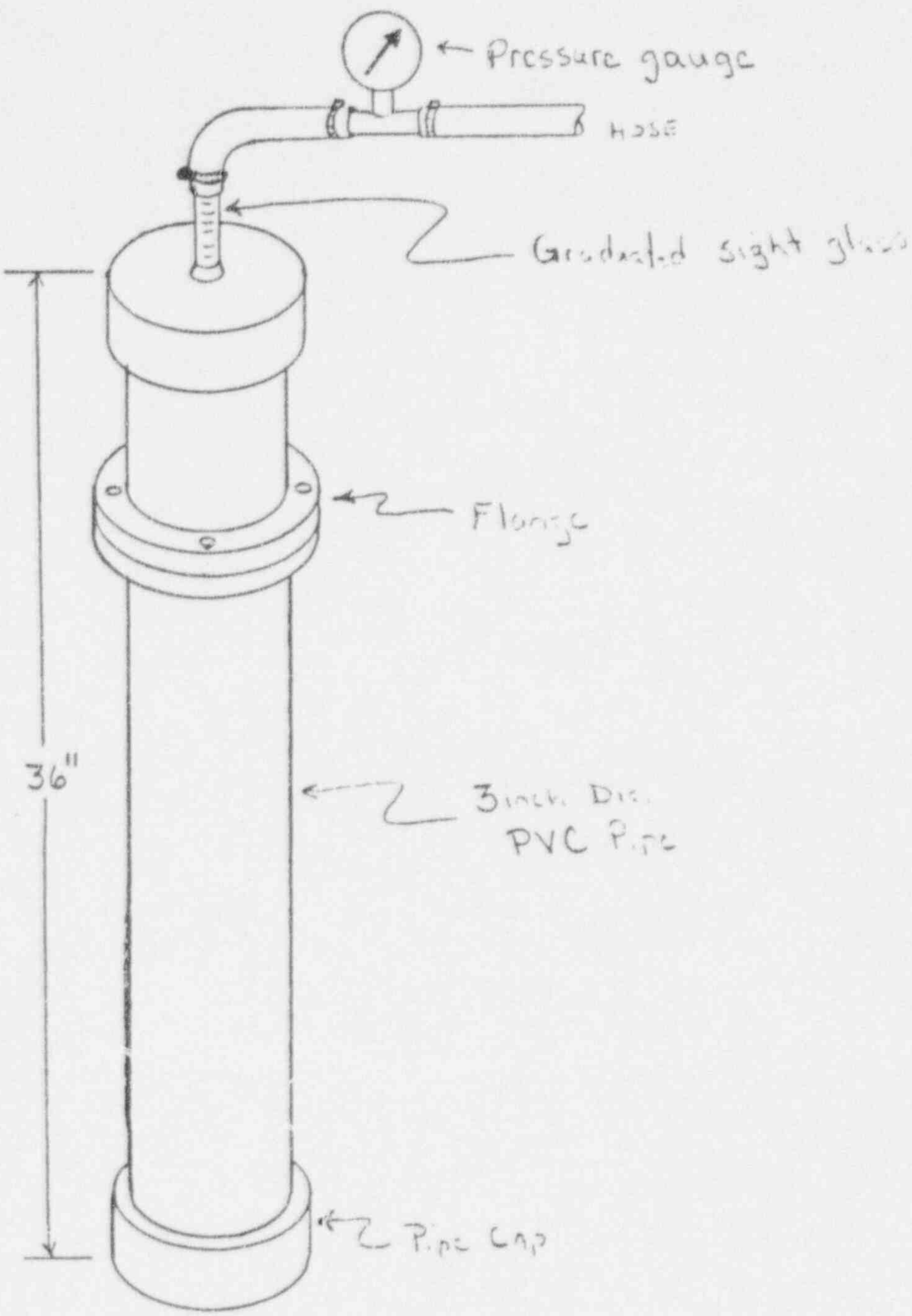


Figure 2: A test chamber



Procedure
for
Establishing LEU Core 2

LEU Core 2 Procedure

I. Description:

Partially graphite reflected (South-west corner). Non-referenced - Operational (see Attachment 2 for core loading map, page 34).

II. Preliminary (data from LEU Core 1 Procedure):

____ A. Subcritical multiplication data obtained.

____ B. Critical mass data obtained.

____ C. Control rod reactivity worth data obtained.

____ D. Excess reactivity and shutdown margin calculated.

____ E. Partial element reactivity worth obtained.

____ F. Primary flow and pump coastdown data obtained.

____ G. Void measurements completed.

III. Loading

<u>NOTE</u>
Ensure the Daily Checklist is completed prior to the first reactor startup each day that the reactor is to be taken critical from a secured condition.

