**Westinghouse
Astronuclear
Laboratory**

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**WANL-TME-1913
SEPTEMBER 1970**

DATA ITEM T-119

**CONTROL VANE HEATING
MEASUREMENTS**

FINAL REPORT

MASTER

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Westinghouse Astronuclear Laboratory

Subcontract NP-1
CODE IDENT NO. 14683

WANL-TME-1913
SEPTEMBER 1970

DATA ITEM T-119

CONTROL VANE HEATING MEASUREMENTS

FINAL REPORT

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APPROVED BY:

J. G. Gallagher, Manager
Design Engineering

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ABSTRACT

The R-1 test sector of the PAX-G2A reactor was used to obtain radiation measurements on the surfaces of a CuB (24 v/o ^{10}B) R-1 prototype control vane located at a drum angle of 115° . To determine the $^{10}\text{B}(n, \alpha)$ heating rate in the vane, measurements of the activation of ^{164}Dy were made as a function of position on the surfaces of the vane. The photon heating rate was determined using data obtained with ^7LiF thermoluminescent dosimeters. Based upon the results of these data, the expected heating rate in an 18 control vane NERVA R-1 reactor with the vanes at 115° is 0.00198 ± 0.0002 megawatts per megawatt of reactor thermal power.

The $^{10}\text{B}(n, \alpha)$ heating rate was analytically determined with the (R, θ) EXTERMINATOR-2 neutron diffusion code using both infinitely dilute and effective absorption cross sections for the vane. The ratio of the calculated to experimentally derived $^{10}\text{B}(n, \alpha)$ heating was $1.17 (+0.16/-0.13)$ and $1.49 (+0.2/-0.17)$ for effective and dilute vane cross sections, respectively.

The activation rates of ^{164}Dy and ^6Li on the inside and outside surfaces of the vane were compared with (R, θ) EXTERMINATOR-2 calculations. The use of effective, rather than dilute, absorption cross sections for the vane material considerably enhanced the agreement of the calculations with the experimental activation rates.

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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 Number is 59 DW-269-2.

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'70, 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 during March, 1970.

1.2 PURPOSE

The purpose of this experiment was to:

1. determine the azimuthal and axial variation in the neutron absorption rate around a control vane located in the R-1/PAX reflector.
2. determine the absolute neutron (n, α) absorption rates at the vane with the R-1 mockup drums positioned at the 115° angle.
3. provide data for comparison with predictions of the neutron absorption rates.
4. provide an improved basis for estimates of hot-test heating rates in the vanes and to provide an estimate of the calculational uncertainties associated with the predicted heating rates.
5. determine the feasibility of using ^7LiF and ^6LiF thermoluminescent dosimeters to measure (n, α) heating in the vane.

2.0 REFERENCES AND ASSUMPTIONS

2.1 REFERENCES

2.1.1 Specification

EC 677559 - Part 1. Performance/Design and Qualification Requirements Reflector, Control Drums and Axial Support for 677555A NERVA Nuclear Subsystem, June, 1968.

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-269-2 Scope of Test for Control Vane Heating Distribution Experiment

2.1.4 Drawing

711J496 - Reactor/Vessel Assembly, R-1 PAX

711J498B - Segment, Reflector Assembly, R-1 PAX

100E174 - Plate, Control Drum R-1 PAX

388D410 - Plate Assembly, Control Drum, R-1 PAX

939J535 - R-1 Reflector (5/68)

2.1.5 External Document

WANL-TME-1915, - "Radiation Environment on CHESH Components. "

WANL-TME-1852, - "R-1 Parametric Shield Measurements Conducted on the NERVA Permanent Assembly Experiment (PAX) Reactor"

WANL-TME-267, - "Westinghouse Astronuclear Experimental Facility Reactor Operations Manual"

2.1.6 Data Release Memorandum

51196 - Control Vane Heating Distribution Experiment

52720 - Calibration of TLDs for Vane Heating Experiment

51189 - Parts Inventory in the PAX-G2 Reactor

51163 - Parts Inventory in the PAX-G1 Reactor

51163A - Parts Inventory in the PAX-G1A Reactor

51163B - Parts Inventory in the PAX-G1B Reactor

- 51166 - PAX-G1 Shim Wire Inventory
- 51166A - PAX-G1 Shim Wire Inventory
- 51105 - Flow Charts for an Integral Nuclear and Radiation, Thermal and
- 51105C - Structural Analysis Procedure, and Identification and Description
of Computer Codes
- 51195 - Power Level Calibration in PAX-G2A
- 51186 - Chemical Analysis of WANEF Reactivity Materials
- 51245 - Test Reports on PAX Control Vanes
- 51612 - Neutron Transmission Measurements on NERVA Reactor Control Vanes
- 51182 - Summary of National Bureau of Standards Calibrations at WANEF
- 51150A - Parts Inventory in the PAX-G0-A, -B, and -C Reactors
- 51150 - Parts Inventory in the PAX-G0 Reactor

2.2 ASSUMPTIONS

1. The passive dosimeters and the materials used to affix them to the vane surface do not significantly perturb the flux or dose rate being measured.
2. The glass envelope surrounding the thermoluminescent powder does not significantly perturb the radiation environment in the vicinity of the dosimeter.
3. The calibration factor obtained from the boron-lined, compensated ion chamber located outside the reactor can be accurately related to ^6Li captures at the vane surface.

3.0 TEST ARTICLE CONFIGURATION

3.1 DESCRIPTION OF TEST CONFIGURATION

These tests were performed on the inner and outer surface of the $\text{Cu-}^{10}\text{B}$ control vane of control drum B located in the 60 degree R-1 mockup reflector sector of the PAX-G2A assembly. The experimental test geometry, including a plan view of the location of the control drum B and control vane is shown in Figure 3-1. An isometric view of the PAX-G2A reflector assembly is given in Figure 3-2. Descriptions of the components used for the measurements are given below.

3.1.1 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 Reference R-1 reactor core 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 design calls for uranium loadings as high as 630 mg/cm^3 , available elements have uranium loadings of less than 500 mg/cm^3 . 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 April, 1968, R-1 reference design described in WANL Dwg. 939J535.

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 sector 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:

1. Substitution of Cu-¹⁰B control vanes for the Al-¹⁰B 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.

3.1.2 Control Vane Description

The control vanes are 100 mils thick, with a ¹⁰B surface concentration of 0.13 gram per square centimeter and a vane span of 120 degrees around the control drums. The vanes are detailed in WANL Drawings 100E174 and 388D410. Figure 3-1 shows the location of the vanes on a control drum.

The Cu-¹⁰B control vane information including the serial numbers of the vanes, their location on the R-1 drums, the test reports on vane weight and boron content and the uniformity of boron distribution in the vanes are detailed in DRMs 51612, 51163B, and 51245.

*The April, 1968, R-1 reference design described in WANL Dwg. 939J535.

Figure 3-1. Experimental Test Geometry

612397-3

Figure 3-2. PAX-G2A Reflector Assembly

4.0 SUMMARY OF TESTS

4.1 NARRATIVE

4.1.1 Test Description

The radiation environment was measured on the inner and outer surface of the three ^{10}B -Cu control vanes of control drum B in the R-1 mockup sector of the PAX-G2A assembly. Passive dosimetry techniques were used with bare and half-covered* (with Cd) foils of Dy-Al, bare wires of Dy-Al, and with glass-encapsulated thermoluminescent dosimeters of CaF_2 , ^6LiF and ^7LiF . Axial traverses were made at or near the inner and outer edges of the vanes, and azimuthal traverses were made on both inner and outer surfaces of the vanes at a number of axial positions in the vicinity of the core midplane. A total of 147 Dy-Al dosimeter locations and 123 TLD locations were measured and the data reported in tabular and graphical form in DRM 51196.

The measurements were made at a cold critical drum bank angle of $114.7^\circ \pm 0.4^\circ$. The three R-1 drums and the two adjacent PAX drums were held at angles of $115.0^\circ \pm 0.1$ during the run. The test was carried out in accordance with the procedures set forth in Appendix B.

4.1.2 Passive Dosimetry

4.1.2.1 Dosimeter Types

The types and sizes of passive dosimeters used are presented in Table 4-1. A more detailed description of the Dy-Al dosimeters appears in Appendix A of WANL-TME-1915. The glass-encapsulated thermoluminescent dosimeters (TLD) are described in DRM 51196 and the TLD data are recorded in the same manner as that reported in Appendix A of WANL-TME-1915 for CaF_2 TLD hot pressed chips.

