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Westinghouse
Astronuclear
Laboratory

MASTER

WANL-TME-1910
JANUARY 1970

DATA ITEM T-119
PAX-GO CONTROL DRUM SPANS
AND REACTIVITY
COEFFICIENT MEASUREMENTS (U)
FINAL TEST REPORT

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ABSTRACT

Core material reactivity worths and control drum reactivity measurements performed in the PAX-G0 reactor are compared in this document with predictions calculated by using Westinghouse Integrated Standard Design Method (WISDM). Based on this comparison, a drum span normalization factor of 0.90 was generated and will be applied to future R-1 drum span calculations. Calculated material reactivity worths in $\text{\$/Kg}$ as a function of radial position for uranium and carbon are in good agreement with the experimental measurements for these materials. However, the calculated niobium worth overpredicts the experimental curve by approximately 20 percent. The standard design method which preceded WISDM underpredicted the experimental niobium worth by approximately 20 to 30 percent. Consequently, an investigation of the niobium worth discrepancy has been initiated to resolve the inconsistency between calculation and measurement.

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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

The applicable Scope of Test Document Numbers are 59DW-225-0 and 66DW-227-0.

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, CY 69, is the contractor.

1.1.5 Test Facility

These tests were performed at the Westinghouse Astronuclear Experimental Facility, located at the Westinghouse Waltz Mill Site, between January and April of 1969.

1.2 PURPOSE

The worths of the control drums in the PAX-G0B reactor were measured in order to provide normalization of future analytical predictions of R-1 control drum bank worth. Reactivity coefficients for niobium, graphite, and uranium were measured as a function of radius in order to verify the corresponding analytical predictions.

2.0 REFERENCES AND ASSUMPTIONS

2.1 REFERENCES

2.1.1 Specification

EC 677559 - Part I. Performance/Design and Qualification Requirements
Reflector, Control Drums & Axial Support for NERVA Nuclear Subsystem 677555A, 1/23/69

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

2.1.2 Data Item Description

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

2.1.3 Scope of Test Document

59DW-225-0 - PAX-G0 Control Drum Spans
66DW-227-0 - PAX-G0 Reactivity Coefficients

2.1.4 Data Release Memorandum

51186 - Chemical Analysis for WANEF Reactivity Materials
51154-A - PAX-G0B Control Drum Worth Measurements
51153 - Nb, Graphite & U Reactivity Coefficients in the First PAX/R-1
(PAX-G0A) Reactor Assembly
51152 - PAX-G0B Shim Wire Inventory
51152A - PAX-G0 Shim Wire Inventory
51150 - Parts Inventory in the PAX-G0 Reactor
51150A - Parts Inventory in the PAX-G0-A, -B, and -C Reactors
51105 - Flow Charts for an Integrated Nuclear and Radiation, Thermal and
Structural Analysis Procedure and Identification and Description of Computer Codes
51057 - Nuclear Predictions for the PAX/R-1 Experimental Program

2.1.5 Drawing

(U) 711J496 - Reactor/Vessel Assembly, R-1 PAX

2.1.6 TME

(U) WANL-TME-267, Revision H - Westinghouse Astronuclear Experimental Facility
Reactor Operations Manual

2.2 ASSUMPTIONS

2.2.1 Shadowing Effects

(U) In the treatment of the control drum data, it was assumed that there were no shadowing effects caused by other drums; i.e., each drum worth is completely independent of the position of the remaining drums.

2.2.2 Self-Shielding Effects

(U) Because of the thin wall (0.0015") niobium tubing used in the niobium reactivity coefficients, it is not necessary to correct for self-shielding effects.

2.2.3 Streaming Effects (U)

(CRD) Axial streaming effects are negligible when changing from solid graphite elements to 19-hole graphite elements.

2.2.4 Axial Correction Factor (U)

(CRD) The reactivity coefficients given are axial averages and thus, in the case of the niobium tubing, the actual mass is corrected for the 52" long portion actually in the fuel elements by proportioning the measured weight by 52"/actual tubing length.

3.0 TEST ARTICLE CONFIGURATION

3.1 TEST SETUP

Reactivity measurements have been made with two systems: the period-pickoff system for reactivity coefficient measurements and the reactivity computer system for determining integral control drum worths. Figures 3-1 and 3-2 show block diagrams of the two systems. System and component descriptions are given in the following paragraphs.

3.1.1 Period-Pickoff System

The normal method for measuring the reactivity changes associated with reactor configuration changes at WANEF is to use positive period techniques. In using this method, the reactor period is determined for a given reactor configuration and then, after a configuration change is made, a second period measurement is obtained at the same drum positions as the first. The two period measurements are then converted to reactivity using the "in-hour" relationship* and the difference in the two reactivity values constitutes the effect of the configuration change.

In order to accurately and efficiently measure the reactor periods, WANEF has designed and installed a reactor-period measuring system referred to as a period-pickoff system. A block diagram of the system is shown in Figure 3-1. Operation of the system originates with a Westinghouse compensated ion chamber which produces a signal proportional to the reactor neutron level. This signal is routed to a linear picoammeter located in the reactor control room. The linear picoammeter has been equipped with electronic trip circuits which, at preset levels, start and stop a scaler. This timing scaler measures the lapsed time between the start and stop trips. The start and stop trips have been positioned so that the scaler measures the lapsed time required for the reactor neutron level to increase by a factor of e . Thus, we have the following equation:

$$n(t) = n(0) e^{t/\tau}$$

* The "in-hour" equations and values of the constants used therein are the same as those given in Appendix D of this document.

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Figure 3-1. Block Diagram of the Period-Pickoff Data Acquisition System

where

$n(t)$ = level at time t

$n(0)$ = level at time 0

t = lapsed time

τ = reactor period

The lapsed time is thus equal to the reactor period since

$$\frac{n(t)}{n(0)} = e = e^{t/\tau}.$$

Therefore,

$$t/\tau = 1$$

and

$$t = \tau$$

As can be seen from the block diagram, the high level or stop trip not only stops the scaler but also issues a print signal to the scaler which, in turn, routes the lapsed time signal to the printer and at the same time upscales the linear picoammeter to the next higher range.

During normal reactor runs, an average of four to six period measurements are obtained, thereby providing enough period measurements for statistical determination of uncertainties.

Descriptions of the components of the period pickoff system are given in the following paragraphs.

3.1.1.1 Detector

The neutron detector is a Westinghouse WL-7741 ion chamber, Serial Number 634303, operated in the uncompensated mode. It was mounted inside a polyethylene cylinder 24" long, 5-1/2" diameter with a 3-1/8" diameter hole.

3.1.1.2 High Voltage Supply

The high voltage supply was a Burgess U 200 battery.

3.1.1.3 Picoammeter

The picoammeter was a Keithley Instruments, Inc. Model 410C micro-microammeter.

3.1.1.4 Level Trips

The low and high level trips which provided the start and stop signals were Keithley Instruments, Inc., Model 4103, electronic trips.

3.1.1.5 Scaler

The scaler was a Computer Measurements Company (CMC) Model 306B, Serial Number 99020.

3.1.1.6 Master Clock

The master clock was a CMC Model 2602A, Serial Number 1.

3.1.1.7 Digital Printer

The digital printer was a CMC Model 400C, Serial Number 10135.

3.1.2 Analog Reactivity Computer System

A large portion of the reactivity and all of the drum worth measurements made at WANEF employ the use of an on-line analog reactivity computer system for which a block diagram is shown in Figure 3-2. This system provides both positive and negative reactivity measurements. These results can be directly obtained from a digital voltmeter or plotted by using an X,T or strip chart recorder. The heart of the system is an EAI PC12 Multi-Purpose Analog Computer, a photograph of which is shown in Figure 3-3.