A. Initial and date each major component listed below as the step is completed.

B. Limit maximum power level to 10^6 cps on main source range with fission chamber completely inserted (approximately 250 watts).

C. Shuffle LEU fuel IAW SOP 5.4.2.C and Attachment 1 (core 2 loading map, page 34).

____ 1. Desired graphite reflectors and plugs in place.

____ 2. Control rods moved IAW SOP 5.4.2.D. (if necessary)

III. C. Loading (cont.)

_____ 3. Control rod drop times completed satisfactorily IAW SOP 7.3 (as necessary).

_____ 4. Subcritical multiplication (1/M) data obtained.

_____ 5. Banked initial critical rod configuration rod heights obtained (for critical mass measurement, see Attachment 2, page 35).

_____ 6. Core loaded in desired configuration.

_____ 7. Integral & differential rod worths obtained IAW SOP 7.4.

_____ 8. Core base excess reactivity calculated IAW SOP 5.5.

Base excess reactivity is ____________ % $\Delta k/k$ (< 5.0 % $\Delta k/k$).

_____ 9. Core base shutdown margin calculated IAW SOP 5.5.

Base shutdown margin is ____________ % $\Delta k/k$ (> 0.4 % $\Delta k/k$).

_____ 10. Non-fixed experiment reactivity values measured IAW SOP 6.5.

_____ 11. Core working shutdown margin calculated IAW SOP 5.5.

Working shutdown margin is ______ % $\Delta k/k$ (> 0.4 % $\Delta k/k$).

_____ 12. Core working excess reactivity calculated IAW SOP 5.5.

Working excess reactivity is ______ % $\Delta k/k$ (< 5.0 % $\Delta k/k$).

_____ 13. Total experimental reactivity worth calculated.

Total experimental worth is _________ % $\Delta k/k$ (< 2.0 % $\Delta k/k$).

_____ 14. Minimum permissible critical rod positions established.

_____ 15. Operational working core established.

IV. Power ascension

NOTE

Ensure the Daily Checklist for **FORCED CONVECTION** is completed prior to the first reactor startup each day that the reactor is to be taken critical from a secured condition.

A. Perform SOP 7.1.5., Primary Heat Balance Calibration.

1. At the low power critical point, less than 10^6 cps, record the following:

_____ a. Critical rod heights

Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

_____ b. Pool temperature: (_______ ∘ F)

_____ c. Core Delta-T: (_______ ∘ F)

2. After reaching 200 kW, increment reactor power increases in 500 kW steps to approximately 2 MW IAW SOP 7.1.5.d

Adjust nuclear instrumentation detector position at each step, so to have nuclear instrumentation agree (-5% to +15%) with calculated heat balance power (see Table 1).

Table 1
Power vs Instrument reading

Power level	Delta T (°F)	Power Range (%)	Intermediate Range (nV)	Linear Range (μA)	Core Gamma (μA)
200 kW	1.285	100**	4 E7	2 E-6	1.85 E-10
500 kW	3.21	25	1 E8	5 E-6	4.62 E-10
1.0 MW	6.22	50	2 E8	1 E-5	9.25 E-10
1.5 MW	9.63	75	3 E8	1.5 E-5	1.39 E-9
2.0 MW	12.85	100	4 E8	2 E-5	1.85 E-9

** in 200 kW position on the Range Switch

B. Shut down the reactor IAW SOP 5.3

V. Power reactivity coefficient measurement

NOTE
Ensure the Daily Checklist for **FORCED CONVECTION** is completed prior to the first reactor startup each day that the reactor is to be taken critical from a secured condition.

A. Perform Power reactivity coefficient measurement IAW *Procedure for Measuring Power Reactivity Coefficient of UVAR*, pg. 37.

VI. Temperature reactivity coefficient measurement

NOTE
Ensure the Daily Checklist for **FORCED CONVECTION** is completed prior to the first reactor startup each day that the reactor is to be taken critical from a secured condition.

A. Perform Temperature reactivity coefficient measurement IAW *Procedure for Measuring Temperature Reactivity Coefficient of UVAR*, pg. 41.

Attachment 1: Core 2 map (example)

Core Loading: LEU-2 ; Date: __________; U - 235: 4944 Grams;

F	Normal Fuel Element	**P**	Grid Plate Plug
PF	Partial Fuel Element	**HYD RAB**	Hydraulic Rabbit
CR	Control Rod Fuel Element	**THER RAB**	Thermal Pneumatic Rabbit
G	Graphite Element	**EPI RAB**	Epithermal Pneumatic Rabbit
S	Graphite Source Element	**RB**	Radiation Basket
REG	Control Rod Fuel Element with Regulating Rod		