The Dy-Al foils and wires and the CaF_2 , ^6LiF , and ^7LiF TLDs were irradiated simultaneously.

The Dy-Al foils were counted on the WANEF NC-8010 flow proportional counters described in Section 4.4 of WANL-TME-1852.

*Foil was placed on vane surface and covered with a cadmium disc.

TABLE 4-1. PHYSICAL DESCRIPTION OF PASSIVE DOSIMETERS

Type	Length (l) Thickness (t) (cm)	Diameter (cm)	Average Weight (grams)	Radiation Measured
CaF ₂ TLD ⁽¹⁾	1.2 (l)	0.14	0.031*	Gamma Dose
⁶ LiF TLD ⁽²⁾	1.2 (l)	0.14	0.032*	⁶ Li Captures Gamma Dose Neutron (n, α)
⁷ LiF TLD ⁽³⁾	1.2 (l)	0.14	0.031*	Gamma Dose
Dy-Al Foils ⁽⁴⁾	0.013 (t)	0.635	0.011	Neutron (Sat. activity ¹⁶⁴ Dy)
Dy-Al Wires ⁽⁵⁾	1.27 (l)	0.076	0.016	Neutron (Sat. activity ¹⁶⁴ Dy)

(1) EG&G TL-31 Mini Dosimeter

(2) EG&G TL-22 Mini Dosimeter (Using Harshaw TLD-600 Powder, Manufacturer Spec. of 95.62 w/o ⁶LiF)

(3) EG&G TL-23 Mini Dosimeter (Using Harshaw TLD-700 Powder, Manufacturer Spec. of 0.007 w/o ⁶LiF)

(4) 4.0 Weight Percent Dy As Documented In Appendix A of WANL-TME-1915

(5) 10.9 Weight Percent Dy As Documented In Appendix A of WANL-TME-1915

* Includes weight of glass envelope.

Powder weight about 0.010 grams.

4.1.2.2 Dosimeter Calibrations

The Dy-Al dosimeters required calibration factors to enable count rates to be converted to activities. This was accomplished by counting several irradiated dosimeters on the WANEF instrumentation and then sending them to the Analytical Service Laboratory of Westinghouse Advanced Reactor Division for activation analysis to have their absolute activity determined. The results of absolute activity determination are presented in Appendix A. The accuracies obtained are included in the uncertainty analysis described in Section 4.1.2.5. The procedures used for the calibration are described in more detail in Appendix A of WANL-TME-1915.

The thermoluminescent dosimeters were calibrated with an NBS -calibrated 70 millicurie ^{60}Co secondary radiation standard, (Reference: DRM 51182), located at WANEF. More detailed descriptions of the TLD calibrations appear in DRMs 52720 and 51196.

4.1.2.3 Positioning Techniques and Accuracies

The desired axial location of all dosimeter traverses was marked with pencil on the inner and outer surfaces of the vanes. The Dy-Al foils were taped directly to the vanes using "Scotch" mending tape. In order to position the Dy-Al wires and the TLDs, the areas where they were to be placed were sprayed with "Scotch-Grip" adhesive and allowed to dry to a tacky condition. The TLDs and Dy-Al wires were then positioned with tweezers on the vane surface where they adhered to the adhesive. Strips of "Scotch" mending tape were then placed over the dosimeters to further ensure that they remained in position during the experiment. After the dosimeters were positioned, measurements of each dosimeter position were taken by marking the vane edges and the center of each dosimeter on a strip of paper and measuring the locations as marked on the paper. Figure 4-12 shows a photograph of a portion of the outer surface of the center vane with the dosimetry in place. Other photographs appear in DRM 51196.

The accuracy of placement of any of the dosimeters is known to within ± 0.2 cm in any direction as referenced from the bottom and from the centerline of drum B. The measured positions are reported in the data tables which appear in DRM 51196.

4.1.2.4 Data Reduction Techniques

The data reduction techniques used are described in Section 4.1.2.2 of WANL-TME-1915. The computer codes used are described in DRM 51105C.

4.1.2.5 Uncertainty Analysis

The accuracy of the two types of TLD data has been estimated and is summarized in Table 4-2. This table summarizes the principal sources of uncertainty on the basis of one-sigma estimates given in percent. The total uncertainty is in the range of ± 11 to ± 16 percent for the gamma dose and ± 14 to ± 19 percent for the ^6Li captures/gram (^6Li)-sec-watt data.

TABLE 4-2. TLD MEASUREMENT UNCERTAINTIES

Source of Uncertainty	One-Sigma Percent	
	TLD Dose Rate	^6Li Capture Rate
Reproducibility	5	5
^6Li Calibration		8.9
Power	6	6
^{60}Co Calibration	7.4	7.4
Readout Accuracy	1 to 12.5	1 to 12.5
TOTAL	± 10.8 to 16.5	± 14.0 to 18.7

The analysis of the Dy-Al counting data included an uncertainty analysis for each dosimeter based on counting statistics and uncertainties of background rates, system resolving times, dosimeter weights and counting time. In addition to these quantities, the other possible sources of uncertainty were estimated and were inserted into the final steps of the data reduction. Table 4-3 lists the significant sources of uncertainty and estimated magnitudes in terms of one-sigma standard deviations in percent.

In order to more completely describe the uncertainty calculation, consider E_0 to be defined as the uncertainty calculated from the quantities listed in the first sentence of the preceding paragraph and the quantities E_1 , E_2 , and E_3 to be defined as shown in Table 4-3. Then the uncertainty calculated for the cadmium ratios is the vector sum of E_{0B} , E_{0C} , E_{1B} and E_{1C} ; where the subscripts, B and C, denote the bare and Cd-covered activities, respectively. Using the same subscripts, the "statistical" uncertainty calculated for the thermal flux is composed of E_{0B} , E_{0C} , E_{1B} , E_{1C} , T1 and T2, where T1 and T2 are, respectively, the percent uncertainties in the C_S and C_E parameters of the thermal activity calculation:

$$A_T = C_S \left[A_B - (C_E) A_C \right]$$

where C_S and C_E are the first order correction factors relating to perturbations of the sub-cadmium and epi-cadmium flux by the foils and the cadmium covers, and where A_B and A_C are, respectively, the bare and cadmium-covered activities. The "total" uncertainty calculated for the thermal flux is the vector sum of the "statistical" uncertainty described above plus the uncertainties E_{2B} and E_{3B} .

4.1.3 Power Level Calibrations

The reactor power level calibration is described in DRM 51195.

TABLE 4-3. UNCERTAINTIES IN DY MEASUREMENTS

	One-Sigma Percent
Random and Biasing Uncertainties	
Spectral Dependent Variations of Cross Section	1.0
Variations in Alloy Content	2.0
Counter Inter-Normalization	2.0
	<hr/>
Sub-Total E1	3.0
Systematic Uncertainties in Activity	
Isotopic Abundance	0.1
Alloy Content	7.0
Normalizer Count Rate	1.0
Saturation Exposure Calculation	0.1
Reactor Power	6.0
Absolute Counting Efficiency of Normalizer	6.0
	<hr/>
Sub-Total E2	11.0
Systematic Uncertainties in Flux Cross Section	7.4
	<hr/>
Sub-Total E3	7.4

4.2 TEST RESULTS

4.2.1 General

The test results are presented in graphical form. All uncertainties are reported as one-sigma standard deviations. Complete tables of the results are reported in DRM 51196. The plots include one-sigma error bars to describe the uncertainty on each point. The derivation of these uncertainties is discussed in section 4.1.2.5. Positions are reported in terms of the radius in centimeters from the centerline of the drum, the axial distance in centimeters above the bottom (dome end) of the PAX core, and the azimuthal angle in degrees measured from a theta-zero at the inner edge of the vanes. Figure 3-1 shows a sketch of the vanes and the coordinate system used.

4.2.2 Dysprosium-Aluminum Measurements

The bare and cadmium-covered Dy activities are presented in units of disintegrations per second per gram of ^{164}Dy per watt of reactor power. Some of the Dy data are also presented as thermal flux ($E < 0.4$ ev) and as cadmium ratios (i. e., $\frac{\text{Bare activity}}{\text{Cd-covered activity}}$) where both of these quantities were obtained from comparison of bare and Cd-covered data taken at similar locations on the vane.