The EAI PC12 analog computer has been programmed to calculate reactivity directly from the signal of a neutron-sensitive ionization chamber. To accomplish the reactivity calculation, the analog computer has been programmed to solve the standard space-independent reactor kinetics equations which are assumed to describe the kinetic behavior of the reactor. Further description of the basic programming of this computer is given in Appendix D.

Figure 3-2. Block Diagram of the EAI-PC12 Reactivity Computer Data Acquisition System

Figure 3-3. Photo of the EAI PC-12 Reactivity Computer

The following components were used in the setup:

3.1.2.1 Detector

The neutron detector was a Neutronics Laboratories Model BR, Serial 158, ion chamber inside a polyethylene block 5-3/4" square, 8-1/2" long with a 3-1/2" diameter bore along the major axis.

3.1.2.2 High Voltage Supply

An NJE Corporation Model S-325, Serial 15571-2, provides regulated high voltage to the ion chamber.

3.1.2.3 Analog Computer

An Electronic Associates, Inc., (EAI) Series PC12, Model 4.154, Serial 107, analog computer calculates reactivity from the input ion chamber current which is proportional to reactor neutron level.

3.1.2.4 Digital Voltmeter

An EAI Series 6000, Model 26.257/2.394, Serial 163, digital voltmeter displays the reactivity information.

3.1.2.5 Strip Chart Recorder

A Weston Model 6708, Serial 21434-1, strip chart recorder was used to record the remainder of the reactivity information.

3.1.3 PAX-G Reactor Description

The PAX-G reactor is basically an NRX type assembly which was modified to be an early nuclear mockup of the R-1 reference design. Basically, it is a beryllium reflected reactor with a core consisting of a highly enriched uranium dicarbide fuel contained in a graphite matrix. Control is obtained through the rotation of 12 beryllium control drums which contain neutron absorbing plates on one side. These control drums are contained in the reflector. Further details of the reactor components may be found by reference to Appendix A of this document.

3.2 ADDITIONAL TEST EQUIPMENT

The following special items were used during the test:

3.2.1 Special Fuel Elements

Table 3-1 presents the nuclear data for the special fuel elements used in these measurements.

3.2.2 Niobium Tubing

Table 3-2 contains the dimensions and average weight of the niobium tubing used. The chemical analysis of the niobium is given in DRM 51186.

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TABLE 3-1
NUCLEAR DATA FOR ELEMENTS USED TO MEASURE URANIUM AND
GRAPHITE REACTIVITY COEFFICIENTS (U)

<u>Element Serial Number</u>	<u>C (Kg)</u>	<u>U (Kg)</u>
59-32016	0.53590	0.046103
59-32013	0.53861	0.046389
59-32006	0.53765	0.046348
59-32001	<u>0.53853</u>	<u>0.046470</u>
TOTALS	2.151	0.1853
99-33794	0.52155	0.126755
99-30840	0.51994	0.126960
99-30987	0.54155	0.108050
99-31076	<u>0.51981</u>	<u>0.126192</u>
TOTALS	2.103	0.4880
GA-4022 ⁽¹⁾	0.6805	
GA-4013	0.6842	
GA-4031	0.6815	
GA-4024	<u>0.6815</u>	
TOTALS	2.728	
PF-5042 ⁽²⁾	0.572	
PF-6551	0.567	
PF-3624	0.571	
PF-7104	<u>0.571</u>	
TOTALS	2.281	

1. The elements (in this table) with GA prefix are solid graphite elements.
2. The elements (in this table) with a PF prefix are 19-hole graphite elements.

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TABLE 3-2
CALCULATIONS OF NIOBIUM TUBING WEIGHTS (U)

220 pieces of 54" long Nb tubing (.0015" wall x .084" OD)	= 627.0 gms*
Weight of one length of plastic handle	= 0.065 gms

Correcting for the mass of the plastic handles, we have:

$$627.0 - (0.065 \times 220) = 612.7 \text{ gms Nb}$$

Correcting for the actual number of tubes used (218) and the actual length in the fuel (52"), we have:

$$612.7 \times \frac{218}{220} \times \frac{52}{54} = 584.6 \text{ gms Nb}$$

* Includes weight of 220 plastic handles.

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4.0 SUMMARY OF TESTS

4.1 PAX-GOB CONTROL DRUM SPANS

4.1.1 Narrative

Measurements of the PAX-GOB control drum spans were performed by measuring the reactivity change caused by moving the individual control drums from their most reactive position (180°) to their least reactive position (0°). Although there are several different ways to measure this reactivity change, WANEF's method involves a continuous, on-line determination of reactivity by an analog computer programmed to solve the inverse of the standard point reactor kinetics equations. By recording the output of the analog computer as a function of control drum position, one then obtains the integral control drum worth curve for an individual control drum. By differentiating this curve, one may then easily obtain a differential drum worth curve. If it may be assumed that there are no interaction effects between drums, then all of the individual integral and differential drum worth curves may be added to produce integral and differential drum bank worth curves.

4.1.2 Test Conditions

The exact steps involved in these measurements are detailed in Appendix B. Briefly, a BF_3 detector was placed underneath the dome end of the reactor* and connected to the WANEF reactivity computer. The selected drum was positioned at 180° and the remaining drums were positioned at 114.00° , giving a positive period. When a detector voltage suitable for use with the WANEF analog reactivity computer was reached, the selected drum was driven in to 0° while the output of the reactivity computer was recorded on a strip chart recorder. Indications were made on the recorder chart at every 10° decrement of the drum position. As the recorder was calibrated in cents worth of reactivity, the desired information was obtained directly from the graphical strip chart data.

4.1.3 Test Results

Figure 4-1 contains a typical integral control drum worth curve for control drum number 5. Figure 4-2 contains the corresponding differential control drum worth curve. Table 4-1 presents a tabular summary of the individual differential and integral control

* The detector was located approximately 4 inches away from the axial centerline of the reactor.

drum worths as well as the differential and integral control drum bank worths. The differential and integral control drum bank worths are presented graphically in Figures 4-3 and 4-4, respectively. Figure 4-5 presents a graph of the integral control drum worths versus azimuth.

Figure 4-1. Drum No. 5 Integral Drum Worth Curve in the PAX-G0B Reactor

Figure 4-2. Differential Drum Worth for Drum No. 5 in the PAX-G0B Reactor

Figure 4-3. Differential Drum Bank Worth in the PAX-G0B Reactor

Figure 4-4. Integral Drum Worth in the PAX-G0B Reactor

Integral Drum Bank Worth in Cents

Figure 4-5. Individual Integral Drum Worth Versus Azimuth

TABLE 4-1

INTEGRAL AND DIFFERENTIAL DRUM WORTHS (U)

Drum Angle θ (degrees)	Differential Individual Drum Worth*												Drum Bank Worth	
	(¢/degree)												Differential** (¢/degree)	Integral (¢)
	1	2	3	4	5	6	7	8	9	10	11	12		
175	0	.004	.025	.071	.021	.025	.029	0	.012	.012	.017	.017	.233	2.33 + .24
165	.083	.100	.079	.158	.129	.099	.146	.054	.087	.083	.129	.104	1.251	14.84 + .24
155	.157	.187	.209	.228	.183	.181	.208	.212	.162	.195	.167	.199	2.288	37.72 + .25
145	.265	.250	.209	.290	.266	.264	.287	.253	.274	.241	.288	.262	3.149	69.21 + .25
135	.273	.275	.284	.353	.312	.325	.396	.332	.349	.362	.338	.349	3.948	108.69 + .25
125	.348	.371	.384	.373	.408	.383	.396	.374	.362	.408	.400	.386	4.593	154.62 + .26
115	.427	.404	.417	.436	.396	.403	.387	.420	.457	.379	.404	.394	4.924	203.86 + .26
105	.402	.446	.430	.415	.429	.461	.429	.428	.416	.437	.429	.415	5.147	255.33 + .27
95	.456	.437	.409	.394	.421	.354	.441	.461	.424	.470	.425	.399	5.091	306.24 + .27
85	.414	.396	.438	.373	.429	.486	.470	.453	.449	.403	.459	.486	5.256	358.80 + .28
75	.394	.416	.376	.436	.408	.428	.396	.553	.436	.416	.413	.394	5.066	409.46 + .29
65	.373	.416	.417	.382	.404	.379	.379	.328	.378	.387	.417	.390	4.650	455.96 + .29
55	.331	.341	.313	.332	.333	.362	.375	.332	.378	.403	.375	.349	4.224	498.20 + .29
45	.340	.304	.255	.282	.333	.358	.316	.341	.366	.308	.325	.328	3.856	536.76 + .30
35	.290	.262	.301	.249	.271	.268	.308	.270	.295	.337	.296	.291	3.437	571.13 + .30
25	.240	.225	.217	.187	.254	.231	.212	.307	.241	.216	.221	.228	2.779	598.92 + .30
15	.124	.167	.138	.145	.133	.173	.142	.133	.187	.166	.154	.149	1.811	617.03 + .31
5	.133	.096	.083	.029	.050	.078	.083	.079	.096	.054	.083	.062	.926	626.29 + .31
Integral*** DrumWorth	50.5	50.8	50.0	50.9	51.8	53.0	54.0	53.3	53.7	53.2	52.9	52.1		

