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**Westinghouse
Astronuclear
Laboratory**

WANL-TME- 2719
MARCH 1971

MASTER

DATA ITEM T-119

**REACTIVITY WORTH
OF ISA MATERIAL IN THE
PAX-G2 REACTOR**

FINAL REPORT

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Westinghouse Astronuclear Laboratory

Subcontract NP-1
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ABSTRACT

Measurements were performed to experimentally determine the reactivity worths of selected samples of the In-Place Shim Adjustment (ISA) materials, and the perturbation of that worth caused by support stem and propellant hydrogen. Three shim materials were investigated: HfO_2 , TaC, and HfC . These materials were plated onto the outside of stainless steel tubes with nominal coating thicknesses of 3 mils and 1/2 mil. These measurements were performed at four different radial core locations. The reactivity worth of hydrogen was also measured at selected locations in the core. The hydrogen was introduced in the form of polyethylene "wires" of 80-mil nominal diameter with the polyethylene "wires" placed in the shim tubes and also in the central flow channels immediately surrounding the test locations.

Analysis of these measurements was performed using the ANISN one-dimensional transport code to generate 16-group forward and adjoint fluxes for input to the PERT-1D to obtain reactivity worths per unit mass for the coated shim tubes vs. radial position.

The good agreement between measurements and predictions for the dry, ambient shim tubes of TaC and HfO_2 with a nominal 3-mil thickness in the graphite fueled PAX/R-1 indicates that the worth of shim tubes of comparable thickness can be predicted for the R-1 composite and HCTE fuel designs. The experimental results for the nominal 1/2 - mil and 3 - mil thick coatings also provided self-shielding data which can be extrapolated to determine the reactivity worths of other shim tube thicknesses. In addition, the experimental results confirmed that TaC will provide a greater shim capability than HfO_2 for a given coating thickness. Based on the result of the shim tube experiments, the TaC coating thickness has been specified for two, alternate shim procedures.

The experiments confirmed previous predictions that HfO_2 shim coating reduces the effective reactivity worth of hydrogen relative to an unshimmed configuration more so than a TaC shim. With a \$1.50 shim content distributed uniformly throughout the core, the average support stem hydrogen is reduced by approximately 14% with HfO_2 but only by 9% with TaC. Because TaC does provide a greater dry shim worth for a given thickness than HfO_2 and results in a smaller reduction of stem hydrogen, TaC was tentatively selected as the prime shim coating for the R-1 reference design.

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1.0 INTRODUCTION

1.1 TEST IDENTIFICATION

1.1.1 Type of Report

This report is a complete Final Report.

1.1.2 Scope of Test Document/Test Information Sheet

The applicable Test Information Sheet numbers are TIS DW-11.1D and TIS DW-11.2C.

1.1.3 Functional Category of Test

This is a Development Test.

1.1.4 Contractor

The Westinghouse Astronuclear Laboratory (WANL/14683), under Subcontract NP-1, CY70, is the Contractor.

1.1.5 Test Facility

These tests were performed at the Westinghouse Astronuclear Experimental Facility, located at the Waltz Mill Site, during July 1970.

1.2 PURPOSE

The In-Place Shim Adjustment (ISA) Material Worth Measurements are part of a series of experiments leading up to the specification of fuel for the R-1 reactor. The data requested will aid in the selection of an In-Place Shim Material. Also, the effect of H₂ on the shim material reactivity worth is required.

2.0 REFERENCES AND ASSUMPTIONS

2.1 REFERENCES

2.1.1 Specification

EC 677566 - Part 1. Performance/Design and Qualification Requirements Fuel Element for 677555A NERVA Nuclear Subsystem 1/23/69.

2.1.2 Data Item Description

Form 9 Data Item Description - T-119, dated 4/2/69.

2.1.3 Test Information Sheet

TIS DW-11.1D and DW-11.2C Test Information Sheet for Reactivity Worth of ISA Material in the PAX-G2 Reactor.

2.1.4 Drawing

711J496 - Reactor/Vessel Assembly, R-1 PAX
711J498 B - Segment, Reflector Assembly, R-1 PAX
939J740 - R-1 Reflector, Study Layout of
388D561 - Tube, Shim
711J491 - Cluster Assembly, Fuel (Regular & Irregular) R-1 PAX
711J489 - Cluster Assembly Fuel R-1 PAX
711J490 - Cluster Assembly, Fuel (Regular) R-1 PAX Fueled Centrals
909E109 - Block Support, Regular Fuel Cluster Support
800C578 - Sleeve Liner Assembly, Fuel Cluster Assembly, R-1 PAX
800C572 - Spacer
388D342 - Support, Stem Assembly

2.1.5 Data Release Memorandum

52730 - Reactivity Worth of ISA Material in the PAX-G2 Reactor
52731 - "EXFIT" - A Period Fitting Program for the Packard Bell 250 Computer

- 52732 - MIDAS-1 Data Acquisition System
- 51189 - Parts Inventory in the PAX-G2 Reactor
- 51186 - Chemical Analysis of WANEF Reactivity Materials
- 51612 - Neutron Transmission Measurements on NERVA Reactor Control Vanes
- 51166A - PAX-G1 Shim Wire Inventory
- 51166 - PAX-G1 Shim Wire Inventory
- 51163B - Parts Inventory in the PAX-G1B Reactor
- 51163A - Parts Inventory in the PAX-G1A Reactor
- 51163 - Parts Inventory in the PAX-G1A Reactor
- 51245 - Test Reports on PAX Control Vanes
- 51150A - Parts Inventory in the PAX-G0A, -B, and -C Reactors
- 51150 - Parts Inventory in the PAX-G0 Reactor

2.1.6 TME

WANL-TME - 1910 "PAX-G0 Control Drum Spans and Reactivity Coefficient"

WANL-TME - 1916 "PAX-G1 Reflector Interchange, Control Drum Span, and Aluminum Reflector Barrel Experiments"

2.2 ASSUMPTIONS

2.2.1 Uniformity of Shim Tube Coating

The coating of the shim tube is assumed to be axially uniform.

2.2.2 Effect of Material Outside the Core

Material outside the axial core boundary was assumed to have no effect on the measured reactivity; i.e. material samples which exceeded the 52 inch core length were corrected to include only the 52 inch length equivalent mass.

3.0 TEST ARTICLE CONFIGURATION

3.1 SPECIAL TEST EQUIPMENT

The following special items were used during the test:

3.1.1 In-Place Shim Adjustment (ISA) Shim Tubes

Three shim materials were investigated: HfO_2 , TaC, and HfC. These materials were plated onto the outside of stainless steel tubes 0.294" OD, 0.288" ID and 55" long, with nominal coating thicknesses of 3 mils and 1/2 mil (see WANL Dwg-388D561). Seven tubes were provided of each type* and coating thickness. In addition, seven uncoated stainless steel tubes were available. The weights and serial numbers for the ISA shim tubes used in TIS-DW-11 are given in Appendix A.

3.1.2 Polyethylene "Wires"

The polyethylene "wires" used were the standard 0.080" nominal diameter 54.3" long "wires" available at WANEF.

3.2 REACTIVITY MEASURING SYSTEMS

Reactivity measurements were made with three different systems: the period pickoff system, the analog reactivity computer, and MIDAS-1, a digital data acquisition system.

3.2.1 Analog Reactivity Computer and Period Pickoff System

The first two systems have been described in Section 3.1 of WANL-TME-1916, "PAX-G1 Reflector Interchange, Control Drum Span, and Aluminum Reflector Barrel Experiments." The period pickoff system was not changed, but minor changes were made in the reactivity computer. The time constant of the input amplifier was increased to 0.2

* No 1/2 mil (thin) coating HfC tubes were available.

seconds to improve its operation at high gain and to provide some filtering of the signal to the servo-multiplier. Also, the gains of amplifiers 7 and 8 (see Figure D-1, WANL-TME-1910) were doubled to increase the input voltages supplied to the servo-multiplier. Additionally, the servo-multiplier was replaced with a functionally equivalent unit. Further description of the basic programming of the reactivity computer is given in WANL-TME-1910, Appendix D, "PAX-G0 Control Drums Spans and Reactivity Coefficient Measurements."