Figure 4-1 shows the azimuthal distribution of thermal flux on both surfaces of the central vane and Figure 4-2 shows the cadmium ratios from the same data. Figure 4-3 is a composite plot of all the bare Dy data azimuthal distributions. Figure 4-4 shows a plot of the most detailed Dy traverse on both sides of the central vane. Figure 4-5 shows the three axial traverses made with bare Dy.

4.2.3 Thermoluminescent Dosimeter Measurements

The ^7LiF and CaF_2 TLD data are presented as dose rate in rads(Material)*/hour-watt based on calibrations in a ^{60}Co field.

The ^6LiF TLD data are presented as ^6Li captures/gram (^6Li)-sec-watt based on calibrations in a ^{60}Co field as well as calibrations in the PAX reactor external radiation environment. A detailed discussion of the method of calibration is contained in DRM 52720.

* Detector material refers to not only the contained ^7LiF or CaF_2 powder but also includes the glass container which accounts for about 2/3 of the dosimeter weight.

TLD - Rads(Material)/Hour-Watt

The dose rate data obtained with the CaF_2 and ^7LiF TLDs, both at the same traverse location, is plotted in Figure 4-6. This data, as requested in the Scope of Test document, was only obtained on the outside surface of the central vane. It is interesting to note the difference in magnitude between the CaF_2 and the ^7LiF TLD data. This difference is approximately 30 to 50 percent although the distributions appear similar. It is expected that this difference is real due to the difference between the large low energy gamma response of the unshielded CaF_2 TLD's and the relatively flat gamma energy response of the ^7LiF TLDs. Because of this large difference in magnitude, the units of Rads(Material), where material refers to detector material, per hour per watt have been used.

The dose rate data obtained with the ^7LiF TLDs have been shown cross-plotted with CaF_2 data in Figure 4-6 for the same traverse. Figure 4-7 presents an azimuthal distribution of the ^7LiF data for two different traverses and Figure 4-8 presents the ^7LiF data obtained on the inner and outer vane edges as a function of axial position.

TLD - ^6Li Captures/Gram(Li)-sec-watt

The ^6Li captures data obtained with the ^6LiF and ^7LiF TLDs are plotted in Figure 4-9 for the detailed azimuthal traverses on the inner and outer surfaces of the central vane. Figure 4-10 presents the azimuthal traverse data obtained at slightly different axial elevations on the inner and outer surface of the central vane. Figure 4-11 presents the ^6Li captures obtained on the inner and outer vane edges as a function of axial position.

4.2.4 Dy-Al Measurement Comparison with TLD- ^6Li

A visual examination of Figures 4-3 and 4-9 shows somewhat similar azimuthal distributions on the inner and outer vane surfaces for the Dy-Al saturated activity and the ^6Li capture rate. However, the resolution and uniformity of the Dy-Al saturated activity data are much better than the ^6Li capture rate data.

The data in Figure 4-9 can be scaled for comparison with the saturated ^{164}Dy activity, by multiplying the data by 0.106 to obtain an absolute comparison between ^6Li data and the Dy-Al data*. This results in relatively close agreement between the two independent systems.

Based upon the data obtained from this experiment, the ^6LiF and ^7LiF TLD method is not recommended for further use because of the complexity of obtaining the desired information, the lack of spatial resolution, and the inherent scatter in the data as shown in Figure 4-9. However, some improvement could perhaps be achieved in this technique when the new Radiation Calibration Facility is completely operational by performing repeated calibrations of selected, individual dosimeters.

*See DRM 51196.

Figure 4-1. Azimuthal Thermal Flux

Figure 4-2. Azimuthal Cadmium Ratio

Figure 4-3. Azimuthal Activity of Bare Dy

Figure 4-4. Azimuthal Activity of Dy Wires

Figure 4-5. Axial Distributions - Dy

Figure 4-6. Azimuthal Distribution - Gamma Dose Rate

Figure 4-7. Azimuthal Distribution - ⁷LiF Measured Gamma Dose Rate

Figure 4-8. Axial Distribution - ^7LiF Measured Gamma Dose Rate

Figure 4-9. Azimuthal Distribution - ${}^6\text{Li}$ Capture Rate

Figure 4-10. Azimuthal Distribution - ${}^6\text{Li}$ Capture Rate

Figure 4-11. Axial Distribution - ${}^6\text{Li}$ Capture Rate

Figure 4-12. Detail of Dosimetry on Outer Surface of The Central Vane

5.0 ANALYSIS OF TESTS

5.1 INTRODUCTION

This section presents a comparison of the experimental and calculated radiation environment on the surface of an R-1 type CuB (24 v/o ^{10}B) control vane located in the reflector region of the test sector of the PAX-G2A reactor. The radiation environment data that are compared consists of the ^{164}Dy saturated activity, ^6Li (n, α) reaction and gamma Kerma rate (CaF_2 and ^7LiF thermoluminescent detectors). From these data are obtained a comparison of the total heating rate in the vane and an azimuthal distribution at the core midplane of the inferred (n, α) heating. This is obtained from the measured ^{164}Dy activation.

The calculational techniques used to obtain the heating rate from the experimental data are presented in conjunction with a brief description of the analytical techniques used to analyze the experiment.

This section also presents uncertainty factors applicable to the analytical data.

5.2 METHOD OF ANALYSIS

5.2.1 Calculational Procedure

The PAX-G2A "as-built" R-1 60° test sector inventory was used as the detailed nuclear model in the calculations. An R, θ EXTERMINATOR - 2⁽¹⁾ problem which applies neutron diffusion theory was employed to predict the neutron fluxes in the central 20° portion of the test sector. This model was centered about the middle drum of the three drum test sector. The control drums were placed at 115° in both the experiment and in the EXTERMINATOR problem. The calculations were initially performed to determine the PAX-G2A power distributions. The results of these calculations and comparison with the experiment are presented in WANL-TME-2692⁽²⁾. The neutron fluxes in the test sector obtained from the calculations presented in Reference 2 were used for the purpose of the comparison with experimental neutron data.

The photon calculations presented in WANL-TME-1914⁽⁷⁾ on the PAX-G1A reactor were used to compare with the experiment. This was determined to be sufficient since the differences between the PAX-G1A and PAX-G2A reactor are minor.

The G2A had the TaC central elements that were near the core center for G1A, dispersed in the core periphery. The G2A had CuB control vane material versus AlB in G1A with approximately the same gm/cm² of ¹⁰B. These differences were determined to have an insignificant (< 1%) effect on the neutron environment in the reflector by comparing the 16 group neutron fluxes in the G1A and G2A obtained from similar EXTERMINATOR calculations.

The neutron environment at the vane location in PAX-G2A was determined with two different sets of neutron absorption cross sections for the control vane material. These were infinitely dilute and effective absorption cross sections. The following sections describe the techniques used to obtain these cross sections.

5.2.1.1 Region Dependent and Infinitely Dilute Absorption Cross Sections for the Control Vane Material

The procedure employed to obtain all of the basic cross sections for use in the EXTERMINATOR - 2 calculations is presented in this section.

Figure 5-1 is a flow chart of the basic computational procedure used to obtain the analytical results presented in this report.

With the exception of using effective absorption cross sections for the control vane material, the procedure outlined in Figure 5-1 is basically the WISDM (WANL Integrated Nuclear, Radiation and Shielding Standard Design Method) technique⁽³⁾.

Region dependent 16 energy group P_0 , transport corrected macroscopic neutron cross sections for use in EXTERMINATOR - 2 were obtained from the iterative loop employing the GAMB1T⁽⁴⁾ - ANISN⁽⁵⁾ - ANISIG codes. On the first iteration, GAMB1T uses the P_1 equations to generate 52 group, P_0 transport corrected, neutron cross sections for an infinite media spectrum. These cross sections are employed in the radial one-dimensional, discrete ordinates transport code, ANISN, to obtain 52 group average fluxes and currents for each

region describing the reactor. These 52 group data are interpolated by the ANISIG code to 155 neutron energy groups which then become the region dependent fine energy group spectrum employed in GAMBIT to generate new spectrum averaged cross sections. This process is repeated until a converged, region dependent, 155 neutron energy group spectrum (change in spectrum between two successive iterations is small) is obtained. This converged spectrum is then employed in the GAMBIT code to generate the 16 group region dependent macroscopic cross sections. These cross sections were used in EXTERMINATOR - 2 to obtain 16 energy group neutron fluxes as a function of (R, θ) in the test sector.