* The estimated precision for each value is $\pm .017\text{¢/degree}$. (1σ)** The estimated precision for each value is $\pm .059\text{¢/degree}$. (1σ)*** The estimated precision for each value is $\pm .23\text{¢}$. (1σ)

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4.2 NIOBIUM, GRAPHITE, AND URANIUM REACTIVITY COEFFICIENTS

4.2.1 Narrative (U)

(CRD) Reactivity coefficient measurements are performed by determining the reactivity change associated with small mass perturbations at a given location. The reactivity coefficient is then determined by dividing the measured reactivity change by the mass change. In the case of the niobium, thin wall niobium tubes were used to introduce the mass change. In the case of the graphite and uranium, actual fuel elements containing different amounts of graphite and uranium were interchanged. In all cases, the reactivity coefficient was determined for a 52" long section and hence is an axial average measurement.

4.2.2 Test Conditions (U)

(CRD) All of the reactivity coefficient measurements contained in this report were made in the PAX-G0A reactor at the same four different radii, 1.9 cm, 26.3 cm, 35.5 cm, and 45.0 cm. Although the shim wires were left in place for the niobium measurements, they were removed for the graphite and uranium measurements. Figures 4-6 and 4-7 show a top view of the niobium tubes in place at a location typical of the three smallest radii, and at a location typical of the largest radius, respectively.

(U) All control drums were set at 118.00° for these measurements.

(U) Basically, the control drums are set at an angle such that the reactor is on a suitable positive period. This period is then measured through use of the period pickoff system, and the reactor is shutdown. The period is then converted to a reactivity through use of the "in-hour" equation. The material which is to be measured is then inserted into the core in the proper positions. The reactor is again brought to critical with the control drums at the same angle as before. Again, a period is measured and converted into a reactivity. The difference between the two reactivities may then be attributed to the insertion of the material. More detailed steps of the procedures involved with this series of measurements may be found in Appendix C. However, as may be seen from Table 4-2, the sequence was changed slightly from that given in the appendix.

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Figure 4-6 . Photo of Typical Placement of Nb
Tubing at Locations 000, 4F4, and 4H6 (U)

Figure 4-7 . Photo of Typical Placement of Nb Tubing at Location 4K6 (U)

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TABLE 4-2

SUMMARY OF PAX-G0A PERTINENT REACTOR RUN DATA FOR THE
Nb, U, AND C REACTIVITY COEFFICIENT MEASUREMENTS (U)

Run (PAX-G0A)	Date 1969	ρ^* (%)	Location Measurement (Cluster Designation)	Material Change and/or Comments
41	1/21	15.13 + .14**	--	Basepoint
42	1/21	11.19 + .18	000	Nb
44	1/22	12.04 + .10	4F4	Nb
45	1/22	15.24 + .02	--	Basepoint
47	1/23	14.11 + .06	4K6	Nb
48		13.36 + .18	4H6	Nb
49		15.33 + .16	--	Basepoint
50		17.57 + .03	--	Basepoint (No wires in 000-existing fuel)
51		21.04 + .04	000	Code 99 Elements
52		13.85 + .17	000	Code 59 Elements
53	1/24	11.93 + .10	000	Solid Graphite Elements
54	1/24	10.14 + .04	000	19-Hole Graphite Elements
55	1/27	9.13 + .02	--	Basepoint (19-Hole Graphite Elements)
56		20.41 + .05	000	Code 99 Elements
57		16.90 + .06	--	Original Code 89 Elements in 000
58		13.16 + .10	4F4	Solid Graphite Elements
59		11.15 + .03	4F4	19-Hole Graphite Elements
60	1/28	11.20 + .06	--	Basepoint (19-Hole Graphite Element)
61		17.50 + .17	4F4	Code 99 Elements
62		13.25 + .01	4F4	Code 59 Elements
63		14.11 + .05	4H6	Solid Graphite Elements
64		12.38 + .16	4H6	19-Hole Graphite Elements
65		13.75 + .02	4H6	Code 59 Elements
66		16.42 + .03	4H6	Code 99 Elements
67	1/29	16.65 + .01	4K6	Solid Graphite Elements
68		15.27 + .04	4K6	19-Hole Graphite Elements
69		16.07 + .23	4K6	Code 59 Elements
70		17.82 + .16	4K6	Code 99 Elements

* Drum bank at 118.00°.

** The uncertainties were determined from examining the spread in the period-pickoff system printouts for each set of measurements.

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4.2.3 Test Results

Table 4-2 contains a summary of the reactor run data obtained during this series of measurements. The information from this table, in combination with the information from Table 3-1, may then be used to generate the reactivity coefficients as shown in Table 4-3.

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TABLE 4-3

SUMMARY OF PAX-G0A REACTIVITY COEFFICIENT MEASUREMENTS (U)

I. Niobium

Location (Cluster/Radius)	$\Delta \rho$ (¢)	Δm (Kg)	$\Delta \rho / \Delta m$ (¢/Kg)
000 (1.90 cm)	$-3.94 \pm .23$	$0.585 \pm .001$	$-6.74 \pm .39$
4F4 (26.3 cm)	$-3.20 \pm .10$	$0.585 \pm .001$	$-5.47 \pm .17$
4H6 (35.5 cm)	$-1.97 \pm .24$	$0.585 \pm .001$	$-3.37 \pm .29$
4K4 (45.0 cm)	$-1.22 \pm .17$	$0.585 \pm .001$	$-2.09 \pm .29$

II. Graphite

Location (Cluster/Radius)	$\Delta \rho$ (¢)	Δm (Kg)	$\Delta \rho / \Delta m$ (¢/Kg)
000 (1.90 cm)	$1.79 \pm .11$	$0.477 \pm .002$	$4.00 \pm .25$
4F4 (26.3 cm)	$2.01 \pm .10$	$0.477 \pm .002$	$4.50 \pm .22$
4H6 (35.5 cm)	$1.73 \pm .17$	$0.477 \pm .002$	$3.87 \pm .38$
4K4 (45.0 cm)	$1.38 \pm .04$	$0.477 \pm .002$	$3.09 \pm .09$

III. Uranium (Code 59 elements)

Location (Cluster/Radius)	$\Delta \rho$ (¢)	Δm_U (Kg)	Δm_C (Kg)	$\Delta \rho / \Delta m_U$ (¢/Kg)*
000 (1.90 cm)	$4.09 \pm .18$	0.185 ± 0.000	$-0.130 \pm .008$	24.88 ± 1.00
4F4 (26.3 cm)	$2.05 \pm .06$	0.185 ± 0.000	$-0.130 \pm .008$	14.22 ± 1.04
4H6 (35.5 cm)	$1.37 \pm .16$	0.185 ± 0.000	$-0.130 \pm .008$	10.11 ± 1.94
4K6 (45.0 cm)	$0.80 \pm .23$	0.185 ± 0.000	$-0.130 \pm .008$	6.49 ± 3.74