3.2.2 Model Integrated Data Acquisition System (MIDAS-1)

The third system used was the Model Integrated Data Acquisition System Mark 1 (MIDAS-1), which can take data from the PAX reactor using the Packard Bell PB-250 computer. This system is described further below.

Figure 3-1 shows a block diagram of this system. Basically, this system consists of a Packard Bell PB-250 digital processor capable of digitizing analog voltage data through an analog-to-digital converter and multiplexer. The results of this conversion may then be recorded on a printed record and on punched paper tape, as desired. Further details regarding MIDAS-1 may be found in DRM 52732.

The following components are part of MIDAS-1:

3.2.2.1 Digital Computer

The digital computer is a Packard Bell Model 250. The program used for data acquisition, DATA, is described in DRM 52732. The sense switches and Friden Flexowriter are an integral part of the computer. The Flexowriter is used to provide printed and punched paper tape outputs.

Figure 3-1. Block Diagram of Model Integrated Data Acquisition System Mark 1 (MIDAS-1)

3.2.2.2 Master Clock

The master clock is a Computer Measurements Corporation Model 2602A, Serial 1.

3.2.2.3 Dual Preset Counter

The dual preset counter is a Computer Measurements Corporation Model 786C, Serial 99696.

3.2.2.4 Multiplexer

The multiplexer is a Packard Bell Model EM-3 analog multiplexer, Serial unknown.

3.2.2.5 Analog-to-Digital Converter

The analog-to-digital converter is a Packard Bell Model M3 multiverter, Serial 35, 10-bit output plus sign. Full scale range is ± 10 volts.

For these measurements, a signal proportional to reactor power level was smoothed with 1/2 second time constant filter and connected to one of the analog inputs to MIDAS which periodically (usually once per second) digitized the signal and punched out the result on paper tape. The data on the punched tapes was later fitted to a simple exponential by a least squares method programmed for the Packard Bell PB-250 computer. The exponential fitting program, EXFIT, is described in DRM-52731.

3.3 PAX-G REACTOR DESCRIPTION

The PAX-G reactor has been used to perform standard reactor experiments during the early phases of the R-1 design program to support the release of R-1 fuel specifications and provide information on the adequacy of the control capability of the R-1 reflector system.

The R-1 graphite core reactor design* contains 1878 fueled and 349 unfueled elements having a hex shaped cross section approximately 3/4" across the flats and a length of approximately 52". The PAX-G reactor also contains a total of 2227 elements, but the number of fueled elements is greater. Although the R-1 graphite core design calls for uranium loadings as high as 630 mg/cm³, available elements have uranium loadings of less than 500 mg/cm³. Thus, in order to mockup the overall uranium content using available fuel, approximately one-half of the central elements in PAX-G are fueled. These fueled central elements were made from existing fuel elements by drilling and tapping each end. To accommodate the increase in the total number of elements from NRX PAX, an extension to the core support plate was inserted into the support plate region of the PAX-G as seen in Figure 3-2. The PAX-G core contains approximately 245 kg of highly enriched uranium.

The original PAX-G build (PAX-G0) had a reflector with 12 NRX type control drums in available KIWI reflector sectors.

The next major modification to the PAX-G reactor involved the replacement of two KIWI reflector sectors together with their associated control drums with a 60 degree R-1 reflector mockup segment containing 3, R-1 mockup control drums. This resulted in a reactor with a total of 13 control drums. **The 60 degree reflector mockup segment is constructed from laminated beryllium slabs and contains the same non-beryllium fraction as that of the earlier R-1 reference design.** This mockup sector also contained mockup lateral support hardware, as may be seen in Figure 3-2. This configuration, after suitable reshimming and reclustering of the core, was designated PAX-G1A. The conversion from PAX-G1A to PAX-G2A, the reactor in which the measurements reported in this document were made, involved the following changes from PAX-G1:

* The R-1 reference design is described in WANL Drawing No. 939J740, November 12, 1970.

Figure 3-2. PAX-G2A Reflector Assembly

1. Substitution of Cu-B¹⁰ control vanes for the Al-B¹⁰ control vanes on the 3, R-1 mockup drums.*
2. Redistribution and addition of TaC shim elements and shim pencils.
3. Removal of 12 fueled centrals and replacement with TaC centrals.
4. Removal of all "X" material.
5. Reshimming to a θ_{DC} of $115^\circ \pm 1^\circ$ by the addition of Nb wire.

The PAX-G2A reactor build (including shim wire inventory, parts inventory, fuel element listing, and representative as-built weights) is detailed in WANL Drawings 711J496 and 711J498B, and DRMs 51612, 51245, 51189, 51186, 51166, 51166A, 51163, 51163A, 51163B, 51150 and 51150A.

*Both type of control vanes are 100 mils thick, with a B¹⁰ surface concentration of 0.13 gram per square centimeter and a vane span of 120 degrees around the control drums.

4.0 SUMMARY OF TESTS

4.1 NARRATIVE

Reactivity worth measurements are performed by determining the reactivity change associated with small mass perturbations at a given location. Table 4-1 defines the matrix of experiments performed. Reactivity worths were measured for the three test materials with samples of two thicknesses at up to four different radial positions. At two radial positions, the reactivity interaction of ISA material and hydrogen (in the form of polyethylene) was determined. In all cases, the reactivity was determined for a 52" long section and hence is an axial average measurement.

4.2 TEST CONDITIONS

A base reactor configuration was established which permitted easy insertion and removal of the stainless tubes and of the polyethylene "wires." The base configuration consisted of the PAX-G2A reactor with the fuel elements modified at the 27 locations indicated in Figure 4-1. All clusters were modified to accept the shim tubes, but only those at radii 2* and 4* were made to accept polyethylene "wires." All TaC central elements and pencils were removed from each cluster containing them in the test locations. The parts which were removed from the six clusters at radius 1* were the liner tubes, pyrotils and tie rod caps. At radius 2*, the existing central elements were removed with their associated hardware leaving the support blocks and PAX separable tie rods, and replaced with graphite central elements with mockup support stem hardware. Removal of the support stems after the clusters were in the reactor permitted insertion of the test specimens. Two fueled centrals and two TaC centrals were removed from radius 2*. Because each test cluster at radius 3 already contained a fueled central, one peripheral fuel element was replaced by an unfueled graphite central and the regular support block was exchanged for one which was used in a pre-

*See Figure 4-1 for the radial position designation.

TABLE 4-1
MATRIX OF ISA SHIM TUBE EXPERIMENTS

RADIAL POSITION (See Figure 4-1)	NUMBER OF TUBES	SHIM COATING THICKNESS		SHIM MTL.	NO. OF POLY WIRES PER STEM			
		0.5 Mil	3 Mil		0	2	4	7
1	6	X	X	HfO ₂	X			
1	6	X	X	TaC	X			
1	3		X	HfO ₂	X			
1	3		X	TaC	X			
2	7	NO SHIM MTL. ON TUBE-----			X	X	X	X
2	7		X	HfO ₂	X	X	X	X
2	7	X		HfO ₂	X			
2	7		X	TaC	X	X	X	X
2	7	X		TaC	X			
2	7		X	HfC	X			
2	4		X	HfO ₂	X			
2	4		X	TaC	X			
3	7		X	HfO ₂	X			
3	7		X	TaC	X			
4	7	NO SHIM MTL. ON TUBE-----			X	X	X	X
4	7		X	HfO ₂	X	X	X	X
4	7	X		HfO ₂	X			
4	7		X	TaC	X	X	X	X
4	7	X		TaC	X			
4	4		X	HfO ₂	X			
4	4		X	TaC	X

Figure 4-1. PAX-G2 Configuration Showing Radial Position of Measurements to be Made

vious experiment. These modified support blocks are described in Appendix A of WANL-TME-1914. Three sets of TaC pencils were also removed from this radius. The changes at radius 4 were similar to those at radius 2 with two TaC central elements being removed. The reactivity of the modified core was adjusted by the uniform addition of 48 Nb shim wires to maintain an average drum bank angle of $115 \pm 1^\circ$.

The approximate positions of the 4 radii used are 4.8 cm, 22.3 cm, 35.4 cm, and 45.0 cm from core centerline.