5.2.1.2 Effective Absorption Cross Sections for the Control Vane Material

Since the EXTERMINATOR-2 geometrical model employed a single mesh interval across the vane thickness, and since there is no provision in the code to handle a "thick" absorber, it was deemed appropriate to use effective absorption cross sections for the control vane material. These effective cross sections were calculated using first-flight transport theory for a thick absorber according to the formulation presented in Reference 6. The use of these cross sections should give a better approximation of neutron transport with a single mesh interval for a localized heavy absorber rather than use of infinitely dilute cross sections since the flux depression is calculated more accurately. It is also not considered to be practical to use many mesh intervals in the vane since the computer storage requirements are drastically increased, and hence, the computer running time per problem is increased. It should be mentioned that the EXTERMINATOR - 2 code is used principally for the determination of the power distribution in the core and all of the calculations are normalized to experimental data, thus, minimizing calculational uncertainties.

The effective absorption cross sections for the vane replaced the infinitely dilute values in the calculational scheme as shown in Figure 5-1. These values were calculated in the following fashion: the effective microscopic absorption cross section which permits the correct calculation of the total absorptions in the absorber is

defined as

$$\sigma_{\text{eff}} \equiv \sigma_a f_o \quad (5-1)$$

where:

σ_a = the infinitely dilute microscopic absorption cross section

f_o = the overall self-shielding factor, i.e., the ratio of the average flux throughout the absorber to the value of the flux at the absorber position before it was present.

The σ_a values were obtained from the GAMBIT - ANISN - ANISIG loop shown in Figure 5-1. The overall self-shielding factor was calculated with the equations 5.313 and 5.314 given on page 250 of Reference 6. These values were calculated for a semi-infinite slab with a thickness of 0.1 inch (the gauge thickness of the control vane). The slab was considered to be appropriate as the vane is a very heavy absorber. The overall self-shielding factor was calculated for the 16 neutron energy group structure by the equations (from Reference 6).

$$(f_o)_i = \frac{1 - \alpha_i}{2\chi_i} \quad (5-2)$$

where:

$$\chi_i \equiv 2a \sum_i$$

$\sum_i$ = infinitely dilute macroscopic absorption cross section for vane material for the i^{th} energy group

$2a$ = gauge thickness of the control vane, 0.1 inches

$$\alpha_i = e^{-\chi_i} - \chi_i e^{-\chi_i} + \chi_i^2 E_1(\chi_i)$$

$E_1(\chi_i)$ = first-order exponential integral

$$\equiv \chi_i^{n-1} \int_{\chi_i}^{\infty} \frac{e^{-y}}{y^n} dy$$

The 16 group effective macroscopic cross sections obtained from the above formulation are presented in Table 5-1 along with the infinitely dilute values for the control vane material.

The diffusion constant for the vane region was not changed from the dilute data when these cross sections were used.

The calculations obtained with both sets of cross sections are compared with the experimental Dy-Al data in Section 5.3 of this report.

5.2.1.3 Detector Response Functions

In order to compare the calculations with the experimental data, the EXTERMINATOR - 2 fluxes were multiplied by group dependent response functions (R_i). These response functions converted the fluxes to the experimentally reported quantity. The Dy-Al data are reported as saturated activity (denoted as A_s) of ^{164}Dy (disintegrations (captures)/sec-gm (^{164}Dy) - watt) and the ^6LiF data (denoted as C_s) as ^6Li captures/sec-gm (^6Li)-watt.

The calculated data were obtained as follows:

$$A_s = \sum_{i=1}^{16} R_{iD} \phi_i = \text{caps. } (^{164}\text{Dy})/\text{sec-gm } (^{164}\text{Dy})\text{-watt} \quad (5-3)$$

$$C_s = \sum_{i=1}^{16} R_{iL} \phi_i = \text{caps. } (^6\text{Li})/\text{sec-gm } (^6\text{Li})\text{-watt} \quad (5-4)$$

where:

R_{iD}, R_{iL} = microscopic absorption cross section times Avogadro's number divided by the atomic weights for ^{164}Dy and ^6Li , respectively, for energy group i .

ϕ_i = normalized EXTERMINATOR - 2 fluxes at (R, θ) location.

As shown in Figure 5-1, the 16 energy group microscopic absorption cross sections used to obtain the response functions for ^{164}Dy and ^6Li were obtained from the converged

fine group spectra. The GAMBIT code spectrally weighted the fine group cross sections to obtain 16 group data by using the converged reflector spectra. There were three region spectra available and all were used to obtain the microscopic absorption cross sections for the detector. The variation of the spectrally weighted microscopic absorption cross sections was of the order of 1% on an energy group comparison; thus, the cross sections obtained using the outer reflector spectrum were arbitrarily chosen to obtain the response functions for the vane region. The core spectra were used to obtain the response functions for calculations in the core region.

The self-shielding of the ^{164}Dy detectors was estimated in the manner described in Reference 6. This was estimated to be negligible and was not included in the response functions.

The EXTERMINATOR - 2 neutron fluxes obtained from the printout were normalized to core midplane fluxes on a per watt* basis by multiplying the fluxes by the following normalization factor:

$$K = \frac{2.445 \times 3.21 \times 10^{10} \times 1.35}{132.08 \times 18} = 4.457 \times 10^7 \quad (5-5)$$

where:

2.445 = average numbers of neutrons per fission. This normalizes the EXTERMINATOR - 2 values to the absolute number of neutrons within the mockup sector since the code uses one fission neutron for the transport analysis.

3.21×10^{10} = fissions/sec/watt.*

132.08×18 = length of fuel times the total number of azimuthal sectors that would equal 2π radians (EXTERMINATOR - 2 included 20° sector). This quantity accounts for the total volume of the PAX core in relation to that used in the code.

* Thermal watts.

1.35 = ratio of calculated peak-to-average fission distribution.

Since EXTERMINATOR-2 calculates axial average fluxes, the flux values at core midplane are thus obtained. *

The absolute flux values at the core midplane, ϕ_i in equations 5-3 and 5-4, were the fluxes calculated by the EXTERMINATOR - 2 code multiplied by the normalization factor, K, derived above.

5.2.2 Determination of Control Vane Heating from Analytical and Experimental Data

It is also important in the comparison of the calculations with experimental data to determine the adequacy of the calculational techniques to predict the radiation heating in the control vanes. The following sections describe the techniques used to obtain the heating rates for a given drum angle.

5.2.2.1 Determination of Control Vane Heating from Analytical Calculations

The EXTERMINATOR - 2 program calculates the total number of absorptions by cell that have the same composition; thus, the total number of absorptions for the vane material is calculated. For the high ^{10}B content vane, these absorptions can be considered to occur specifically in the ^{10}B and are (n,α) reactions. To obtain the total (n,α) heating in an 18 vane reactor from the absorptions (denoted by A_v) calculated by EXTERMINATOR - 2, the following equation is used:

$$H_{v,\alpha} = \frac{K \times 132.08 \times 18 \times 2.33 \times 1.602 \times 10^{-13}}{1.35} A_v, \text{ Watts } (n,\alpha) \text{ per watt of reactor thermal power} \quad (5-6)$$

where:

$H_{v,\alpha}$ = total (n,α) heating in watts in an 18 vane reactor per watt of reactor power at ambient conditions.

$\frac{K}{1.35}$ = normalization constant, K, defined by equation 5-5 divided by 1.35 to yield absolute axial average fluxes (absorptions).

132.08×18 = quantity to yield total volume of vane material from the volume presented in EXTERMINATOR - 2.

* This value is used for the calculations rather than the experimental value obtained in the reflector since it represents the normalization used in the EXTERMINATOR-2 calculations.

2.33 = MeV deposited in the vane per ^{10}B (n, α) reaction.

1.602×10^{-13} = factor to convert from MeV/sec to watts.

A_v = absorptions/sec obtained from EXTERMINATOR - 2 for the volume included in the geometry model.

The gamma heating contribution to the vane was obtained from the PAX-GIA DOT calculations described in Reference 7.

The neutron kinetic energy deposition was determined from the neutron fluxes and response functions and was found to be negligible when compared to the (n, α) and gamma heating; thus, this contribution is not included herein.