IV. Uranium (Code 99 elements)

Location (Cluster/Radius)	$\Delta \rho$ (¢)	Δm_U (Kg)	Δm_C (Kg)	$\Delta \rho / \Delta m_U$ (¢/Kg)*
000 (1.90 cm)	$11.28 \pm .05$	0.488 ± 0.000	$-0.178 \pm .008$	$24.57 \pm .15$
4F4 (26.3 cm)	$6.30 \pm .18$	0.488 ± 0.000	$-0.178 \pm .008$	$14.55 \pm .38$
4H6 (35.5 cm)	$4.04 \pm .16$	0.488 ± 0.000	$-0.178 \pm .008$	$9.69 \pm .36$
4K6 (45.0 cm)	$2.55 \pm .16$	0.488 ± 0.000	$-0.178 \pm .008$	$6.35 \pm .33$

* Corrected for loss in carbon mass by $\Delta \rho / \Delta m_U = \frac{\Delta \rho (\text{¢}) - \Delta m_C [\Delta \rho / \Delta m]_C}{\Delta m_U}$

5.0 ANALYSIS

5.1 PAX-G0 CONTROL DRUM SPAN PREDICTIONS

5.1.1 Predictions

The WISDM* method was employed to predict the PAX-G0 total control drum span. As specified by WISDM, spectrally weighted regionwise cross sections in 16 energy groups were generated for each reactor region of the PAX/R-1 calculational model. With these cross sections as input, explicit R-0 EXTERMINATOR calculations were performed with test sector fuel simulated in the core and the KIWI sectors represented in the reflector. These calculations were performed at 0° and 180° drum bank positions. The difference in reactivity worth between these two calculations predicted a total control span of \$6.94.

5.1.2 Predictions versus Measurements

The total integral drum span of the 12 PAX-G0 control drum span was measured to be \$6.26 (see Section 4.0 for a detailed explanation of the measurements). The corresponding predicted drum span was calculated as \$6.94 (see Section 5.1.1). Dividing the measurement (\$6.26) by the prediction (\$6.94) results in a calculated to experimental normalization factor of 0.90. All future R-1 drum span calculations should be corrected by this normalization factor (see Section 6.1).

5.2 REACTIVITY WORTH PREDICTIONS

Radial reactivity worth curves were calculated for niobium, carbon and uranium by WISDM for the R-1 reactor configuration. One-dimensional ANISN's in

*Further details regarding the Westinghouse Integrated Standard Design Method (WISDM) and the computer codes referred to in this document may be found in DRM 51105.

16 neutron energy groups were used to solve for the forward and adjoint fluxes. These fluxes, in turn, were used in the PERT-1D code which calculates reactivity changes due to small perturbations in units of ρ/kg of the perturbing material. The resulting reactivity worths in ρ/kg as a function of radius for niobium, carbon, and uranium are presented with the corresponding experimental data in Figures 5-1 through 5-4, respectively.

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Figure 5-1. Niobium Reactivity Coefficients Versus Radial Distance from the Core Center in the PAX-G0A Reactor (U)

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Figure 5-2. Carbon Reactivity Coefficients Versus Radial Distance from the Core Center in the PAX GOA Reactor (U)

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~~CONFIDENTIAL~~URANIUM REACTIVITY COEFFICIENT, ρ /KG

N58831-1

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Figure 5-3. Uranium Reactivity Coefficients Versus Radial Distance from The Core Center in the PAX-G0A Reactor (U)

~~CONFIDENTIAL~~URANIUM REACTIVITY COEFFICIENT, ρ /KG

Figure 5-4. Uranium Reactivity Coefficients Versus Radial Distance from the Core Center in the PAX-G0A Reactor (U)

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6.0 CONCLUSIONS

6.1 PAX-G0 CONTROL DRUM SPAN (U)

(U) As presented in Section 5.1.2, a calculated to experimental drum span normalization factor of 0.90 was obtained from the PAX-G0 measurements and predictions. The 0.90 normalization factor compares favorably with the corresponding NRX-A6 value of 0.88.

6.2 REACTIVITY WORTH MEASUREMENTS (U)

(CRD) The experimental reactivity coefficients for the three materials measured in the center of the reactor differ from the calculated coefficients due to the concentration of the shim elements in the central region of the PAX-G0A configuration. As these shims were subsequently redistributed uniformly to approximately 36.4 centimeters in the PAX-G0B and PAX-G0C configurations, the ANISN predictions were performed with the poison shims smeared over 36.4 centimeters rather than in the PAX-G0A experimental configuration. This model will, therefore, be consistent with the TaC distribution when the reactivity coefficients are remeasured in PAX-G2 early in CY '70.

(U) The overall calculated reactivity worth curves are generally in good agreement with the experimental data except for niobium. While the niobium radial reactivity worth calculated with NSDM in DRM 1057, "Nuclear Predictions for the PAX/R-1 Experimental Program" underpredicted the experimental worth by approximately 20 to 30 percent, the calculated worth with WISDM (see Figure 5-1) overpredicts the experimental curve by approximately 20 percent. Because of the discrepancy observed between the measurements and the calculated reactivity worth curve for niobium, a study has been initiated to re-evaluate the niobium cross sections and the calculational model used to represent the discrete wires.

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APPENDIX A

ACTUAL AND/OR REPRESENTATIVE AS-BUILT WEIGHTS FOR THE PAX-G0-A and PAX-G0-B REACTORS

The PAX-G0 reactor is described in Drawing 711J496. The only differences between different members of the PAX-G0 series (PAX-G0, -G0A, -G0B, -G0C) of reactors are in the reactor cores. DRM's 51150, 51150A, and 51152 contain actual and/or representative as-built weights of the reactor components and fuel element inventories. DRM 51186 contains the chemical analysis for the different shim wires. It should be noted that both the fuel and non-fuel element positions are in the PAX/R-1 notation, and are not in the R-1 notation. The only difference between the two notations is in the outer peripheral region of the core. In the former, the peripheral clusters are given J and K designations. In the latter, J and P notations are used. The former notations, however, correspond to the actual as-built conditions while the latter correspond to an R-1 Reference Design. Figures A-1 and A-2 contain a one-sector representation of the two different notations.

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LOOKING FORWARD
PAX R-1 NOTATION

Figure A-1. PAX/R-1 Core Notation (U)

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Figure A-2. Core Notation (U)

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TABLE A-1
CHEMICAL ANALYSIS FOR SHIM WIRES

Copies of actual or representative chemical analyses as supplied by the vendor for the different shim wires used in the PAX-G0 reactor are contained in Sections 1 through 4 of this table, on the following pages.

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1. TYPICAL CHEMICAL ANALYSIS FOR 0.031" OD "X" MATERIAL SHIM WIRE (U)

FANSTEEL

METALLURGICAL CORPORATION

NUMBER ONE TANTALUM PLACE
NORTH CHICAGO ILLINOIS • 60064
Phone 312/336 4900 TWX 312/244 4530

CERTIFICATE OF ANALYSIS

Date May 25, 1966

Customer Westinghouse Electric Corp.