The test ISA shim tubes were inserted into the desired clusters manually, and were supported axially by the same cluster hardware which holds the liner tubes. The polyethylene "wires" were always used with a tube (ISA shim or uncoated stainless) to provide lateral support. The cluster plate insured that the shim tubes and polyethylene wires would not fall out of the core, even in the peripheral element locations at radius 3, where the only hole in the cluster plate was considerably smaller than a polyethylene "wire". One polyethylene "wire" showed no evidence of sagging when tested in a shim tube held vertically.

The reactivity of each configuration was measured by establishing a drum bank with the R-1 drums at 115° and the KIWI drums at either 120° or 115° , depending on the expected reactivity of the configuration. The resulting period was measured with the period pickoff (PPO) system and MIDAS-1, and the reactivity was measured directly with the WANEF analog computer.

During the first run of each operating day, the reactivity of the base configuration was remeasured. ISA shim tubes and/or polyethylene "wires" were then inserted into the desired test positions and the resulting reactivity was measured.

The weights of the ISA shim tube coatings and the uncoated stainless steel tubes are given in Table 4-2 according to tube number. When the tubes were used at radial position 1, (see Figure 4-1 for radial position nomenclature) the tube numbers corresponded with the sector numbers. At the other three radial positions, the tube numbers increased from one to seven in going through sector four and sector five. Several measurements were made with every

TABLE 4-2 WEIGHTS OF ISA SHIM TUBE COATINGS, UNCOATED STAINLESS STEEL TUBES,
AND POLYETHYLENE "WIRES"

Tube Number	Uncoated Stainless Steel	Weight of Test Samples, gms.				HfC Thick
		HfO ₂ Thick	HfO ₂ Thin	TaC Thick	TaC Thin	
1	17.72	24.156	2.359	28.918	6.235	27.168
2	17.89	19.055	4.271	31.700	6.7422	28.181
3	18.77	21.621	3.383	28.244	9.5859	29.494
4	17.72	20.668	2.839	33.474	9.9652	26.427
5	17.89	20.241	2.861	30.998	4.3515	27.458
6	17.63	22.528	3.029	30.182	4.2394	25.600
7	17.63	18.832	2.864	29.473	4.3815	26.128

NOTE: Weight of one 52" long, 0.08" diameter polyethylene wire = 4.493 grams obtained from weighing the 49 wires used in the experiment.

All weights are corrected to a 52" length. Thick coatings are a nominal 0.003" thick. Thin coatings are a nominal 0.0005" thick.

other shim tube removed. In each such case, the even-numbered tubes were omitted while the odd-numbered tubes remained in the same locations which they occupied in the other measurements. The last run of each operating day was usually a repeat of the baseline configuration.

4.3 TEST RESULTS

The results of the reactivity measurements with the ISA materials and polyethylene are given in Tables 4-3 and 4-4 for all radial positions. The standard deviations from the three systems are: a) analog computer = 0.11% , b) MIDAS = 0.11% , c) period pickoff = 0.21% .

4.4 DISCUSSION

4.4.1 Reproducibility of Base Configuration

The standard deviation of the measurements was determined from the reproducibility of the baseline reactivity. The reproducibility of the baseline reactivity was examined two ways: a) by averaging all baseline measurements together, and b) by using the measurements from each day separately. Baseline reproducibility by method a) is $\pm 0.48\%$ from the period pickoff (PPO) system, and $\pm 0.35\%$ from both analog computer and MIDAS-1 systems. On seven of the operating days, the baseline was measured twice and applying method b), gives $\sigma = \pm 0.21\%$ from the PPO and $\pm 0.11\%$ from the analog computer and MIDAS-1. These results indicate that the period pickoff system introduced measurement uncertainties during this experiment which were greater than those of the other two measuring systems.

An additional test of the measuring systems was made by measuring the reactivity difference between two reproducible control drum banks three times. In the first drum bank set, all drums were at 115.0° . For the second drum bank set, the R-1 drums were at 115.0° and the remaining drums at 120.0° . The average reactivity worth of the three trials from the PPO was $21.07 \pm 0.30\%$, the analog gave $21.26 \pm 0.04\%$, and MIDAS-1 gave $21.24 \pm 0.05\%$. Again the PPO shows the largest uncertainty. These uncertainties, when corrected

to one measurement, are in reasonable agreement with the standard deviations given in Section 4.3.

4.4.2 Repeatability of Test Results and Special Tests

In measuring polyethylene worth at radial position 2 with no shim material present, the low worth measurement (2 "wires" per tube) was initially done with the more reactive drum bank, i. e., the second drum bank set noted above. In order to determine if the change in drum bank had any effect upon the measurements, the 2 "wires" per tube value was remeasured with the less reactive drum bank. The result is given in Table 4-3 under "check results" and agrees with the previous value to 0.22%, as expected. At the same time, the 7 "wires" per tube value was repeated, and agreement was obtained to about 2%.

A special measurement was also made at radial position 2 to investigate the "bunching" effect of polyethylene. "Bunching" (or clustering the polyethylene into a smaller area) tends to increase the measured reactivity since the specific worth increases slightly as the number of "wires" in a single location increases due to local increased hydrogen moderation effect on spectrum. Seven wires were placed in the two end locations at radial location 2. The measured reactivity (7.45% by analog computer) was higher than that of the 2 "wires" per tube value (7.1%), and agrees better with 2/7 of the value for 7 "wires" per tube ($2/7$ of $26.56\% = 7.59\%$).

TABLE 4-3 REACTIVITY MEASUREMENTS OF HfO₂ TaC,
AND HfC SAMPLES WITHOUT POLYETHYLENE

Shim Material	Thickness	Number of Tubes	Measured By	Radial /Position					
				1	2	3	4		
HfO ₂	thick (0.003")	7,6*	Analog	-8.07	-6.24	-4.64	-7.13		
			MIDAS	-8.1	-6.21	-4.66	-7.15		
			PPO	-8.14	-5.96	-4.65	-7.14		
		thin (0.0005")	7,6	Analog	-1.70	-1.59		-1.78	
				MIDAS	-1.71	-1.61		-1.88	
				PPO	-1.87	-1.37		-1.17	
	thick	4,3**	Analog	-4.11	-3.73		-4.20		
			MIDAS	-4.15	-3.66		-4.13		
			PPO	-4.22	-3.42		-4.27		
		TaC	thick	7,6	Analog	-10.58	-8.50	-5.39	-5.20
					MIDAS	-10.6	-8.59	-5.39	-5.22
					PPO	-10.71	-8.55	-5.39	-4.90
thin	7,6		Analog	-3.30	-2.47		-1.56		
			MIDAS	-3.22	-2.47		-1.68		
			PPO	-2.77	-2.40		-0.86		
TaC	thick	4,3	Analog	-5.23	-5.09		-2.99		
			MIDAS	-5.24	-5.02		-2.99		
			PPO	-5.24	-4.60		-2.98		
HfC	thick	7	Analog		-8.35				
			MIDAS		-8.32				
			PPO		-8.38				

*7 tubes were used at Radii 2-4, 6 tubes at Radius 1.

**4 tubes were used at Radii 2-4, 3 tubes at Radius 1.

****The 1 σ uncertainties are: Analog = $\pm 0.11\beta$, MIDAS = $\pm 0.11\beta$, PPO = $\pm 0.21\beta$.

TABLE 4-4 REACTIVITY MEASUREMENTS WITH POLYETHYLENE

Shim Material & Thickness	Measured by	No. of Poly Wires Inside Shim Tube				6 Poly Wires In Fuel Cluster
		0.0	2	4	7	
Measured Reactivity, ρ ***						
A. Radial Position 2						
None	Analog	0.0	+7.1	+14.50	+26.56	+21.34
	MIDAS	0.0	+7.11	+14.50	+26.72	+21.33
	PPO	0.0	+7.18	+14.53	+26.74	+21.32
HfO ₂ thick	Analog	-6.24	-.71	+4.96	+14.50	+13.70
	MIDAS	-6.21	-.68	+5.07	+14.51	+13.69
	PPO	-5.96	-.52	+4.82	+14.67	+14.24
TaC thick	Analog	-8.50	-2.71	+3.50	+14.06	+11.65
	MIDAS	-8.59	-2.67	+3.58	+14.06	+11.65
	PPO	-8.55	-2.57	+3.62	+13.96	+12.34
None*	Analog				+ 7.45	
	MIDAS				+ 7.59	
	PPO				+ 7.17	
Check Results:**						
None	Analog		+7.28		+26.91	
	MIDAS		+7.35		+26.93	
	PPO		+7.39		+26.91	
B. Radial Position 4						
None	Analog	0.0	+2.84	+5.89	+10.86	+8.77
	MIDAS	0.0	+2.90	+5.98	+10.79	+8.79
	PPO	0.0	+3.73	+5.62	+11.54	+9.60
HfO ₂ thick	Analog	-7.13	-5.13	-2.92	+.54	+.89
	MIDAS	-7.15	-5.11	-2.95	+.60	+.88
	PPO	-7.14	-5.07	-2.93	+.61	+1.68
TaC thick	Analog	-5.20	-2.79	-.30	+ 3.64	+3.13
	MIDAS	-5.22	-2.80	-.34	+ 3.64	+3.12
	PPO	-4.90	-2.35	-.37	+ 4.44	+3.89

* Special experiment in which 7 poly wires were placed in locations 1 and 7 at radial position 2.