North ⇑

G 11	F VS-001 12	F VS-002 13	F-REG VC-001 14	F VS-003 15	F VS-004 16	P 17	P 18
G 21	F VS-005 22	F-CR1 VC-002 23	F VS-006 24	F VS-007 25	F VS-008 26	P 27	P 28
G 31	F VS-009 32	F VS-010 33	F VS-011 34	F-CR2 VC-003 35	F VS-012 36	P 37	P 38
G 41	F VS-013 42	F VS-014 43	F-CR3 VC-004 44	F VS-015 45	F VS-016 46	P 47	P 48
G 51	G 52	HT 53	G 54	HT 55	S 56	P 57	P 58
G 61	G 62	G 63	EPI RAB 64	G 65	G 66	G 67	G 68
G 71	G 72	THER RAB 73	G 74	G 75	HYD RAB 76	G 77	G 78
G 81	G 82	G 83	G 84	G 85	G 86	G 87	G 88

Loading Approved By: ______________________ Date: ____________

Attachment 2: Worksheet for calculating Critical Mass (Core 2)

List each fuel element placed in core and associated U-235 content (in grams)

Element	Mass	Σ Mass	Banked Rod heights	Banked Height %	C/C_o mass prediction	est. Critical Mass
VC-001						
VC-002						
VC-003						
VC-004						

Banked Height % = Banked rod height/26

Estimated Critical Mass = Σ Mass of the n-1 elements + [mass of the nth element * banked rod height %] (note: valid only when criticality is achieved.

Procedure
for Measuring
the Power Reactivity Coefficient

Procedure for
Measuring the Power Reactivity Coefficient of UVAR

I. Prerequisites

A. This procedure is to be done in conjunction with the normal start up procedure of SOP 5.1.A. Nothing in this procedure requires, or allows for, a deviation from SOP 5.1.A.

B. The UVAR reactor must be in a condition to be brought to full power with no restrictions other than stated in SOP 5.1.A.

C. The UVAR core must not be in a noticeable xenon transient.

D. Reactor pool temperature and Delta-T instruments must be in a valid state of calibration. If other temperature indications are used such as the Systemteknik Temperature system, they must also be in a state of valid calibration.

II. Measurements

A. Take the reactor critical in forced convection with the power low in the indicating range of the Linear Power instrument.

B. Set the critical rod position such that one rod is well into the linear portion of its integral rod worth curve (flat part of its differential rod worth curve) such that an addition of up to 0.222% $\Delta k/k$ (30 cents) of reactivity can be calculated from the linear slope of the rod worth curve.

C. Record the core inlet temperature (pool temperature) and outlet temperature (Pool temperature Plus Delta T). They should be the same temperature. The average core temperature is defined as the average of the inlet and outlet temperatures.

Temperatures: ________ ∘ F ________ ∘ F
Pool Delta-T

II. D. Record the critical rod positions and determine which rod is to be used for the rest of this procedure.

Critical rod heights

Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

E. Establish a period of about 40 to 60 seconds using the selected rod in the linear portion of its integral rod worth curve. Record the rods new position.

Rod heights

Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

F. Measure the doubling time as if this were a rod calibration. If it is less than 21 seconds (Period less than 30 seconds), insert the rod and return to a low power and try again with a shorter rod pull.

G. If the period is acceptable allow power to rise to the power range. Continue measuring doubling times as power rises until it is apparent that significant negative reactivity is being added to the core as a result of the rise in power.

H. If power reaches 1.8 MW, insert the one rod pulled in step E. as necessary to level power at or below 2 MW.

I. If it is apparent that the power rise will be stopped at less than 2 MW without further rod motion, allow the reactor to come to a steady level power at whatever power results from the negative temperature reactivity balancing the reactivity added by the initial rod withdrawal.

J. Once power is level, record the rod positions, the core inlet temperature (Pool Temperature) and the core outlet temperature (Pool temperature plus Delta-T).

Note:
If final power is not at least 1.5 MW, repeat with somewhat larger reactivity insertion as calculated by using the previously determined power coefficient value.

1. Final power level was _______ ($\leq$ 2 MW).

2. Doubling time was _______ seconds (> 21 sec).

II.D. 3. Final critical rod heights:

Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

4. Final temperatures: _______ ∘ F (Pool) _________ ∘ F (Delta-T)

K. Continue operating the reactor in accordance with SOP 5.2. or shut down the reactor in accordance with SOP 5.3. as the operation schedule dictates.

III. Calculations

A. Determine the amount of positive reactivity added to the core at the beginning of the approach to power by either noting the difference in rod position and using the rod worth curves (either directly reading curves or using slope of curve), or the reactivity vs. doubling time relation (if no rod motion was required to stop the transient.)

B. Determine the average core temperature at the beginning and end of the transient. The average core temperature is the inlet temperature plus outlet temperature divided by two, or the pool temperature plus one half Delta T.