Purchase Order No 39NYB5776

Material Molybdenum Wire 0.031" x coil

Production No 434-W24318-1

Lot No 589-B-2

Quantity 6.565 lbs

TYPICAL CHEMICAL ANALYSIS

C 20 PPM
N 10 PPM
O 40 PPM
Ca 10 PPM
Cr 10 PPM
Cu 10 PPM
Fe 30 PPM
Mg 10 PPM
Ni 30 PPM
Si 50 PPM
W 80 PPM
Ag Less than 10 PPM
Al Less than 10 PPM
Co Less than 10 PPM
Mn Less than 10 PPM
Sn Less than 10 PPM
Ti Less than 100 PPM
Zr Less than 100 PPM
Molybdenum 99.95% Min

Robert C. Davis
FANSTEEL METALLURGICAL CORPORATION

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2. TYPICAL CHEMICAL ANALYSIS FOR 0.040" OD "X" MATERIAL SHIM WIRE (U)

FANSTEEL

METALLURGICAL CORPORATION

NUMBER ONE TANTALUM PLACE
NORTH CHICAGO, ILLINOIS • 60064
Phone 312/336 4900 TWX 312/244 4530

CERTIFICATE OF ANALYSIS

Date May 9, 1966

Customer Westinghouse Electric Company

Purchase Order No. 53NYB85778

Material Molybdenum Wire 0.040" x Coil

Production No. 434-024318-2

Lot No. 585C-2

Quantity 15.600 Kgs.

TYPICAL CHEMICAL ANALYSIS

C 20 PPM
N 10 PPM
O 40 PPM
Ca 10 PPM
Cr 10 PPM
Cu 10 PPM
Fe 30 PPM
Mg 10 PPM
Ni 30 PPM
Si 50 PPM
W 80 PPM
Ag Less than 10 PPM
Al Less than 10 PPM
Co Less than 10 PPM
Mn Less than 10 PPM
Sn Less than 10 PPM
Ti Less than 100 PPM
Zr Less than 100 PPM

Molybdenum 99.95% Min.

Quality Control Representative

FANSTEEL METALLURGICAL CORPORATION

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3. CHEMICAL ANALYSIS FOR 0.068" OD NIOBIUM SHIM WIRE

FANSTEEL CERTIFICATION

FANSTEEL

METALLURGICAL CORPORATION

NUMBER ONE TANTALUM PLACE
NORTH CHICAGO ILLINOIS • 60064
Phone 312/689 4900 TWX 312/244 4530

CERTIFICATE OF ANALYSIS

Date Dec. 22, 1967

Customer Westinghouse Electric Corp.

Purchase Order No. 59N1094156

Astro-Nuclear Laboratory

Material Columbium Ingot As Forged - 2.375" diameter x RL

Production No. 896-033794-1

Lot No 89B2149
89B2153

Quantity 500 Kgs.

CHEMICAL ANALYSIS

LOT ANALYSIS

89B2149

C	23	ppm
O	42	ppm
N	20	ppm
H	5-	ppm
Ta	450	ppm
W	100-	ppm
Zr.	50-	ppm
Mo	100-	ppm
Ti	20-	ppm
Fe	50-	ppm
Ni	20-	ppm
Si	50-	ppm
Mn	20-	ppm
Ca	20-	ppm
Al	20-	ppm
Cu	20-	ppm
Sn	20-	ppm
Cr	20-	ppm
V	20-	ppm
Co	20-	ppm
B	2-	ppm
Cd	5-	ppm
Mg	20-	ppm
Hf	100-	ppm
Pb	20-	ppm
Cb	Balance	

89B2153

C	30	ppm
O	75	ppm
N	19	ppm
H	5-	ppm
Ta	360	ppm
W	100-	ppm
Zr	50-	ppm
Mo	100-	ppm
Ti	20-	ppm
Fe	50-	ppm
Ni	20-	ppm
Si	50-	ppm
Mn	20-	ppm
Ca	20-	ppm
Al	20-	ppm
Cu	20-	ppm
Sn	20-	ppm
Cr	20-	ppm
V	20-	ppm
Co	20-	ppm
B	2-	ppm
Mg	20-	ppm
Cd	5-	ppm
Pb	20-	ppm
Hf	100-	ppm
Cb	Balance

Quality Control Representative

4. A CHEMICAL ANALYSIS FOR THE 0.077" OD NIOBIUM SHIM WIRE

KAWECKI CHEMICAL COMPANY

CERTIFICATE OF COMPLIANCE

Date June 7, 1966

To Westinghouse Electric Co.
Astronuclear Laboratory
P. O. Box 10864
Pittsburgh, Penna. 15236
Attn: G. R. Bock

Ship To Same
Route 51
Large, Pennsylvania

Specification No. ---

Customer P. O. No. 5982D76195

Drawing No. ---

K.C.C. O. No. 36220

ITEMS AND/OR MATERIALS

(1) 6,000 Ft. Niobium Wire, Metallurgical Grade, Annealed,
99.8% Minimum:
.078" $\pm$.003" Diameter (4780)

CHEMICAL ANALYSIS

Ingot#2661-C

C	30ppm	O ₂	115ppm
H ₂	13.1	N ₂	10
Ta	550	Ti	<10
Fe	60	Mn	10
Si	20	Sn	ND<10
Ni	<10	Cr	<10
Ca	<10	Na	ND
Al	30	Mo	ND<10
Zr	ND<100	Co	ND<10
Mg	<10	B	ND<10
W	ND<100		

1. Raw Materials

- ☒ We certify that the raw materials used for the items listed conform to accepted commercial specifications.
☐ We certify that the raw materials used for the items listed conform to your specifications.

2. Product

- ☒ We certify that the items listed conform to commercial specifications and to your order.
☐ We certify that the items listed conform to your specifications.

3. Suitable evidence of compliance to your requirements is available in our files.

Witnesses:

1. _____
2. _____

Sworn to before me this _____
day of _____, 19____

Notary Public

Attachment(s)

John M. Muir Authorized Signature
Chief Inspector

APPENDIX B

THE PAX-G0B CONTROL DRUM WORTH EXPERIMENTAL PROCEDURE

In accordance with WANEF procedures*, an Experimental Details Checklist (EDC) was written to set forth the details of measuring the integral control drum worths for the PAX-G0B reactor as well as evaluating any nuclear hazards resulting from such procedures. Those portions of the experimental procedure applicable to this TME may be found in Part 4 of the EXPERIMENTAL DETAILS section of EDC 66.** The body of EDC 66 is contained in this appendix.

- * WANL-TME-267, Rev. H, "Westinghouse Astronuclear Experimental Facility Reactor Operations Manual"
- ** In order to more closely conform to the Scope of Test, a minor change was made to Part 2b of the EXPERIMENTAL DETAILS section. The revision should read: After each poison removal step, the data taken in Part 2a will be repeated in the same sequence as given above except that the 115° data need only be taken a total of three times during the entire wire removal process.

WANEF EXPERIMENTAL DETAILS CHECKLIST

No. 66

Date 12/19/68

TITLE OF EXPERIMENT: PAX/R-1 (KIWI) (PAX-G0) Fuel Loading, Poison Wire Removal, Criticality, and Control Drum Worths*

OBJECTIVES:

1. To load the PAX-G0 fuel clusters.
2. To perform 1/M measurements during initial approach to criticality, including 1-, 2-, and 3-drum roll-out information.
3. To remove poison wires and attain clean criticality with a predicted drum bank angle of approximately 115 degrees.
4. To shim the core through the use of niobium wires (and beryllium shim rods in the reflector, if required) to attain a delayed critical drum bank angle of 115 degrees.
5. To perform drum worth measurements in preparation for PAX/R-1 (Build 1)(PAX-G1).

EQUIPMENT REQUIREMENTS:

1. A full core of fuel clustered and poisoned, as given in Appendix I. The fuel will contain an initial loading of Nb wires as indicated in Appendix II.
2. A special cluster for position 000 complete with the loading source.
3. Additional niobium wires and beryllium rods, as required for shimming to the final delayed critical drum bank position.
4. An assembled reflector consisting of 12 KIWI sectors with PAX drums and graphite liner plates installed. The control drum system will have been checked out to assure compliance with operational limits.
5. Fuel support assembly and miscellaneous hardware needed for a reactor assembly.
6. Four data channels for the 1/M measurements, of which a minimum of three are required.
7. The WANEF reactivity computer and recorder.