**See discussion, section 4.4.2.

* *The 1 σ uncertainties are: Analog = $\pm 0.11\rho$, MIDAS = $\pm 0.11\rho$, PPO = $\pm 0.21\rho$.

5.0 ANALYSIS

5.1 REACTIVITY WORTH OF SHIM TUBES IN THE DRY, AMBIENT CONFIGURATION

5.1.1 Prediction of Reactivity Worths of Dry, Ambient Tubes

The design of the poison tubes for In-Place Shim Adjustment (ISA) for the NERVA employs a thin coating of neutron poison on a base tube of stainless steel. For experimental purposes, test articles were designed and ordered with nominal coating thickness of 3 and 1/2 mils. These test articles are specified in WANL Drawing 388D561. Five materials were initially elected as candidates: TaC, HfO₂, HfC, W, and Gd₂O₃. All candidates but three were subsequently deleted from consideration in the experiments. Tungsten (W) was eliminated because detailed analyses indicated that the reactivity worth was considerably less than the other candidates. Gadolinium Oxide (Gd₂O₃) was eliminated because the material could not be successfully fabricated by the coating technique. Hafnium Carbide (HfC) was eliminated because the material did not adhere to the stainless steel. Thus, the ISA experiments were restricted for the most part to measurements of the reactivity worth of TaC and HfO₂. However, one reactivity measurement was performed for HfC.

The reactivity worths per unit mass (ρ /kg) for HfO₂, TaC, and HfC coated tubes were calculated as a function of radial position in the PAX-R1 via the PERT-1D perturbation code. The core averaged reactivity coefficient is also provided by the PERT-1D code. The PERT-1D code employed 16-energy group forward and adjoint fluxes which were obtained from ANISN, a one-dimensional transport code. An appropriate 16-group cross section set was input to PERT-1D for each poison material and configuration. The cross section sets were generated through the GAMBIT code and were spectrally weighted over the central and edge spectra, respectively.

Dilute homogeneous cross sections ($\Sigma_p = 100,000$ barns/absorber atom) were utilized to perform the analysis on the 1/2 mil thick coatings. The cross sections for the analysis of the 3 mil thick coatings were obtained through the heterogeneous option of GAMBIT in which a mean-chord length is provided to specify the escape probability. The GAMBIT does not provide a direct calculation for tube geometries. Thus, the cross sections were evaluated in alternate approximations to the hollow tube geometry. One set of cross sections treated

the poison coating as a thin foil (GAMBIT slab option) with the mean chord length equal to $2t$ (t is the coating thickness). Another cross section set was generated in which the tube was treated as an equivalent solid cylinder (GAMBIT cylindrical option) with the mean chord length equal to $2R$ (R is the tube radius). The actual coating density was replaced with an effective density in the solid cylinder. Either approximation gave nearly equal reactivity worths in PERT-ID.

The results of the PERT-ID analysis are shown as "Predicted-3mil" and "Predicted-Dilute" in Figure 5-1 through 5-5, respectively. While all of the coatings considered are primarily resonance absorbers, the HfO_2 and HfC exhibit a large reactivity worth at the periphery due to thermal neutron absorption in the soft peripheral spectrum.

Additional analyses were performed to assess the change in reactivity worth of TaC shim tubes as a function of total shim content in the core. This is related to the shadowing effect which was assessed in the experiment.

5.1.2 Measured Reactivity Worths of Dry, Ambient Shim Tubes

5.1.2.1 Radial Dependence of Reactivity Coefficients

As noted in Section 4.2, the test articles were inserted in groups of 3, 4, 6, or 7 in support stems at four, respective, nominal radial locations. The mass of shim coating varied between test samples of the same material and same nominal thickness. Thus, the masses employed in the measurements varied with the grouping of tubes inserted. Table 5-1 shows the masses of the individual test sample (per 52" as effective in the core) and the masses of the various experimental groupings.

Table 5-2 displays the reactivity coefficients calculated from the reactivity measurements made when the respective test samples were inserted. The measured reactivities, reported in Table 4-3, were divided by the corresponding mass insertion from Table 5-1 to obtain the experimental reactivity coefficients, ρ/kg . The error band is derived from the $\pm 0.11\rho$ uncertainty as cited in Section 4.3. The experimental coefficients are plotted in Figures 5-1 through 5-5 for comparison with predictions.

Figure 5-1. Reactivity Worth of TaC, Nominal 3-Mil Coating

Figure 5-2. Reactivity Worth of HfO_2 , Nominal 3-Mil Coating

Figure 5-3. Reactivity Worth of HfC, Nominal 3-Mil Coating

Figure 5-4, Reactivity Worth of TaC, Nominal 1/2-Mil Coating

Figure 5-5. Reactivity Worth of HfO_2 , Nominal 1/2-Mil Coating

TABLE 5-1 WEIGHTS OF ISA SHIM TUBE COATINGS*

Identifying Tube Number for Each Coating Type	HfO ₂		TaC		HfC Thick
	Thick	Thin	Thick	Thin	
1	24.156	2.359	28.918	6.235	27.168
2	19.055	4.271	31.700	6.7422	28.181
3	21.621	3.383	28.244	9.5859	29.494
4	20.668	2.839	33.474	9.9652	26.427
5	20.241	2.861	30.998	4.3515	27.458
6	22.528	3.029	30.182	4.2394	25.600
7	18.832	2.864	29.473	4.3815	26.128
Average per Tube	21.014	3.086	30.427	6.5001	27.208

Tube Grouping	Weight of Tube Groups as Employed in Tests, gms				
1 through 7	147.101	21.606	212.989	45.501	190.456
1 through 6	128.269	18.742	183.516	41.119	
1, 3, 5, 7	84.850		117.633		
1, 3, 5	66.018		88.160		

* All weights are in grams and are corrected to a 52" length. Thick coatings are a nominal 0.003" thick. Thin coatings are a nominal 0.0005" thick.

TABLE 5-2 MEASURED REACTIVITY COEFFICIENTS OF HfO₂, TaC, AND HfC SAMPLES
WITHOUT POLYETHYLENE (Based on analog results)

Shim Material	Thickness	Radial Position			
		1	2	3	4
		Coefficient, μ /Kg			
HfO ₂	thick	62.91+0.86 ⁺	42.42+0.75*	31.54+0.75*	48.47+0.75*
	thin	90.71+5.87 ⁺	73.59+5.09*		82.38+5.09*
	thick	62.26+1.67 ⁺⁺	43.96+1.30**		49.50+1.30**
TaC	thick	57.65+0.60 ⁺	39.90+0.52*	25.31+0.52*	24.41+0.52*
	thin	80.25+2.68 ⁺	54.28+2.42*		34.29+2.42*
	thick	59.32+1.25 ⁺⁺	43.27+0.93**		25.42+0.93**
HfC	thick		43.84+0.58*		

*Tube Grouping 1 through 7

⁺Tube Grouping 1 through 6

⁺⁺Tube Grouping (1,3,5)

**Tube Grouping (1,3,5,7)

5.1.2.2 Self-Shielding Factors

The reactivity coefficients for 6 and 7 tube groups are plotted in Figure 5-6 as a function of the reciprocal of the coating thickness. The data are plotted in log-log coordinates to facilitate the determination of self-shielding factors at other coating thicknesses. As noted, TaC data for the respective radii display a set of parallel lines without consideration of experimental error. This indicates that the relationship between coating thickness and self-shielding varies as $t^{-1/5}$ for all radial positions. The HfO_2 data do not show such consistency in the self-shielding relationship (slope for Position 1 different than Positions 2 and 4). However, the reactivity coefficient for HfO_2 varies approximately as $t^{-1/3}$.