5.2.2.2 Determination of Control Vane Heating from Experimental Data

Experimental data were obtained on the inside and outside surface of the vane with Dy-Al and ^6LiF detectors. From these data, the saturated activity of ^{164}Dy and the capture rate (n, α) of ^6Li were determined. Due to inherent difficulties associated with the use of ^7LiF and ^6LiF TLD dosimeters, the data obtained for the ^6Li are scattered making an accurate assessment of the neutron heating rate in the vane difficult. The analysis of these data, therefore, was not performed in detail and reliance was placed totally upon the Dy-Al data.

Two types of Dy-Al data were obtained: the Dy-Al wire and Dy-Al foil. The comparison of the wire and foil data was good with the difference between the two sets being at most about 20%, the majority of the data being less than this; thus, the wire data were analyzed as it had considerably better spatial resolution than the foil data.

The procedure used to obtain the distribution and magnitude of ^{10}B (n, α) heating rate for a control vane placed at 115° drum angle from the Dy-Al data was as follows:

1. The saturated activity of ^{164}Dy per watt of reactor power on the inside and outside surfaces of the vane near the core midplane (~ 1.5 cm from midplane) was plotted as a function of azimuthal angle around the vane.

2. The relative distribution of the saturated activity on the surfaces was determined by the relationship

$$f_R(\alpha) = f(\alpha)/f_m \quad (5-7)$$

where:

$f_R(\alpha)$ = relative distribution of the saturated activity of ^{164}Dy on the surfaces of the vane as a function of the azimuthal angle, α , from the leading edge* of the vane.

$f(\alpha)$ = experimental distribution of the absolute saturated activity of ^{164}Dy on the surfaces of the vane as a function of the azimuthal angle, α , from the leading edge of the vane

f_m = normalization constant determined from the experimental data and defined by

$$f_m = \frac{\int_0^{s_1} f(R, \alpha) ds}{\int_0^{s_1} ds} \quad (5-8)$$

s = arc length along circular surface of the vane and is equal to $R\alpha$.

R = radius of vane from center of drum.

s_1 = arc length of the vane corresponding to $\alpha = 120^\circ$.

The quantity f_m corresponds to the average saturated activity of ^{164}Dy at the respective vane surfaces. It is assumed that the relative ^{164}Dy activity corresponds to the relative (n, α) heating rate in the vane material. Calculations of the capture in a $1/v$ absorber (^6Li) on the inside and outside surfaces of the vane show that it is proportional to ^{164}Dy absorptions; thus, the assumption that the (n, α) heating in ^{10}B obtained

* Leading edge of vane being that nearest the core edge.

from ^{164}Dy data is valid. This conclusion is of course based upon the accuracy of the calculated spectra.

3. An absolute 16 neutron energy group spectrum was obtained on the vane surface by equating the calculated ^{164}Dy activation with the experimentally observed value, i.e.,

$$f_m = K \sum_{i=1}^{16} R_i \phi_i / \text{PA.} \quad (5-9)$$

where:

PA = axial peak-to-average ratio of the flux.

K = constant

R_i = response function for ^{164}Dy used to obtain activity
(see Section 5.2.1.3) for the i^{th} neutron energy group.

ϕ_i = relative neutron flux at vane surface for i^{th} energy group.

$$\sum_{i=1}^{16} \phi_i = 1.$$

The PAX reflector spectrum was used in equation 5-9 to obtain an average absolute 16 neutron energy group flux on the surfaces of the vane, i.e.,

$$\phi_{s,i} = K \phi_i / \text{PA.}$$

4. A 16 neutron energy group first-flight transport analysis was performed on the vane using the absolute neutron fluxes at the surfaces obtained from equation 5-9 to obtain the average number of (n,α) absorptions in the vane. The following are the equations used to obtain the (n,α) heating from the experimental data for an 18 vane reactor at ambient conditions and 115° drum angle. The procedure used is that obtained from Reference 6.

The total $^{10}\text{B}(n,\alpha)$ heating rate in an 18 vane system obtained from the above procedure is:

$$H_{E, \alpha} = 2.33 \times 1.602 \times 10^{-13} V_T \sum_{i=1}^{16} f_{s,i} \phi_{s,i} \sum_{a,i} , \frac{\text{Watts}}{\text{Watt (Power)}} \quad (5-10)$$

where:

2.33 = MeV deposited in the vane per $^{10}\text{B}(n, \alpha)$ reaction.

1.602×10^{-13} = factor to convert from MeV sec to watts.

V_T = total volume of 18 vanes, cm^3 .

$\sum_{a,i}$ = infinitely dilute macroscopic absorption cross section for the vane, cm^{-1} .

$\phi_{s,i}$ = average neutron energy flux at the surface of the vane for i^{th} neutron energy group, $\text{n/cm}^2\text{-sec-watt (power)}$ obtained in the manner described in item 3, above.

The quantity $f_{s,i}$ is defined as the self-shielding factor of the vane for the i^{th} neutron energy group and was evaluated in the manner outlined in Reference 6 for the first-flight transport approximation:

$f_{s,i} \equiv$ the ratio of the average flux throughout the volume of the vane to the average flux at the surface of the vane for the i^{th} group.

This quantity was evaluated for a semi-infinite slab (considered the best geometry approximation to the vane) according to the equation:

$$f_{s,i} = \frac{1 - e^{-x_i} + x_i e^{-x_i} - x_i^2 E_1(x_i)}{x_i \{1 + E_2(x_i)\}}$$

where: $x_i \equiv 2a \sum_{a,i}$

$2a$ = gauge thickness of vane, 0.254 cm

$\sum_{a,i}$ = infinitely dilute macroscopic absorption cross section of the vane material for i^{th} energy group, cm^{-1} .

E_1, E_2 = first and second order exponential integral functions.

The photon heating rate in the vane was determined from the experimental data in the following manner. The 13 photon energy group spectrum calculated for the PAX-G1A reactor⁽⁷⁾, at the core midplane near the vane, was combined with photon energy deposition response functions to obtain the ratio of photon energy deposition in the vane material to that of LiF. This calculated ratio was applied to the experimental data to obtain photon heating rates in the vane.

The average photon heating was determined in the same manner as the neutrons by evaluating equation 5-7. The total heating was calculated by multiplying the azimuthal average at the core midplane by the vane volume for an 18 vane reactor and dividing by the axial peak-to-average distribution.

5.3 COMPARISON OF RESULTS

The comparisons of the experimental data with analytical calculations are presented in this section. The comparisons are not made with the axial distribution of the neutron data as: 1) the EXTERMINATOR - 2 is an (R, θ) calculation and this does not calculate an axial distribution*, and, 2) the (R, Z) DOT calculation uses a cylindrical ring prescription for the vane. Comparisons of the calculated and experimental distribution of the photon data are not made since: 1) EXTERMINATOR - 2 does not calculate photon transport, and, 2) the DOT calculations for PAX-G1A employed a control vane ring prescription⁽⁷⁾ which is cylindrical in shape and is positioned at the mass centroid of the vane (for a drum angle of 115°). Comparisons of the total photon heating in the vanes calculated with the DOT-NAGS** codes are presented. Finally, the comparison of calculated and

* Comparisons of axial ^{164}Dy data in the reflector region are presented in Reference 7 and the calculated axial distribution was in excellent agreement with experiment.

** The NAGS code takes the 2-D DOT photon fluxes times a heating rate response function to obtain total photon heating in the vane region.

experimental total heating rate in the vane and selected distributions on the inside and outside surfaces of the vane is presented. Where applicable, ratios (uncertainties) of calculated to experimental data are presented.

5.3.1 The ^{164}Dy Neutron Absorption Rate

Figures 5-2 and 5-3 present a comparison of the calculated and experimental azimuthal distribution of the saturated activity of ^{164}Dy near the core midplane on the inside and outside surfaces of the vane, respectively. The experimental data presented were obtained with Dy-Al wires. The bare Dy-Al foil data are not presented in the figures; however, the foil data were in excellent agreement with the wires on the inside surface of the vane. Deviations between the wires and foils were on the average less than 5 percent and only at one azimuthal position was the difference 10 percent. On the outside surface, however, the differences between the foils and wires were approximately 20 percent within the azimuthal angle range of 40 to 80 degrees. The reason for this is not understood at this time, but could be due to differences in geometry of the wires and foils with respect to the surfaces of the vane. The wire data were chosen for comparison with calculations rather than the foils due to the finer spatial resolution.