HAZARDS CONSIDERATIONS:

Since the PAX-G0 reactor has not been previously assembled, the fuel will be poisoned before insertion into the reactor to assure that the reactor will be shut down by 20\$ per S.O.P. 5.5.1.2.1. Based upon past data**, credit for the poison wires will be taken at the rate of 1.1¢ per wire for the first 350 wires, and 0.9¢ per wire for the remaining wires. A credit of 3.25\$ will also be taken for the shutdown in the 12 drums. Using the standard loading of 42 poison wires per cluster cup, 43 full cluster cups are

* In response to Scope of Test Document M 58 DW-216-0, 12/20/68

** A differential poison wire worth obtained in the PAX-E reactor is shown in Figure 1. Since the PAX-G0 neutron spectra near the center of the core would be very close to that in the PAX-E reactors, it is felt that this wire worth curve can be used with a reasonable degree of confidence.

required to provide the necessary 20\$ shutdown. For purposes of symmetry, we will actually employ 48 cluster cups full of the poison wires. These cluster cups will be positioned in every cluster in Rows A, B, and C, and in two clusters in each sector for Row D.

Three data channels and their associated polyethylene moderator will be positioned in a horizontal attitude next to the pressure vessel supported by the test stand deck before loading begins. Since they are at the position of maximum worth (core midplane), any reasonable displacement of these polyethylene-wrapped detectors will result in a negative reactivity insertion of only a few cents. After the removal of all of the poison wires, these detectors will be removed from the test stand deck. Thus, the presence of these detectors next to the reflector presents no nuclear safety hazard. The fourth channel (polyethylene-wrapped detector) will be placed underneath the dome end of the reactor. Any failure of its support would cause only a negative reactivity insertion. Thus, no nuclear safety hazards are presented by the new position of this detector.

Assembly of the core and removal of the poison wires to attain initial criticality, and clean criticality will be done according to S.O.P.'s 5.5.1, 5.5.2, and 5.5.3, respectively. To obtain all of the requested information during the approach to initial criticality, however, 1/M data in addition to the standard 1/M data required during the approach to critical will be required. Since these additional measurements will only entail running a maximum of 3 drums to 115 degrees, with the remaining 9 drums at 0 degrees, this additional data will present no unevaluated safety hazard.

The interchange of the special clusters containing the loading source and the cluster specified for 000 will present no unevaluated safety hazard since the reactivity change will be of the order of a few cents.

Drum worth measurements, when performed within the limitations described herein and in the WANEF OLD, present no unevaluated hazards.

All operations will be performed within the limitations set forth in the OLD and in the framework of the SAR as amended for the PAX/R-1 experiment.

EXPERIMENTAL DETAILS:

1. The reactor will be loaded with poisoned fuel in accordance with the loading sheets provided in Appendices I and II. In accordance with S.O.P. 5.5.1, the following steps will be taken:
 - a. A loading source will be installed in cluster 000 before any fuel is loaded in the core.
 - b. At least 3 pulse channels having adequate detector response to the loading source and core, will be used to obtain 1/M data. One detector (associated with the "flux-up" interlock) shall have a minimum coun. rate of 120 cpm.

- c. The fuel will be added to the reactor in an incremental manner from the center outwards using the core assembly frame.
 - d. The initial fuel increment will not exceed 10% of the total fuel complement in the assembled reactor. Each succeeding increment will be no more than 20% of the total fuel complement or $1/2$ of the extrapolated additional fuel loading required for criticality, whichever is the smaller. The count rate data upon which to base this extrapolation will be obtained after each increment with the control drums at zero degrees and a plot of the inverse count rate vs. the number of fuel clusters in the reactor will be constructed. Count rate data will be taken as a series of five one-minute counts which will be individually examined for spurious response.
 - e. After the core and filler strips have been completely assembled, the core will be bundled using the core bundling device and the PASS cans will be inserted. The bundling devices will be torqued alternately in sequence in 5 inch-lb. increments until a total of 30 inch-lbs. is applied to each bundling device. A final count rate will then be taken.
2. In order to obtain initial criticality, the poison wires will be removed in an incremental manner in accordance with S.O.P. 5.2.2. The following steps will be taken:
- a. Before any poison wires are removed, count rate data will be obtained with at least three pulse channels for a drum bank position of zero degrees. Drum 9 will then be driven to 115° and additional count rate data obtained. Drum 8 will then be driven to 115° and a second set of count rate data obtained. Drum 10 will then be driven to 115° and a third set of count rate data taken. Drums 8, 9, and 10 will then be driven back to 90° and the remaining 9 drums will be driven to 90° in order to take additional count rate data. Finally, the whole bank will be driven to 180° and the final set of count rate data will be taken. After each step, a plot will be made of the inverse count rate vs. the amount of poison in the reactor. Finally, the drum bank will be scrambled to 0° in preparation for removing the next poison wire increment. The initial increment of poison removed would be no more than 20% of the initial content. Each succeeding increment removed would be no more than the smaller of 20% of the initial poison content or $1/2$ of the extrapolated additional poison removal required for criticality with the drums full out. Data obtained with the control drums full out will be utilized for the prediction of criticality.
 - b. After each poison removal step, the data taken in Part 2a, will be repeated in the same sequence as given above.

- c. The final poison increment to be removed will be specified by the Experimentalist such that the 50% excess reactivity limit is not exceeded. After initial criticality, a measurement of the shutdown will be performed by the standard "rod drop" method.
3. Clean criticality will be obtained by removal of the remaining poison wires in accordance with S.O.P. 5.5.3, in the following manner:
- a. The remaining poison wires will be removed in increments such that the positive reactivity insertions are not greater than 50%.
 - b. The bank position for delayed critical and period measurements will be determined after each increment until all of the poison wires have been removed. From this, one will obtain a calibration of the drum bank position as well as a differential wire worth curve.
 - c. The core shutdown reactivity will be monitored at each step by 1) a delayed critical bank position vs. poison wire content, 2) rod drop shutdown measurements, or 3) by integrating differential bank worth measurements.
 - d. In the event that poison wires remain in the core and shutdown measurements indicate the minimum shutdown limit of β_{eff} would be violated by further removals, Nb wires will be inserted into the core in accordance with Appendix III in order that the minimum shutdown is not compromised. Nb wires will thus be traded for the poison wires until all of the poison wires are removed.
 - e. In the event that all poison wires are removed and the delayed critical drum bank position is less than 115° , Nb wires will be added in accordance with Appendix III in order to bring the delayed critical drum bank position to 115° .
 - f. In the event that the clean critical drum bank position is between 115° and 180° , a decision will be made whether to remove Nb wires or insert Be shims. Otherwise, Be shims will be inserted into the reflector in accordance with Appendix IV to bring the delayed critical drum bank position to 115° . If the decision is made to remove Nb wires, they will be removed according to Appendix III.
 - g. After all poison wires have been removed, the special cluster in 000 containing the loading source will be removed and the specified central cluster (see Appendix I) will be inserted in its place.

4. Individual control drum worth measurements will be performed within the limits set forth in the OLD and will be done in the following manner:
 - a. The reactor will be brought critical with Drum No. 1 at 180° with approximately a 20% period. The positioning of the remaining drums should agree with each other within $\pm 1/2$ degree. At a power level between 5 and 10 watts (as determined by the input requirements of the reactivity computer), Drum 1 will then be driven full in* and the output of the reactivity computer recorded on a recorder. The computer operator will record the positions on the curve as the drum passes through 10° increments as determined by the drum position readout on the console.
 - b. The procedure designated in part a, will then be followed for the remaining drums until all the drum worths have been obtained.