5.1.2.3 Mutual Shadowing of Shim Tubes

The reactivity coefficients for the 6 or 7 tube groups (many tubes) of 3-mil coatings are compared with those of the 3 or 4 tube groups (few tubes) in Table 5-3. This difference, in general, illustrates the mutual shadowing effect which occurs when absorbers are placed in close proximity to each other. Also shown are the associated (1σ) uncertainty in the ratios.

5.1.3 Comparison of Predictions and of Experimental Results

The predicted reactivity coefficients for the 3-mil coatings are shown in Table 5-4 for the radii which correspond to the experimental positions 1 through 4. The measured coefficients for thick (nominal 3-mil) coating are compared to the predicted coefficients. Except for the coefficients at the periphery (position 4), all measurements and predictions are within $\pm 6\%$. The predictions underestimated the peripheral worth of TaC by 13.5% and overestimate the worth of HfO_2 by 28%. These differences are illustrated in Figures 5-1 through 5-3. The discrepancy in HfO_2 predictions is attributed primarily to the fact that thermal neutron self-shielding was not factored into the HfO_2 cross sections. It is felt that the discrepancy in the TaC predictions is primarily due to the representation of the control vanes by an annular ring in the one-dimensional calculational model.

The measured reactivity coefficients for the 1/2-mil coatings were expected to yield smaller reactivity coefficients than the dilute predictions because of self-shielding. The coefficients for 1/2-mil TaC, as shown in Figure 5-4, display this expected behavior.

Figure 5-6. Shim Tube Worth as Function of Coating Thickness (Self-Shielding)

TABLE 5-3 SHADOWING EFFECT OF 3-MIL SHIM TUBES

Shim Material	Radial Position			
	1	2	3	4
	Ratio of Coefficients*			
HfO ₂	0.989 _{-0.030}	1.036 _{-0.035}	-----	1.021 _{-0.031}
TaC	1.029 _{-0.025}	1.084 _{-0.027}	-----	1.041 _{-0.043}

*Ratio of Coefficients (c/Kg) of 3-Tube and 6-Tube groupings at Position 1, and Ratio of Coefficients of 4-Tube and 7-Tube groupings at Positions 2 and 4.

TABLE 5-4 COMPARISON OF PREDICTED AND MEASURED REACTIVITY COEFFICIENTS
FOR THICK TUBES*

Shim Material		Radial Position			
		1	2	3	4
		Coefficient, $\mu\text{/Kg}$			
HfO ₂	Measured	62.91 $\pm$ 0.86	42.42 $\pm$ 0.75	31.54 $\pm$ 0.75	48.47 $\pm$ 0.75
	Predicted	60.82	40.62	33.52	67.90
	Difference between Measured and Predicted	+3.43%	+4.4%	-6.0%	-28%
TaC	Measured	57.65 $\pm$ 0.60	39.90 $\pm$ 0.52	25.31 $\pm$ 0.52	24.41 $\pm$ 0.52
	Predicted	56.00	42.25	26.66	21.51
	Differences between Measured and Predicted	+2.94%	-5.3%	-5.24%	+13.5%
HfC	Measured		43.84 $\pm$ 0.58		
	Predicted		43.11		
	Difference between Measured and Predicted		+1.7%		

*The measured data is for the 1 through 6 and 1 through 7 groupings.

The measured coefficient for HfO_2 , as shown in Figure 5-5, appears to be higher than the dilute coefficients at the two central locations, but is in good agreement with the dilute prediction at the core periphery.

5.1.4 Relationship of Dry, Ambient Experimental Results to NERVA Design

The preliminary design specifications for shim tube sizing for NERVA are derived here from experimental shim worths for the PAX/R-1 configuration. Since there are considerable differences in the fuel and reflector of PAX/R-1 and the NERVA reference design, analyses appropriate to the reference design must be performed in order to define the final shim specifications.

Based on the experimental results presented above and previous analysis, TaC is tentatively selected as the shim coating for the ISA tubes in R-1. HfO_2 was rejected because (1) the experimental results show that it yields less total shim capability for a given coating thickness than TaC, (2) calculations have indicated that a material with a higher peripheral worth, such as HfO_2 , will reduce the drum span, and (3) HfO_2 reduces the effective worth of core hydrogen more than TaC does.

This reduction in hydrogen worth is discussed in Section 5.2. Because of the elimination of HfO_2 as a candidate for ISA shim material, the remainder of this section is limited to a discussion of the application of TaC shims in the R-1 design.

Two alternate shim schemes are being considered for the R-1 reactor. One scheme would provide $\pm \$1.50$ shim capability (\$3.00 maximum shim content). Shim tubes would be placed in one-half of all support stems at the initial construction. This scheme is designated as the "(1/2) (1/2)" shim method. The other scheme would provide $+\$1.50$ to $-\$3.00$ shim capability (\$4.50 maximum shim content). Shim tubes would be placed in one-third of all stems at initial construction. This scheme is designated as the "(1/3) (2/3)" shim method. The shim additions or deletions are to be made uniformly across the core to maintain a flat power profile. The specification of the mass of TaC coating per tube for the design depends on (1) the shim scheme, (2) shim requirement, (3) the self-shielding factor, (4) mutual shadowing, (5) uncertainty in the measured reactivity coefficient, and (6) allowance for manufacturing tolerance. The mass requirements for the respective shim schemes are discussed below.

5.1.4.1 Mass of TaC for the (1/2) (1/2) Shim Scheme

The experimental measurements confirm the predicted core-averaged reactivity coefficient for TaC tubes with a nominal 3-mil thick coating. The experimental core-average coefficient was derived by integrating over an analytic fit to the experimentally determined radial profile. Figure 5-7 shows the analytic (two-part parabolic) fit to the experimental data shown in Figure 5-1. The experiment yields a core-averaged reactivity coefficient of 32.4¢/kg compared to the 32.2¢/kg predicted by PERT-1D. The experimental uncertainty is of the order of 1 to 2%.

Since the measurements were performed with approximately -\$3.00 worth of TaC distributed uniformly in the PAX/R-1 core, the measured coefficient is appropriate for the specification of shim masses in the (1/2) (1/2) shim scheme which requires a maximum shim requirement of -\$3.00.

For the (1/2) (1/2) scheme, each of the 349 shim tubes should have a coating mass of 26.8 grams of TaC per 52 inch length for a \$3.0 shim capability. This is based on the core average coefficient for TaC of 32.4¢/kg. The manufacturing tolerance shown on DWG 940J433 for the coating technique is $\pm 8\%$ and the corresponding uncertainty in the reported experimental results is $\pm 2\%$. Consequently, to account for possible manufacturing variations (all masses at the minimum tolerance) and uncertainties in the experimental results, (all measurements consistently high), the required mass per shim tube is increased to 29.5 (1.10 x 26.8) grams. The thickness of the coating depends on the actual density of the TaC coating and the diameter of the shim tubes.

5.1.4.2 Mass of TaC for the (1/3) (2/3) Shim Scheme

The maximum shim requirement for the (1/3) (2/3) scheme is -\$4.50 with 349 shim tubes. The experimental reactivity coefficient for the nominal 3-mil thick TaC coating was corrected for self-shielding, and mutual shadowing to yield an effective core-averaged coefficient of 28.0¢/kg for the (1/3) (2/3) scheme. Thus, to achieve the shim capability of -\$4.50, each of the 349 shims have a coating mass of 46.0 gms per 52" length. Consequently, to account for possible manufacturing variations and uncertainties in the experimental results,

Figure 5-7. Shadowing Effect and Radial Profile for TaC

the required mass per shim tube is increased to 50.6 (1.10×46.0) gms.