C. The Power coefficient includes moderator and fuel temperature coefficients and treats the entire UVAR core as a unit. The Power coefficient is the change in reactivity divided by change in power. This should be a negative quantity since the temperature rise should add negative reactivity to balance the positive reactivity added by the rod initial rod withdrawal.

Procedure
for Measuring
the Temperature Reactivity Coefficient

Procedure for
Measuring the Temperature Reactivity Coefficient of UVAR

I. Prerequisites

A. This procedure is to be accomplished in conjunction with the normal reactor start up and operating procedures in the Standard Operating Procedures (SOP). Nothing in this procedure allows a deviation from any SOP.

B. The UVAR reactor must be in a condition to be operated at full power with no restrictions other than stated in the SOPs.

C. Reactor pool temperature must be in a valid state of calibration. If other temperature indications are used, such as the Systemteknik Temperature system, they must also be in a state of valid calibration.

D. This measurement should be scheduled for a time when the reactor is not needed at power for several days.

E. The pool temperature at the beginning of section III must be high enough to allow cooling the pool at about 10° F per hour over a temperature span of 10 or 15° F without cooling it below 60° F or more than 20° F. Pre-heating the pool with section II may not be necessary if the pool is already at a sufficiently high temperature to perform section III.

II. Pool Heat-Up (If necessary)

A. Operate the reactor at power in forced convection with the cooling tower fan off long enough to raise the pool temperature to about 100° F. The nominal heat-up rate of the pool is about 10° F per hour. Do not challenge the Pool Temperature Scram at 105° F.

B. Shut down the reactor or reduce power to less than one kilowatt after the heat-up to allow xenon (and iodine) to decay.

C. Avoid operating the cooling system over the next few days. The desired conditions for the next phase of the measurement is to have the pool at a temperature sufficiently high after any xenon transient is over to allow cooling the pool at about 10° F per hour over a temperature span of 10 or 15° F without cooling it below 60° F or more than 20° F.

III. Temperature Coefficient Measurement

A. Allow sufficient time following previous power operations to allow xenon to decay to the point where there will be no significant change in xenon reactivity over the course of a two hour operation. It is anticipated that a shut down over a weekend from a few hour operation should be sufficient, but if longer operations were recently performed, a longer decay period may be warranted.

B. Turn off the secondary pump to prevent cooling the pool until the actual reactivity measurement is performed.

C. Run the primary pump for at least an hour to eliminate any stratification in the pool.

D. Take the reactor critical in forced convection with the power low in the indicating range of the Linear Power instrument with at least one rod in the level part of its differential rod worth curve.

E. Maintain the reactor critical for 30 minutes, noting any rod motion and pool temperature changes to verify that xenon or other effects are not changing core reactivity

F. Record the pool temperature and rod positions.

Temperatures: ________ ∘ F ________ ∘ F
Pool Delta-T

Critical rod heights

Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

G. Start the secondary pump. After the cooling tower basin has refilled, start the cooling tower fan.

H. Maintain the reactor critical as the pool cools by inserting the rod selected in step D.

III. I. Record pool temperature and rod position as the pool cools and the reactor is maintained critical. If possible allow the pool to cool through at least 10 °F. The nominal cool-down rate of the pool is about 10 °F per hour.

1. Critical rod heights:

   Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

2. Temperature: _______ ∘ F
   Pool

3. Critical rod heights:

   Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

4. Temperature: _______ ∘ F
   Pool

5. Critical rod heights:

   Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

6. Temperature: _______ ∘ F
   Pool

7. Critical rod heights:

   Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

8. Temperature: _______ ∘ F
   Pool

9. Final critical rod heights:

   Rod 1: _____ ; Rod 2: _____ ; Rod 3: _____ ; Reg Rod: _____

10. Final temperature: _______ ∘ F
   Pool

J. Turn off the secondary pump to prevent further cooling of the pool.

K. Shut down the reactor in accordance with SOP 5.3.

L. Turn off the primary pump.

III. M. Turn on the secondary pump.

N. Measure the reactivity worth of the reduction in the pool temperature by measuring the doubling times associated with moving the rod(s) moved in step III.I to their positions in step III.F. in accordance with SOP 7.4.

1. Determine the sequence of rod movement to minimize the use of adjacent rods when making the measurement using data obtained in step III.F and III.I of this procedure.

Note
Rod positions and movement sequence will be different than that suggested in SOP 7.4.B.1.d

2. SOP 7.4.B.3 steps d, e, f, and g are not applicable for this use.

IV. Calculations

A. Determine the amount of reactivity added by the rod during the cooling by noting the difference in rod position and using the rod worth curves (verify with reactivity calculated by doubling time measurements).

B. Determine the drop in pool temperature associated with the rod insertion.

C. The temperature coefficient is the change in reactivity divided by change in pool temperature.