DATA REQUIRED:

1. A complete description of the PAX-G0 reactor including but not limited to a parts list, a clustering assignment list and weights (actual or representative) of all core and reflector components.
2. Location, size, and weights (actual and representative) of all Nb wire placed in the core.
3. Standard $1/M$ measurements during the core loading procedure.
4. $1/M$ measurements during poison wire removal with all drums at 0° , 90° , and 180° . Also, $1/M$ measurements with Drums, 9, 8, + 9, and 8 + 9 + 10 at 115° with the remaining drums at 0° for a minimum of three wire pulls. The latter shall be taken with (1) a full load of poison wires, (2) approximately 1000 wires, and (3) no wires in the core. A minimum total of 10^4 counts in each data channel is desirable.
5. θ_{DC} and number of remaining poison wires at initial criticality.
6. θ_{DC} , incremental wire worth curve, and shutdown measurements vs. number of wires remaining in core during attainment of clean criticality.
7. Integral and differential drum bank worth.
8. Integral individual drum worth measurements.
9. Be worths or Nb worths of shimming (as required).

* The estimated worth of the PAX-G0 drums are \$.60 each. Based on past experience, the initial $+ 20\%$ reactivity is necessary in order that meaningful data may be obtained when the drum is full in and the power level has decreased considerably.

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Figure 1. Differential Poison Wire Worth

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APPENDIX C

THE PAX-G0A REACTIVITY COEFFICIENT MEASUREMENT PROCEDURES

In accordance with WANEF procedures*, an Experimental Details Checklist (EDC) was written to set forth the details of measuring the niobium, graphite, and uranium reactivity coefficients in the PAX-G0A reactor as well as evaluating any nuclear hazards resulting from such procedures. These procedures may be found in the EXPERIMENTAL DETAILS section of EDC 68.**The body of EDC 68 is contained in this appendix.

* WANL-TME-267, Rev. H, "Westinghouse Astronuclear Experimental Facility Reactor Operations Manual"

** During the experiment, the procedure was slightly modified. The part of the first paragraph of the EXPERIMENTAL DETAILS sections should read: During all the measurements, all control drums will be set within $\pm 5^\circ$ of the PAX-G0 "delayed critical" drum angle (presently 115°). A minimum shutdown requirement of \$3.40 for the PAX-G0 reactor will be maintained at all times.

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WANEF
EXPERIMENTAL DETAILS CHECKLIST

No. 68

Date 1/15/69

TITLE OF EXPERIMENT: PAX-G0 Reactivity Coefficient Measurements* (U)

OBJECTIVE: Determine the reactivity coefficients of the major PAX-G core materials
(U) in order to provide data which will be used to normalize similar R-1 predictions.

EQUIPMENT REQUIREMENTS:
(CRD) The following materials will be required for the PAX-G0 reactivity coefficient measurements:

1. 4 uncoated code 99 fuel elements and
4 uncoated code 59 fuel elements
2. 4 solid FCX type unfueled elements
3. 4 19-hole unfueled elements
4. Approximately 1/2 Kg. of 0.080" O.D. x 0.0015" wall Nb tubing
5. PAX-G0 reactor shimmed to a θ_{DC} of 115°

HAZARDS CONSIDERATIONS:

(U) The reactivity measurements to be made in the execution of this test involve materials whose reactivity effects have been investigated in previous PAX experiments***. These results, along with the predicted values for the PAX-G0 assembly**, were used to determine the reactivity effects to be encountered in these measurements. These values are included in the Experimental Details section. A calculation was performed to determine the maximum positive reactivity effect which might be expected if the PAX-G0 prediction report were in error and the material worths were similar to previously measured worths obtained from PAX-E experiments. This maximum value is +11.0¢ for the present experimental sequence.

(U) Since the reactivity effects produced by the measurements can be predicted, no unforeseen hazards should arise when the measurements are conducted as outlined in this document. If it is found that the experimental sequence detailed below does not yield large enough reactivity changes to be accurately measured, then it will be necessary to rearrange the experimental sequence to obtain the requested data. A complete recalculation of the expected reactivity effects prior to the continuation of the experiment will be done to determine the maximum positive reactivity effects and insure that the 50¢ reactivity change rule is not violated. In all cases, the reactivity changes will be made in accordance with the limits established in the OLD and the limits and procedures of S.O.P. 5.5.4, "PAX In-Core Experiments," in the WANEF Reactor Operations Manual.

* For partial execution of Scope of Test No. 660W-227-0, dated 12/31/68, by D. Mangan.

** "Nuclear Predictions for the PAX/R-1 Experimental Program," DRM-1057.

*** See For Example WANL-TME-1794, "WANEF Critical Experiments in Support of NERVA".

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EDC No. 68

EXPERIMENTAL DETAILS:

(CRD)

The following measurements are to be made in the 60° core sector of the PAX-G0 reactor facing the reflector sector in which it is planned to perform the R-1 mockup reflector sector interchange. All of the graphite, uranium and niobium reactivity measurements are to be made at 4 radial positions within the PAX-G0 core. All measurements should be completed for each radial location before measurements at the next radial location are started. The locations for the measurements are:

1. 000 C, D, F and G
2. 4F5 C, D, F and G
3. 4H6 C, D, F and G
4. 4K4 C, D, F and G (4P6 C, D, F and G)*

Shim wires will be removed, prior to the interchange of any elements, from the designated measurement locations. After the graphite and uranium reactivity measurements have been obtained at each radial location, the shim wires will be replaced in the original positions. These shim wires will be present during the niobium reactivity measurements. During all the measurements, drums 8 and 9 will be positioned at the "delayed critical" PAX-G0 drum angle and the remaining drums will be within $\pm 5^\circ$ of this angle. The PAX-G0 "delayed critical" drum angle is presently 115° . A minimum shutdown requirement of \$3.40 for the PAX-G0 reactor will be maintained at all times.

(CRD)

A. Graphite Reactivity Measurements

Determine the worth of graphite in the PAX-G0 core by measuring the reactivity effect produced when graphite unfueled elements are substituted for the normal PAX-G0 fueled elements. A reactor basepoint should be established with the normal PAX-G0 fueled elements in position. After the establishment of this basepoint, the 4 normal PAX-G0 fueled elements will be replaced with the 4 solid "FCX" type graphite unfueled elements and the resulting reactivity effect measured. The 4 solid "FCX" type graphite unfueled elements will then be replaced by 4 19-hole unfueled elements and the resulting reactivity effect will be measured again. Measurements for both types of graphite elements are to be made at each of the 4 radial locations. The estimated reactivity effect of these interchanges for each of the radial locations is -7.0% ⁽¹⁾ at 000, -4.1% at 4F5, -3.3% at 4H6, and -0.5% at 4K4 for the 4 solid "FCX" type graphite unfueled elements, and -8.4% at 000, -6.3% at 4F5, -4.3% at 4H6, and -1.9% at 4K4 for the interchange of the 4 19-hole graphite unfueled elements.

(CRD)

B. Uranium Reactivity

Determine the worth of uranium in the PAX-G0 core by measuring the reactivity effect produced when 4 19-hole special uncoated unfueled elements are replaced by 4 special uncoated code 59 fueled elements. After measuring the reactivity effect produced by the special uncoated code 59 fueled elements, these code 59 elements will be removed. They will be replaced by 4 special uncoated code 99 fueled elements and the resulting reactivity effect measured. Measurements for both types of uranium loadings are to be made at all four radial locations. The estimated reactivity effect of

* Dwg No. 100E511, R-1 PAX Core, which gives the R-1 cluster designation.

(1) All values quoted are for the total reactivity change produced by a 4-element interchange.

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(CRD) these interchanges, for each of the radial locations, is +3.6¢ at 000, +2.2¢ at 4F5, +1.5¢ at 4H6, and +0.8¢ at 4K4 for the 4 uncoated code 59 fueled elements, and +6.8¢ at 000, +4.2¢ 4F5, +2.9¢ at 4H6, and +1.9¢ 4K4 for the interchange of the 4 uncoated code 99 fueled elements.