5.1.4.3 Variation of Individual Shim Tube Worth During the Shimming Procedure

Figures 5-8 and 5-9 are working curves to aid in distributing shim tubes during a shimming procedure for the (1/2) (1/2) and (1/3) (2/3) schemes, respectively. These curves are based on the experiments performed in PAX-G2 and are, therefore, only approximate for the R-1 (different fuel and reflector than PAX-G2). The curves show the effect of adding or deleting individual tubes of a given mass from a given radial location. The solid line in each figure represents the radial dependence of the reactivity coefficient for small additions or deletions of tubes with a nominal -1.50 preliminary shim in the core. The upper dashed curve illustrates the enhanced worth of the last tubes which are removed to gain positive reactivity (no shims in core). The lower curve represents the worth when the last tubes are added to achieve the maximum negative reactivity.

Figure 5-8. Variation of Shim Tube Worth in (1/2) (1/2) Shim Scheme

Figure 5-9. Variation of Shim Tube Worth in (1/3) (2/3) Shim Scheme

5.2 INTERACTION OF SHIM MATERIAL AND CORE HYDROGEN

5.2.1 Prediction of Hydrogen Reactivity Versus Shim Content

Calculations were performed to evaluate the mutual interaction between hydrogen and the ISA shim materials. These analyses have investigated the effects of shimming on the hydrogen reactivity coefficient in the PAX/R-1 core. All analyses employed the ANISN one-dimensional transport code using 16-group cross sections.

Preliminary calculations were initiated to determine the relative degree of neutronic interaction of TaC and HfO_2 with support stem hydrogen. These calculations simulated the support stem geometry at the axis of the PAX reactor which was void of hydrogen except for the central stem. The reactivity worth of various hydrogen masses were determined with (1) no shim, (2) a 3-mil TaC coating, and (3) a 3-mil HfO_2 coating. These preliminary results indicated that the effective reactivity worth per unit mass of the stem hydrogen is reduced by about 9% with TaC and by about 27% with HfO_2 . Because of these results, the plan for the ISA experiment was modified to include measurements of the interaction of hydrogen and shim materials.

Additional analyses simulated the experimental conditions in the PAX reactor in which the support stem hydrogen was simulated with polyethylene wires. These calculations considered TaC shims only, although the experiments included both TaC and HfO_2 . The analyses employed radial ANISN calculations in which the support stems were simulated with thin rings at approximately 22 cm and 45 cm, respectively. Appropriate masses of the polyethylene composition (carbon and hydrogen) and TaC used in the experiments were admixed in the respective rings. The hydrogen reactivity coefficients, derived from the ANISN calculations, are presented in Table 5-5 as predictions for the experiments.

5.2.2 Presentation of Experimental Results

The reactivities which were observed from the polyethylene experiments in the PAX-R1 as described in Chapter 4.0, are displayed in Figures 5-10 and 5-11. Arbitrary straight lines are drawn through the data points at 0 and 4 poly wires/per cluster. The effective hydrogen reactivity coefficients ($\rho/\text{gm H}$) associated with each combination of shim tube and polyethylene loading are shown in Table 5-6. These coefficients were extracted from the experimental

TABLE 5-5 PREDICTED HYDROGEN WORTH AT EXPERIMENTAL LOCATIONS

 $\epsilon/\text{gm OF HYDROGEN}$

<u>Core Model</u>	<u>Radial Position 2 (22 cm)</u>	<u>Radial Position 4 (45 cm)</u>
No Shim Tubes ⁺	0.795	0.282
Simulated 7 TaC Shim Tubes in Test Sector ⁺	0.641	0.256

⁺ The base case material distributions included a uniform density of TaC which was equivalent to a \$3.00 shim content in an unperturbed core. However, to simulate the conditions of the ISA experiments, wherein TaC elements and pencils were removed from the respective radial position in PAX, the molecular density of TaC was adjusted in the regions in and near the annuli which represented the support stems.

Figure 5-10. Results of Polyethylene Experiments at Radial Position 2 (22 CM)

Figure 5-11. Results of Polyethylene Experiments at Radial Position 4 (45 CM)

TABLE 5-6 MEASURED REACTIVITY COEFFICIENT OF SUPPORT STEM HYDROGEN
 $\rho/\text{gm H}$

A. Radial Position 2					
<u>Shim Material</u>	No. of Poly Wires Inside Shim Tube			Special*	6 Poly Wires in Fuel Cluster
	2	4	7		
No Shim	.757 $\pm$.012	.776 $\pm$.006	.812 $\pm$.003	.796 $\pm$.012	.760 $\pm$.004
HfO ₂	.586 $\pm$.012	.593 $\pm$.006	.628 $\pm$.003		.708 $\pm$.004
TaC	.613 $\pm$.012	.637 $\pm$.006	.685 $\pm$.003		.715 $\pm$.004
B. Radial Position 4					
<u>Shim Material</u>				Special*	6 Poly Wires in Fuel Cluster
	2	4	7		
No Shim	.298 $\pm$.012	.307 $\pm$.006	.326 $\pm$.003		.306 $\pm$.004
HfO ₂	.203 $\pm$.012	.214 $\pm$.006	.224 $\pm$.003		.282 $\pm$.004
TaC	.248 $\pm$.012	.253 $\pm$.006	.262 $\pm$.003		.299 $\pm$.004

* Special Measurement with 7 wires in 2 widely separated stems

data by correcting for the carbon reactivities presented in Table 5-7. The corresponding hydrogen and carbon masses are also presented. The total reactivity associated with the hydrogen component is shown in Figure 5-12.

The reactivity coefficients of Table 5-6 are plotted in log-log coordinates in Figure 5-13 as a function of the mass of hydrogen loaded into the respective radial regions. It is observed that the reactivity coefficient increases slightly with the mass of hydrogen that is present. The increase is due primarily to the high hydrogen mass per stem which produces local spectral effects. This is shown in the No Shim data of Table 5-6 by comparing the coefficient for 2 wires in each of 7 stems with that for 7 wires in each of 2 stems (labeled "Special" in the table). The latter yields a coefficient which is 5.1% higher than the former. There is an additional enhancement of the hydrogen coefficient when adjacent clusters have a high hydrogen mass. The reactivity coefficient for 7 wires in each of 7 stems is 2.0% higher than the coefficient for 7 wires in each of 2 stems which are spatially isolated. However, the range of hydrogen which is present in the support stem of the R-1 reference designs is simulated by the swing from one to four poly wires per stem. Over this range of poly mass, the reactivity worth is not considered significant enough to warrant a modification of the current NERVA design practice which considers the worth of hydrogen in the support stem to be constant at all flow rates. The appropriate constant reactivity coefficient was determined from the present measurements by assuming a linear dependence between the hydrogen reactivity and the hydrogen mass.

A least square linear fit was found for the experimental polyethylene data shown in Figures 5-11 and 5-12, over the range of 0 to 4 poly wires per stem. This includes the range of hydrogen mass employed in R-1 stems. The slope of these linear fits corresponds to the reactivity coefficients of polyethylene. The carbon contribution was extracted to obtain the hydrogen support stem reactivity coefficients shown in Table 5-8. Table 5-8 also shows core propellant coefficients which were derived from the six hydrogen measurements performed in the fuel.

A comparison of the hydrogen coefficients with and without shims in place in Table 5-8 indicates that the reactivity worth of hydrogen in a support stem is

TABLE 5-7 BASIC DATA USED TO EXTRACT HYDROGEN
REACTIVITY COEFFICIENT FROM POLY MEASUREMENTS

Number of Poly Wires per Stem	Grams Hydrogen per Stem	Grams Carbon per Stem	Carbon Reactivity, ϕ for 7 stems	
			Radial Position 2	Radial Position 4
1	0.6460	3.848	.1160	.0808
2	1.2920	7.696	.2320	.1616
4	2.5840	15.392	.4640	.3232
6	3.8760	23.088	.6960	.4648
7	4.5220	26.936	.8120	.5456

Average weight of each polyethylene wire (0.08" diam. x 52") = 4.493 grams is obtained from weighing the 49 wires used in the experiment.