From Figures 5-2 and 5-3 it is noted that the data points at ~ 1.05 radians on the inside and outside surfaces of the vanes are greater than one would expect. This is deduced from the surrounding points. Since the wires have good spatial resolution, this is attributed to a local spot of the vane that has less boron than the surrounding regions. This condition if not properly controlled could lead to operating difficulties, e.g., local hot or cold spots and change in nuclear control capability from prediction.

The data presented in Figures 5-2 and 5-3 are represented by a visually fit curve rather than a "least squares curve" for two basic reasons: 1) the data were of sufficiently fine spatial resolution so that an adequate visual curve could be drawn, and 2) results of a least squares fit via the OMNIFIT-2⁽⁸⁾ code, utilizing a 2 through 7 order polynomial were not satisfactory. In all cases the distribution obtained at the edges of the vane was judged to be inadequate since it did not follow the gradient through the data points, but

averaged the points such that it underpredicted from 0 to 0.1 radians and overpredicted from 0.1 to 0.3 radians. This was attributed to the choice of the polynomial function and a better fit may have been obtained with a different one; however, due to the large number of data points this was judged to be unnecessary.

From Figures 5-2 and 5-3, it is observed that the use of infinitely dilute absorption cross sections for the vane in the EXTERMINATOR - 2 calculations underpredict the ^{164}Dy saturated activity by factors of 6 to 20. This is to be expected when a single mesh cell is used for the gauge thickness of an absorber that is black to low energy neutrons in a straight diffusion theory code that does not have the ability to use black boundary conditions between adjacent cells within the geometry model. To overcome this deficiency, the EXTERMINATOR - 2 was rerun using effective absorption cross sections obtained from first-flight transport theory (see Section 5.2.1.2) which handles neutron transmission through a heavy absorber considerably more accurate than straight diffusion theory. The results of these calculations are shown in Figures 5-2 and 5-3. As observed, considerable improvement between the calculated and experimental data is obtained.

Figures 5-4 and 5-5 present the ratio of the calculated to experimental saturated activity of ^{164}Dy as a function of azimuthal angle on the inside and outside surfaces of the vane, respectively. As observed, the calculated data are greater than the experimental results by factors ranging from 1.1 to 1.7 on the inside surface and 1.1 to 2.7 on the outside surface. These differences are attributed to a combination of the following:

- 1) The effective cross sections may be too small yielding a neutron transmission through the vane that is too large. As the effective macroscopic absorption cross sections for the vane for the low energy neutron groups (see Table 5-1) is the reciprocal of twice the gauge thickness, the use of mesh cell dependent cross sections rather than a given set may improve the results. This is due to the (R,θ) geometry where a mesh cell is not rectangular, but is a sector of an annulus.

- 2) The geometrical mockup of the vane is relatively coarse (15 mesh cells to cover a vane that has an arc length of approximately 8 cm) in that the mesh line spacing

is much greater than a low energy neutron mean free path in the vane. The use of finer mesh; however, may not be practical due to the large increase in computer time that would result.

3) The inherent inability of diffusion theory to predict the angular distribution of the neutron flux which will be a rapidly varying function over the vane surface.

4) The mesh cell shape of the segment of an annulus yields too large of a surface area that is exposed to beryllium when compared to the experimental setup. This geometry also creates an irregular surface area that will induce local perturbations. This is illustrated in Figure 5-6 which is a sketch typical of the geometrical mockup of part of the vane in R,θ geometry.

5) Another possibility is that the absorption cross sections of ^{164}Dy are in error. However, it is concluded that this possibility would make the difference greater than that observed. This is illustrated by the data presented in Figure 5-7 which are a comparison of the radial distribution of the experimental (PAX-G1A) saturated activity of ^{164}Dy (bare) at the core midplane with DOT (PAX-G1A) and EXTERMINATOR - 2 (PAX-G2A) calculations. The comparison of PAX-G2A and PAX-G1A ^{164}Dy activation is considered valid as there are only minor differences between the two reactor builds and since the comparison of PAX-G1A and G2A neutron fluxes did not exhibit any significant differences. It is observed from Figure 5-7 that the shape of the EXTERMINATOR - 2 calculated radial distribution agrees very well with the experiment, but is consistently low by a factor of 1.35 in the core and reflector. The DOT calculations are also lower than the experimental values in the core (and agree very well with the EXTERMINATOR - 2 data); however, the DOT data agree with the experimental data in the reflector. The lower calculations in the core using both analytical techniques indicate that the ^{164}Dy absorption cross sections may be in error. The consistently lower prediction of the ^{164}Dy activation by EXTERMINATOR - 2 through both the core and the reflector is the same effect observed in the comparison of 16 group DOT calculations of the ^{164}Dy activation with experiment for the FCX reactor⁽⁹⁾. Because the FCX has a graphite reflector and PAX a beryllium reflector,

the consistency of underprediction may be coincidental. This is not considered to be the case; however, but is believed to reinforce the speculation that the ^{164}Dy activation cross sections are in error. The agreement of the (R,Z) DOT calculations, which cannot use an accurate geometry for the PAX reflector, with the experiment in the reflector region may be fortuitous. This is concluded since the use of a calculational geometry model that accurately mocks up the actual reflector (FCX (R,Z) DOT and PAX EXTERMINATOR - 2) underpredicts the measured data. Evidence that a discrepancy between the measured and calculated ^{164}Dy activation does exist; thus a further investigation is warranted to determine the exact source of this discrepancy.

Figures 5-8 and 5-9 present axial distributions of the measured saturated activity of ^{164}Dy bare wire on the edges and bare foils on the outside surface of the vane (4.56 degrees or 0.0796 radians from the leading edge), respectively. As stated previously, comparisons with calculations are not presented as EXTERMINATOR - 2 is a two-dimensional (R, θ) code that does not calculate the axial distribution. The data are presented, however, since they were used to obtain the axial peak-to-average value of (n, α) heating in the vane from experimental quantities. It is observed from the data that the axial distribution is essentially independent of azimuthal position.

It is noted that the value obtained at Z=64.45 cm from Figure 5-9 is in excellent agreement with the value presented in Figure 5-3 for the same azimuthal position.

The relative azimuthal and axial distributions of the ^{164}Dy saturated activity are presented later in Section 5.3.4 where the comparison of the calculated and experimentally derived vane heating is presented.

5.3.2 The ^6Li Neutron Absorption Rate

Figures 5-10 and 5-11 compare the calculated and experimental azimuthal distribution of the ^6Li absorption rate on the inside and outside surfaces of the vane, respectively. The calculations were performed using effective absorption cross sections for the vane. The considerable scatter observed in the experimental data is believed to be due to a combination of: 1) the lack of uniformity of LiF powder in the TLD s, 2) the lack

of good reproducibility of the LiF TLDs , and, 3) non-linear response of the ^6LiF TLDs which occurs at relatively low activation levels. The data were visually fit with a curve that is believed to represent the trend of the data. It is observed from Figures 5-10 and 5-11 that the calculations are greater than the experiment, but positive conclusions cannot be reached as to shape and absolute magnitude due to the scatter in the data.

Figures 5-12 and 5-13 present the ratio of the calculated to experimental ^6Li absorption rate as a function of azimuthal location on the inside and outside surfaces of the vane. The ratios vary from 1.2 to 2.0 on the inside surface and 1.2 to 3.6 on the outside surface. This is the approximate range observed for the ^{164}Dy data. The possible explanations for the difference previously presented in Section 5.3.1 are also applicable here with the exception of the discussion concerning the possible error in the ^{164}Dy cross section. It is possible to fit the ^6Li data with a curve that is greater in magnitude than the one presented in the figures that would yield better agreement with calculations. The self-shielding of the ^6LiF TLDs was not calculated since the exact mass and geometry of the ^6Li in the TLD was unknown and varied for individual TLDs. If the self-shielding is important, it would tend to enhance the agreement with calculations.

5.3.3 The CaF_2 and ^7LiF TLD Photon Kerma Rate

Figures 5-14 and 5-15 present the azimuthal distribution of the gamma Kerma rate for ^7LiF and CaF_2 on the outside surface of the vane near the core midplane and the axial distribution of the gamma Kerma rate for ^7LiF on the leading and trailing edges of the vane, respectively. As stated previously, the EXTERMINATOR - 2 does not calculate the photon environment; however, a comparison of the photon environment with DOT calculations performed for PAX-G1A analysis⁽⁷⁾ are presented in Figure 5-14. No comparisons of the axial distribution are presented as the agreement in shape between the experiment and calculations was excellent for the PAX-G1A distribution in the reflector⁽⁷⁾. The experimental axial data are presented as these data were used to obtain the axial average of the photon heating.