(CRD) C. Niobium Reactivity Measurements

Determine the worth of 0.080 O.D. x 0.0015" wall niobium tubing in the PAX-G0 core by inserting niobium tubing in the flow channels of the original PAX-G0 fuel clusters and surrounding clusters and measuring the resulting reactivity effect. Measurements are to be made at all four radial locations after the graphite and uranium reactivity measurements. The estimated value of the maximum reactivity effect caused by the addition of the niobium tubing is -4.2¢ and -1.0¢ at 000 and 4K4 radial locations, respectively.

DATA REQUIRED: Record the weights, serial numbers when available, positions and reactivity
(U) effects produced by each reactivity change.

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APPENDIX D

DERIVATION OF THE EQUATIONS AND PROGRAMMING FOR THE WANEF ANALOG REACTIVITY COMPUTER

This appendix contains the equations and the programming for the analog reactivity computer.

From the standard space-independent reactor kinetics equations, we have

$$\frac{dn}{dt} = (\rho/l^*)n - (\beta/l^*)n + \sum_{i=1}^6 \lambda_i C_i + S^* \quad (1)$$

and

$$\frac{dC_i}{dt} = (\beta_i/l^*)n - \lambda_i C_i \quad (2)$$

where

n = neutron population in the reactor

t = time

$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} = \text{reactivity}$

k_{eff} = effective multiplication factor of the reactor

l^* = effective neutron lifetime = 4.3×10^{-5} sec

β = fraction of neutrons which are delayed = .0065

$\bar{\beta}$ = effective fraction of neutrons which are delayed = $\bar{\gamma}\beta$ = .0073

$\bar{\gamma}$ = relative importance factor of delayed neutrons to prompt neutrons = $\frac{\gamma_1 + \gamma_2 + \dots + \gamma_6}{6} = 1.12$

- β_i = fraction of delayed neutrons of the i^{th} group
 $\bar{\beta}_i$ = effective fraction of delayed neutrons of the i^{th} group = $\gamma_i \beta_i$
 λ_i = decay constant of the i^{th} group of delayed neutron precursors
 C_i = total population of delayed neutron precursors of the i^{th} group
 S^* = effective source strength

In using equation (1), the $\frac{dn}{dt}$ contribution is small and is thus set equal to zero. Also, the source term S^* is negligible since the flux increases several decades before the computer begins operation. Setting the $\frac{dn}{dt}$ and S^* equal to zero and rearranging equation (1) yields:

$$(\rho/\ell^*) n = (\beta/\ell^*) n - \sum_{i=1}^6 \lambda_i C_i \quad (3)$$

Multiplying equation (3) by ℓ^* and replacing β with $\bar{\beta}/\bar{\gamma}$ yields:

$$(\rho) n = \left(\frac{1}{\bar{\gamma}}\right) \bar{\beta} n - \ell^* \sum_{i=1}^6 \lambda_i C_i \quad (4)$$

Dividing equation (4) by $\bar{\beta}$ to obtain reactivity in dollars (\$) and substituting $X_i = \frac{\ell^*}{\bar{\beta}} C_i$ yields:

$$\rho(\$) n = \frac{1}{\bar{\gamma}} n - \sum_{i=1}^6 \lambda_i X_i \quad (5)$$

Equation (5) is the equation programmed into the computer with a slight modification in that the $1/\bar{\gamma}$ term equated to unity.

To program the $\sum_{i=1}^6 \lambda_i X_i$ term in the computer, equation (2) is multiplied by $\frac{\ell^*}{\bar{\beta}}$ and β_i is replaced with $\bar{\beta}_i/\gamma_i$

$$\frac{dX_i}{dt} = \frac{1}{\gamma_i} \left(\frac{\bar{\beta}_i}{\bar{\beta}} \right) n - \lambda_i X_i \quad (6)$$

Letting $\alpha_i = \bar{\beta}_i / \bar{\beta}$ equation (6) can be rewritten as:

$$\frac{dX_i}{dt} = \left(\frac{1}{\gamma_i} \right) \alpha_i n - \lambda_i X_i \quad (7)$$

Solving equation (7) yields a solution in the form:

$$X_i = A e^{-\lambda_i t} + \left(\frac{1}{\lambda_i} \right) \left(\frac{1}{\gamma_i} \right) \alpha_i n \quad (8)$$

The constant A can be evaluated at $t = 0$ since $X_i(t = 0) = 0$ and yields a value $A = -\left(\frac{1}{\lambda_i} \right) \left(\frac{1}{\gamma_i} \right) \alpha_i n$. Inserting this value of A into equation (8), and rearranging gives:

$$\lambda_i X_i = \left(\frac{1}{\gamma_i} \right) \alpha_i n \left[1 - e^{-\lambda_i t} \right] \quad (9)$$

As in equation (5), the $1/\gamma_i$ term in equation (9) is assumed to be unity and is thus dropped from the equation.

The computer solves equations (5) and (9) using the schematic shown in Figure D-1. Six delayed groups of neutrons are programmed into the computer using the six integrating amplifiers shown in Figure D-2. The value of the constants in equations (5) and (9) are given in Table D-1. These six integrating amplifiers solve an electrical equation which represents equation (9). This electrical equation has the form:

$$\frac{dE_o}{dt} + \frac{\alpha}{R_f C} E_o = \frac{E_{in}}{C R_{in}} \quad (10)$$

and the various parameters are indicated in Figure D-2.

The solution of equation (10) yields:

$$E_o = \left(\frac{1}{\alpha} \right) \left(\frac{R_f}{R_{in}} \right) E_{in} \left[1 - e^{-\frac{\alpha t}{R_f C}} \right] \quad (11)$$

As can be seen, equations (9) and (11) are of the same form with:

$$\lambda_i X_i = E_o$$

$$(a_i)n = \left(\frac{1}{\alpha}\right) \left(\frac{R_f}{R_{in}}\right) E_{in}$$

$$\text{and } \lambda_i \tau = \left(\frac{1}{R_f C}\right) \text{ at}$$

Referring to Figure D-1, it can be seen that the output of the six integrators is summed, added to a voltage proportional to $-n$, inverted by amplifier No. 7 and routed to the servo amplifier. At the same time, this voltage proportional to $-n$ is routed through inverting amplifier 8 and into the servo amplifier where it bucks the $-n \sum \lambda_i X_i$ voltage. A servo motor in turn adjusts the voltage proportional to n to produce a null condition and at the same time adjusts the reactivity output potentiometer. The reactivity output potentiometer has 10 volts impressed across it to ground which is equivalent to 1\$ in reactivity. Thus when the null point is obtained, the output voltage of the reactivity potentiometer is equivalent to ρ (\$).

TABLE D-1. DELAYED NEUTRON DATA^{1/}

Group No.	λ_i (sec ⁻¹)	$\alpha_i = \beta_i / \beta$
1	0.0127	0.038
2	0.0317	0.213
3	0.115	0.188
4	0.311	0.407
5	1.40	0.128
6	3.87	0.026

^{1/} Data of Keepin, Table 1, Nucleonics, Vol. 20, No. 8, August 1962.

Figure D-1. Analog Reactivity Computer Programming Schematic

Figure D-2. Integrating Amplifier Schematic Design

TITLE	
		PAX-G0 Control Drum Spans and Reactivity Measurements	
DOCUMENT NO.		DATE	
WANL-TME-1910		December 1969	
ABSTRACT Core material reactivity worths and control drum reactivity measurements performed in the PAX-G0 reactor are compared with analytical predictions. Based upon this comparison, a drum span normalization factor of 0.90 was generated for use in future R-1 control drum span calculations. Calculated radial reactivity coefficients for uranium and carbon are in good agreement with the measured values. The corresponding predictions for niobium is as much as 20% higher than the measured experimental values.			
DATA ITEM NO.		SECURITY CLASSIFICATION OF DOCUMENT	
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