Figure 5-12. Reactivity Effect of Stem Hydrogen as a Function of Number of Poly Wires Per Stem

Figure 5-13. Reactivity Coefficient of Hydrogen as Function of Hydrogen Mass

TABLE 5-8 COMPARISON OF HYDROGEN REACTIVITY COEFFICIENTS

	Support Stem Hydrogen			Core Propellant Hydrogen		
	No Shims	HfO ₂	TaC	No Shims	HfO ₂	TaC
Radial Position 2						
ϕ /gm H	.776 $\pm$.011	.595 $\pm$.004	.639 $\pm$.013	.760 $\pm$.004	.708 $\pm$.004	.715 $\pm$.004
%Difference from No Shims		-23.2 $\pm$ 1.5	-17.6 $\pm$ 2.0		-6.8 $\pm$ 0.7	-5.9 $\pm$ 0.7
Radial Position 4						
ϕ /gm H	.308 $\pm$.006	.215 $\pm$.006	.252 $\pm$.002	.306 $\pm$.004	.282 $\pm$.004	.299 $\pm$.004
%Difference from No Shims		-30.2 $\pm$ 2.9	-18.2 $\pm$ 2.2		-4.5 $\pm$ 1.8	-2.3 $\pm$ 1.8

reduced by 18% with TaC shim tubes and by 23 to 30% with HfO_2 . This table also shows that the reactivity worth of the propellant in a shimmed cluster is reduced by 2 to 6% with TaC and 5 to 7% with HfO_2 . Because the HfO_2 reduces the hydrogen worth more than TaC, this is one of the principle reasons for rejecting HfO_2 as a shim material. The table also shows that the worth of hydrogen is approximately the same in the stems and in the fuel when there is no shim in the cluster.

The data of Table 5-8 are displayed graphically in Figure 5-14 to illustrate the reduction in hydrogen worth due to nominal 3-mil TaC shims at the two radial positions of the experiment. The relationship of this reduction in hydrogen worth to NERVA design is discussed in Section 5.2.4.

5.2.3 Comparison of Predictions and Measurements of Hydrogen Reactivity Coefficients with Shim Tubes

The measured hydrogen reactivity coefficients as measured with No Shim, TaC, and HfO_2 shim tubes (nominal 3-mil coatings) are presented in Table 5-9 for comparison with the predictions. Predictions were made only for TaC. It is seen that the respective predictions for the No Shim case is slightly higher than the measurement at Radial Position 2 (22 cm) and lower than the measurement at Radial Position 4 (45 cm). However, the predictions with the TaC shims in place are in good agreement with the measurements at both radii.

The measured and predicted effect of the TaC shim on the effective hydrogen reactivity coefficient of the support stems is also shown in Table 5-9. At Position 2, the predictions indicate a 19.4% reduction in hydrogen reactivity coefficient while the measurement shows 17.6% reduction. Thus, the prediction is in good agreement with the measurement. At Position 4, however, the predictions indicate a reduction of 9.2% in the hydrogen reactivity coefficient while the measurements indicate a reduction of 18.2%. This difference is due to the low prediction for the No Shim case at the Radial Position 4 (at the core periphery) which is approximately 8% below the measured hydrogen worth.

Figure 5-14. Effect of 3-Mil TaC Shim Tubes on Hydrogen Reactivity Coefficients

TABLE 5-9 COMPARISON OF MEASURED AND PREDICTED
HYDROGEN REACTIVITY COEFFICIENTS
 $\phi/\text{gm H}$

Shim Material	Radial Position 2		Radial Position 4	
	Measured	Predicted	Measured	Predicted
Reactivity Coefficient, $\phi/\text{gm H}$				
No Shim	0.776 $\pm$.011	0.795	0.308 $\pm$.012	0.282
TaC	0.639 $\pm$.013	0.641	0.252 $\pm$.012	0.256
% Reduction No Shim to TaC	17.6 $\pm$ 2.0	19.4	18.2 $\pm$ 2.2	9.2
HfO ₂	0.595 $\pm$.004	-----	0.215 $\pm$.012	-----
% Reduction No Shim to HfO ₂	23.2	-----	30.2	-----

5.2.4 Relation of Hydrogen Experiments to NERVA Design

An analytical model is used to predict the reactivity worth of hydrogen in NERVA system for use in the TNT (Transient Nuclear Thermal) computer program which calculates cold-to-hot reactivity feedback. The present design model employs a one-dimensional ANISN calculation using 52-group cross sections. In such calculations, the shim material (TaC) is distributed homogeneously through the core to obtain the desired dry, ambient shim worth. The effective reactivity worths of support stem and propellant hydrogen are assumed to be equal. However, the results of the present experiments show that homogeneous calculation underestimates the reactivity worth of propellant and overestimates the reactivity worth of stem hydrogen when TaC shim tubes are employed in the support stems.

For example, a homogeneous 16-group ANISN calculation was performed for a system containing \$3.00 worth of TaC in a uniform distribution. The results show that the effective worth of hydrogen is reduced by 8% relative to an unshimmed core. However, as illustrated in Figure 5-14 for the present experiments, which simulated a \$3.00 distribution of TaC shim tubes, the propellant worth was reduced by only 6% (2% at the periphery) while the stem worth was reduced by 18%. Consequently, the use of a 16-group homogeneous calculation results in an underestimate of propellant worth by 2% and an overestimate of the stem worth by 10%.

The 16-group calculations indicate that the reduction of effective hydrogen worth is proportional to the amount of shim present. Thus, with \$1.50 TaC content, the homogeneous calculations show a hydrogen worth reduction of only 4% relative to the unshimmed core. The heterogeneous experimental results are scaled in proportion to the \$1.50 shim content to give a 3% reduction in propellant reactivity worth and a 9% reduction in stem worth. Consequently, the homogeneous calculation underestimates the propellant worth by 1% and overestimates the stem worth by 5% for a TaC shim content of \$1.50.

For an unshimmed core, the homogeneous calculations yield the base case hydrogen reactivity which equally applies to the propellant and stem hydrogen.

The comparison of 16-group calculations with the present experimental results suggest a means by which the 52-group homogeneous ANISN results which are employed in

the prediction of hydrogen reactivity coefficients for use in TNT analyses may be corrected for heterogeneous effects. The experimental results showed that the reduction of the stem worth due to shim tubes is essentially independent of the radial location in the core. However, the reduction of propellant worth due to shim tubes is less strong (2% versus 6%) at the periphery. It is assumed that the lessened shim effect pertains only at the extreme periphery and that for design purposes, the reduction in propellant worth is independent of the radial position in the core.

Figure 5-15 illustrates the method by which future 52-group ANISN hydrogen calculations will be corrected for heterogeneity for use in the TNT reactivity model. The left portion of the figure illustrates schematically, the results for 52-group homogeneous ANISN calculations: a base case for an unshimmed core with a normalized hydrogen reactivity worth of 1.0; and three shimmed cases of \$1.50, \$3.00, and \$4.50 which show corresponding reductions in hydrogen worth of X, Y, and Z%, respectively. The actual value of X, Y, and Z are to be determined for alternate NERVA designs with composite and/or HCTE fuel.

The right portion of Figure 5-15 illustrates the heterogeneous effects as determined from the present experiments for three TaC shim contents of \$1.50, \$3.00, and \$4.50. For example, the \$1.50 shim system results in a maximum reduction of support stem hydrogen worth of 9% relative to the unshimmed configuration. However, the 52-group homogeneous calculation would yield a calculated gross reduction of hydrogen worth of only X%. The effective worth of the support stem hydrogen in the shimmed system would be interpreted as the 52-group homogeneous worth minus an additional $(9 - X)\%$. This is labeled as the correction factor for stem reactivity. The stem correction factors for the \$3.0 and \$4.5 shim contents are treated similarly using the appropriate $(18 - Y)\%$ and $(27 - X)\%$ factors.

The propellant hydrogen worth is determined from the 52-group homogeneous calculations in an equivalent manner. For example, in the \$1.50 shimmed system, the propellant worth is the homogeneous hydrogen worth plus an additional $(3 - X)\%$ in the reactivity worth. The heterogeneous correction factors are discussed below in terms of the alternate shim schemes which were introduced in Section 5.1.4.