From Figure 5-14, it is observed that the calculated gamma Kerma rate for the PAX-G1A in Rads(C)/hr-watt is approximately a factor of 1.6 to 2.0 less than the ^7LiF data and, within the statistical uncertainty of the data, agrees in shape with the experimental data. The data trend indicates that the CaF_2 Kerma rate is greater than the ^7LiF Kerma rate by factors of 1.2 to 1.5. It is also observed that, within the experimental uncertainty of the data, these differences decrease considerably with increasing azimuthal angle; no definite statement can be made about these factors. One would expect a slightly larger Kerma rate for CaF_2 than LiF since the mass energy absorption coefficient of CaF_2 is greater (on a relative basis) than LiF for photon energies of $E < 100 \text{ KeV}$.

The reasons for the calculations being lower than the experiment could be due to a combination of the following:

- 1) The calculations were performed using Rads (carbon) response functions. The difference between the LiF and carbon response is, however, expected to be minimal and at most yield a 30 percent uncertainty for the photon response for $E < 100 \text{ KeV}$.^{*} This is not expected to be significant since most of the response is due to photons with energy $E > 100 \text{ KeV}$. It is questionable if compensation for the lower energy difference in response between LiF and carbon can be accurately predicted since the calculational photon group structure has a single energy group of $0.0 \text{ MeV} < E < 0.4 \text{ MeV}$. If an estimate of this effect is to be made, a different photon energy group structure must be used in the calculations. In the comparisons presented here, it is assumed that a direct comparison of Rads (C) with Rads (LiF) can be made with a nominal uncertainty.

- 2) The TLDs were placed directly on the surface of the vane and the calculations were performed using a control vane ring prescription located at the mass centroid of the vane. The 0.5 MeV photon released in the $^{10}\text{B} (n, \alpha)$ reaction could increase the data relative to the experiment. From the ^{164}Dy data; however, it is estimated that this contribution is approximately 10 percent of the measured dose rate. The CaF_2 dose rate obtained in the spring holes in the PAX-G1A reflector⁽⁷⁾ are a factor of 1.9 less than those obtained on the vane for the same radial location. This is not expected based upon the small

* Isotopes/Con-Rad Dosimeter Manual, Isotope Inc., New Jersey

differences between the G1A and G2A reactors. Thus, the reason for the differences in CaF_2 for the two reactors cannot be totally explained based upon the 0.5 MeV photons from the vane. The captures in the copper of the vane are insignificant compared to the ^{10}B due to the 24 v/o ^{10}B content and very high ^{10}B to Cu absorption cross section ratio.

3) There is an unknown neutron response to the TLDs which would increase the response. The tendency is for the experimental TLD data to be greater than the calculations (factor of ~ 1.2 for PAX-G1A comparison with DOT in WANL-TME-1914) in the reflector region and has been attributed to neutron response of TLD and higher low energy photon response of CaF_2 compared to carbon.

In summation, it is not presently understood why the CaF_2 data in PAX-G2A are significantly greater than the G1A results in the reflector. As the LiF response approximates that of carbon, these data will be used to obtain the experimental photon heating.

5.3.4 Control Vane Heating

The nuclear heating rate in the vane for a 115° drum angle and ambient conditions was determined from the procedures outlined in Sections 5.2.2.1 and 5.2.2.2 for the analytical and experimental results, respectively. The results of the heating are tabulated in Table 5-2 with the ratios of the calculated to experimental data presented in Table 5-3. These ratios are applicable only to the drum angle of 115° and ambient conditions and should be used for other drum angles as an indication of the calculated uncertainties. However, from the results of this experiment, it is expected that the use of the $^{10}\text{B}(n, \alpha)$ heating using effective absorption cross sections would yield a conservative heating rate. The ratio of calculated to experimental results of the total heating could be as low as 0.97 and as high as 1.2 for effective cross sections and in a range of 1.25 to 1.54 for dilute cross sections. These are based upon an approximate average of the one sigma uncertainty in the experimental data.

The results of the $^{10}\text{B}(n, \alpha)$ heating obtained from the experimental ^{164}Dy data are presented in Table 5-4. From these data, it is observed that most of this heating is

due to the absorption of neutrons with $E < 583$ eV. It is also observed that almost all of the neutrons with $E < 1.86$ eV are absorbed in the vane. The use of dilute cross sections creates more absorptions and depletes the surface flux in the low energy regions (groups > 11) which creates a lower ^{164}Dy saturated activity calculation because the vane is too "black." This is characteristic of using diffusion theory for a heavy absorber in that the neutron transmission is greatly underestimated for a material that has a thickness greater than approximately two mean free paths.

Because the vane is a very heavy absorber, the use of cross sections that are considerably different does not drastically change the total number of neutrons absorbed, but the position within the vane at which absorption occurs would vary considerably. This would be an important factor to consider in heat transfer calculations if the material had a low thermal conductivity, but this is not the case since copper is the major constituent of the vane.

The reason for the factor of 0.61 ratio of calculated to experimental photon heating rate is not understood at this time. It could however, be due in part to the neutron response in the TLD data, which is not accounted for in the data reduction, or to the small differences between the PAX-G1A and G2A cores. Effort is being expended to resolve these differences; however, since the photon heating derived from the experimental data is ~ 20 percent of the $^{10}\text{B}(n, \alpha)$ heating, the uncertainty in photon heating contributes a small contribution to the total uncertainty.

As stated previously, the heating rates presented in Table 5-2 for 1515 MW* do not consider the effect of temperature or hydrogen on the vane neutron and photon absorption rates. An estimate of this effect is obtained from neutron and photon calculations performed with 1-D radial ANISN calculations for the R-1 reactor design drawing 939J685A. The calculations were performed for full power operating conditions and with no LH_2 and ambient temperature. The results of these ANISN calculations are presented in Reference 10. The ratio of the full power group fluxes to ambient at the radial pressure vessel midplane were multiplied by the group heating rates in Table 5-4 to obtain an

* Megawatts thermal.

estimate of the cold-to-hot effect for neutron heating. Similarly, the photon energy flux was ratioed and multiplied by the experimental values obtained in Tables 5-2. The results of the estimate of the heating rate in the vanes for 1515 MW full power operating conditions are presented in Table 5-5. It is observed that the neutron $^{10}\text{B}(n, \alpha)$ heating did not significantly change. Although spectrum shifted considerably, the total number of lower energy neutrons did not. As stated previously, the vanes are heavy absorbers, thus the total number of absorptions did not change.

Figure 5-15 presents the relative azimuthal distribution of the $^{10}\text{B}(n, \alpha)$ heating rate (obtained from ^{164}Dy activation presented in Figures 5-2 and 5-3) on the inside and outside surfaces of the vane. Presented also is an average heating rate distribution through the bulk material. Figure 5-16 presents the azimuthal distribution of the photon heating rate obtained from the TLD data. The data are not presented for surfaces because the photon heating will essentially be uniform through the vane thickness.

The total heating rate distribution as a function of azimuthal angle at the core midplane is presented in Figure 5-18. These data were obtained by multiplying the relative distributions presented in Figures 5-16 and 5-17 by the midplane heating rates of 0.5 watts/cc-mw for $^{10}\text{B}(n, \alpha)$ and 0.0968 watts/cc-mw for photons. These values were obtained from Table 5-2 and were the experimental values of the average heating times the experimentally obtained axial peak-to-average value of 1.45 (same for photons and neutrons). The total heating rate represents the sum of the neutron and photon heating. The neutron heating is the average of the surface values. Similar data can be obtained for the surfaces by taking the relative distributions presented in Figure 5-15, multiplying by 0.50 and adding these values to the photon heating presented in Figure 5-17.

From Figure 5-17 it is observed that the azimuthal distribution of the total heating is not a fixed percentage of the neutron heating, but varies significantly with angle. The photon heating varies from a minimum of approximately 12 percent of the neutron heating at the leading edge to 30 percent at an azimuthal angle of approximately 1.3 radians. Thus, to obtain an accurate azimuthal distribution one cannot add on an average photon value to the neutron heating.

Figure 5-18 presents the relative axial distribution of the total heating rate. As the neutron and photon heating have the same peak-to-average value, the distributions will be the same. This axial distribution was determined to be independent of azimuthal angle on the vane.