Figure 5-15. Determination of Support Stem Reactivity from Homogeneous Core Calculations

5.2.4.1 Stem Reactivity in (1/2) (1/2) Shim Scheme

In the (1/2) (1/2) shim scheme, the nominal pre-loading contains shim tubes in one-half of the 349 stems to achieve a \$1.50 shim. Thus, the preceding discussion of the correction factors of $(9 - X)\%$ for the \$1.50 apply directly.

Similarly, if due to absolute reactivity prediction errors the maximum shim content becomes \$3.00, the preceding discussion for the $(18 - Y)\%$ correction factor in \$3.00 system applies directly.

In the event that the final shim content is less than \$1.50, the stem correction factor is reduced accordingly.

5.2.4.2 Stem Reactivity in the (1/3) (2/3) Shim Schemes

For this shim procedure, only one-third of the 349 are shimmed for \$1.50. However, these tubes are worth 1.5 times the tubes in the (1/2) (1/2) scheme. The net result of the greater tube worth and fewer shimmed clusters yields the same $(9 - X)\%$ heterogeneous correction factor for the average worth of support stem hydrogen with \$1.50 TaC shims. When additional shim tubes are added to achieve a \$3.00 shim, the same $(18 - Y)\%$ correction applies as used in the (1/2) (1/2) shim procedure. The maximum shim capability of the (1/3) (2/3) TaC shim scheme is \$4.50. It is proposed that the large shim content would be employed only in R-1 and not in the flight system. The flight system would be restricted to shims in (2/3) of the clusters, at most, for a maximum shim of \$3.00. Consequently, only the R-1 ground test system would have the possibility of the additional reduction of flow control, $(27 - Z)\%$, when fully shimmed in 349 clusters.

6.0 CONCLUSIONS

The good agreement between measurements and predictions for the dry, ambient shim tubes of TaC and HfO_2 with a nominal 3-mil thickness in the graphite fueled PAX/R-1 indicates that the worth of shim tubes of comparable thickness can be predicted for the NERVA composite and HCTE fuel designs. The experimental results for the nominal 1/2-mil and 3-mil thick coatings also provided self-shielding data which can be extrapolated to determine the reactivity worths of other shim tube thicknesses. In addition, the experimental results confirmed that TaC will provide a greater shim capability than HfO_2 for a given coating thickness.

The experiments confirmed previous predictions that HfO_2 shim coating reduces the effective reactivity worth of hydrogen relative to an unshimmed configuration more than does a TaC shim. With a \$1.50 shim content, the average support stem hydrogen is reduced by approximately 14% with HfO_2 but only by 9% with TaC. Because TaC does provide a greater dry shim worth for a given thickness than HfO_2 and results in a smaller reduction of stem hydrogen worth, TaC was tentatively selected as the prime shim coating for the NERVA reference design.

The results of the experiments were used to derive heterogeneous correction factors by which the respective reactivity coefficients for support stem hydrogen and propellant can be derived from homogeneous calculations which do not differentiate between the two types of hydrogen. Consequently, it is recommended that future TNT reactivity feedback analysis (which presently employs equal coefficients for support stem hydrogen and propellant) be modified to include separate reactivity coefficients for the stem and propellant hydrogen.

Based on the result of the shim tube experiments, the TaC coating mass has been specified for two, alternate shim procedures.

One procedure, termed the (1/2) (1/2) scheme, would place shim tubes initially in one-half of the 349 support stems to achieve \$1.50 shim. Additional tubes would be placed in the remaining stems or removed from the initial shim loading as necessary to achieve the desired cold-critical drum angle. The TaC coating mass for this procedure is approximately 29.5 gms per tube in a 52" length.

The other shim procedure, termed the (1/3) (2/3) scheme, would place shim tubes initially in one-third of the 349 support stem to achieve \$1.50 shim. Additional shims could be placed in all 349 stems if desired, but a total \$3.00 shim content could be achieved with shim tubes in only (2/3) of the 349 stems. The TaC coating mass for this procedure is approximately 50.6 gms. per tube in a 52" length.

The advantage of the latter shimming procedure is that it provides space for an additional \$1.50 shim if needed for R-1. The effect on stem hydrogen reactivity is the same for the two alternate procedures with \$1.50 or \$3.00 shim content.

EDC 91 TIS 11 Page (4) "A" attachment of the Base Configuration
color coding scheme

Black - SS Tubes shown on drawing 388 D 561

Shim Tube No. 1 Serial	is labeled	Blk #	WT
19201-1		# 1	20.1 grams
-2		# 2	20.3 grams
-3		# 3	21.3 grams
-4		# 4	20.1 grams
-5		# 5	20.3 grams
-6		# 6	20.2 grams
-7		# 7	20.0 grams

59" non-adjusted weight

Red G10 Hafnium Canister 388 D 561 G40

Shim Tube No. 1 Serial	is labeled	WT (total)	Coating WT
19256-1	H C 3 1	46.0	28.135
19256-2	H C 3 2	48.6	28.807
19256-3	H C 3 3	48.9	31.196
19256-4	H C 3 4	46.1	27.952
19256-5	H C 3 5	46.2	29.042
19256-6	H C 3 6	45.1	27.077
19256-7	H C 3 7	46.0	27.635

55" long

Brown G09 Hafnium Canister 388 D 561 G09

Shim Tube No. 1 Serial	is labeled	WT (total)	Coating WT
19255-1	H 0 3 1	43.5	25.550
19255-2	H 0 3 2	39.0	20.154
19255-3	H 0 3 3	40.8	22.686
19255-4	H 0 3 4	40.0	21.860
19255-5	H 0 3 5	39.1	21.409
19255-6	H 0 3 6	41.5	23.928
19255-7	H 0 3 7	37.3	19.919

55" long

color coding Shim Tubes

Subject:

Signature(s) person making entry

Read and understood by - witness

7/10/70
Date

Date

APPENDIX A

WEIGHTS AND SERIAL NUMBERS FOR SHIM TUBES USED FOR TIS-DW-11

(From Westinghouse Permanent Record Book No. 36778)

cont.

Green G07 Tantalum Carbide 3880561 G07			
Shim Tube No. 1 Serial LB	is labeled	(total wt)	(Coating wt)
19253-1	T 31	48.7	30.586
19253-2	T 32	51.8	33.529
19253-3	T 33	48.0	29.873
19253-5	T 34	54.2	35.405
19253-6	T 35	51.3	32.786
19253-7	T 36	49.0	31.923
55" / on	19253-8	T 37	50.5 31.173

Purple G04 Hafnium Oxide 3880561 G04			
Shim Tube No. 1 Serial LB	is labeled	(total wt)	(Coating wt)
18218-1	H011	20.5	2.495
18218-2	H012	23.1	4.517
18218-3	H013	21.9	3.578
18218-4	H014	20.9	3.003
18218-5	H015	20.4	3.026
55" / on	18218-6	H016	21.0 3.204
	18218-7	H017	20.9 3.029

Yellow G02 Tantalum Carbide 3880561 G02			
Shim Tube No. 1 Serial LB	is labeled	(total wt)	(Coating wt)
18216-1	T 11	25.0	6.595
18216-2	T 12	24.7	7.1312
18216-3	T 13	27.5	10.1389
18216-4	T 14	28.3	10.5401
18216-5	T 15	23.0	4.6025
55" / on	18216-6	T 16	22.6 4.4840
	18216-7	T 17	22.7 4.6343

Subject

Signature(s) person making entry

Date

7/20/70

Read and understood by - witness

Date

h-11

TITLE Reactivity Worth of ISA Material in the PAX-G2 Reactor	
	DOCUMENT NO. WANL-TME-2719	DATE January 1971
ABSTRACT Tests were made to determine the reactivity worths of sam- ples of ISA candidate materials and the perturbation of these worths by support stem and propellant hydrogen. The worth of hydrogen was measured in the core surrounding the four test locations. Anal- ysis was performed using the ANISN code to generate 16-group forward and adjoint fluxes for input to the PERT-1D. Good agree- ment between measurements and predictions for the dry, ambient shim tubes of TaC and HfO ₂ indicates that the worth of shim tubes of comparable thickness can be predicted for the R-1 composite and HCTE fuel designs. The TaC coating has been specified for two, alternate shim procedures.		
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