It is cautioned that these data and comparisons that have been presented are valid only for a vane angle of 115° and for the reactor considered. The distribution of heating and the total varies considerably with changes in drum angle of the vane.

From Table 5-2, it is observed that the calculated (n,α) heating decreased by a factor of 1.27 while the calculated ^{164}Dy activation on the surface increases by factors of 6 to 25 when effective absorption cross sections for the vane are used rather than infinitely dilute. The reason that the heating and ^{164}Dy activation do not change by equal amounts is attributed to the manner in which the EXTERMINATOR-2 code calculates the absorption rate in the vane mesh cells. The code uses the following equation to calculate the number of absorptions in a mesh cell volume:

$$\text{Absorptions/sec} = \sum_{i=1}^{16} \Sigma_i \bar{\phi}_i V \quad (5-11)$$

where

Σ_i = macroscopic absorption cross section, cm^{-1} , for neutron energy group i .

$\bar{\phi}_i$ = average of the fluxes at the four corners (surface) of the mesh cell, $\text{n/cm}^2\text{-sec}$, for neutron energy group i .

V = volume of mesh cell, cm^3 .

When compared to the results with dilute cross sections, the calculated surface fluxes increase when the smaller effective cross sections are used. It happens that the product of the larger surface fluxes and smaller cross sections, when effective cross sections are used, yields approximately the same number of absorptions as the smaller surface fluxes and larger cross sections for the dilute cross section calculations. The ^{164}Dy activation, however, is only sensitive to the surface flux calculations.

5.4 REFERENCES

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TABLE 5-1
EFFECTIVE AND INFINITELY DILUTE MACROSCOPIC
ABSORPTION CROSS SECTIONS FOR THE CONTROL VANE MATERIAL

NEUTRON ENERGY GROUP	LOWER ENERGY (eV)	Σ INFINITELY DILUTE (CM ⁻¹)	Σ EFFECTIVE (CM ⁻¹)
1	2.87 (6)*	1.03 (-2)	1.02 (-2)
2	1.35 (6)	1.46 (-2)	1.44 (-2)
3	8.21 (5)	1.91 (-2)	1.88 (-2)
4	3.88 (5)	2.59 (-2)	2.54 (-2)
5	1.11 (5)	4.34 (-2)	4.21 (-2)
6	1.50 (4)	1.01 (-1)	9.49 (-2)
7	5.53 (3)	2.06 (-1)	1.89 (-1)
8	5.83 (2)	4.79 (-1)	1.46 (-1)
9	78.9 (0)	1.33 (0)	8.54 (-1)
10	10.68 (0)	3.57 (0)	1.48 (0)
11	1.860 (0)	9.02 (0)	1.88 (0)
12	3.000 (-1)	2.20 (1)	1.97 (0)
13	1.20 (-1)	4.35 (1)	1.97 (0)
14	6.00 (-2)	6.40 (1)	1.97 (0)
15	2.00 (-2)	9.38 (1)	1.97 (0)
16	0.0	1.80 (2)	1.97 (0)

* Numbers in parentheses refer to powers of ten, i.e., 2.87 (6) $\equiv$ 2.87 $\times$ 10⁶.

TABLE 5-2
SUMMARY OF VANE HEATING RESULTS

TYPE	EXPERIMENT			CALCULATIONS ^{1/}			CALCULATIONS ^{2/}		
	<u>WATTS</u> CC-MW	<u>WATTS</u> GM-MW	^{3/} WATTS	<u>WATTS</u> CC-MW	<u>WATTS</u> GM-MW	^{3/} WATTS	<u>WATTS</u> CC-MW	<u>WATTS</u> GM-MW	^{3/} WATTS
Neutron, $^{10}\text{B}(n,\alpha)$	^{4/} 3.44(-1) $\pm 0.41(-1)$	4.82(-2)	2.55(6) $\pm 0.30(6)$	4.02(-1)	5.61(-2)	2.98(6)	5.12(-1)	7.17(-2)	3.79(6)
Photon	6.72(-2) $\pm 1.0 (-2)$	9.40(-3)	4.97(5) $\pm 0.75(5)$	4.10(-2)	5.74(-3)	3.03(5)	4.10(-2)	5.74(-3)	3.03(5)
TOTAL	4.01(-1) $\pm 0.41(-1)$	5.76(-2)	3.05(6) $\pm 0.30(6)$	4.43(-1)	6.18(-2)	3.28(6)	5.53(-1)	7.74(-2)	4.09(6)

^{1/} Use of Effective Absorption Cross Sections for Vane.

^{2/} Use of Infinitely Dilute Absorption Cross Sections for Vane.

^{3/} For 18 Vane System at 115° Drum Angle and 1515 MW Thermal. No Correction for Cold-to-Hot Swing.

^{4/} Uncertainties are Approximate Average of Reported Experimental Data.

NOTES: Numbers in Parentheses Refer to Powers of Ten, i.e., $3.44(-1) \equiv 3.44 \times 10^{-1}$.

WATTS/CC-MW and WATTS/GM-MW are Average Values.

TABLE 5-3

RATIO OF CALCULATED TO EXPERIMENTAL RESULTS OF THE VANE HEATING

TYPE	CALCULATIONS ^{1/}	CALCULATIONS ^{2/}
Neutron, $^{10}\text{B} (n, \alpha)$	1.17 $\frac{+0.16}{-0.13}$ ^{3/}	1.49 $\frac{+0.20}{-0.17}$
Photon	0.61 $\frac{+0.11}{-0.08}$	0.61 $\frac{+0.11}{-0.08}$
TOTAL	1.10 $\frac{+0.13}{-0.10}$	1.38 $\frac{+0.16}{-0.13}$

- ^{1/} Use of effective absorption cross sections.
^{2/} Use of infinitely dilute cross sections.
^{3/} Uncertainties obtained from experimental data.

TABLE 5-4

TABULATION OF DATA USED TO OBTAIN ^{10}B (n, α) VANE HEATING FROM ^{164}Dy EXPERIMENTAL DATA

Neutron Energy Group	Lower Energy of Group (ev)	$\sum_i$ (CM^{-1})	Self-Shielding Factor $f_{s,i}$	Average Surface Fluxes $\phi_{s,i}$ ($\text{n/cm}^2\text{-sec-w}$)	$\sum_i f_{s,i} \phi_{s,i}$	Heating Rate ($\frac{\text{Watts}}{\text{CC-MW (Power)}}$)
1	2.87 (6)	1.03 (-2)	9.99 (-1)	6.62 (3)	6.81 (1)	2.54 (-5)
2	1.35 (6)	1.46 (-2)	9.99 (-1)	2.63 (4)	3.84 (2)	1.43 (-4)
3	8.21 (5)	1.91 (-2)	9.99 (-1)	2.03 (4)	3.87 (2)	1.44 (-4)
4	3.88 (5)	2.59 (-2)	9.98 (-1)	3.58 (4)	9.25 (2)	3.45 (-4)
5	1.11 (5)	4.34 (-2)	9.97 (-1)	5.64 (4)	2.44 (3)	9.11 (-4)
6	1.50 (4)	1.01 (-1)	9.93 (-1)	8.66 (4)	8.69 (3)	3.24 (-3)
7	5.53 (3)	2.06 (-1)	9.86 (-1)	4.57 (4)	9.28 (3)	3.47 (-3)
8	583	4.79 (-1)	9.65 (-1)	1.03 (5)	4.76 (4)	1.78 (-2)
9	78.9	1.33 (0)	9.00 (-1)	8.45 (4)	1.01 (5)	3.77 (-2)
10	10.68	3.57 (0)	7.05 (-1)	7.01 (4)	1.76 (5)	6.57 (-2)
11	1.86	9.02 (0)	4.10 (-1)	4.65 (4)	1.72 (5)	6.42 (-2)
12	0.30	2.20 (1)	1.66 (-1)	3.78 (4)	1.38 (5)	5.15 (-2)
13	0.12	4.35 (1)	8.70 (-2)	2.07 (4)	7.83 (4)	2.93 (-2)
14	0.06	6.40 (1)	6.03 (-2)	2.06 (4)	7.95 (4)	2.97 (-2)
15	0.02	9.38 (1)	4.15 (-2)	2.21 (4)	8.60 (4)	3.21 (-2)
16	0.0	1.80 (2)	2.15 (-2)	5.72 (3)	2.21 (4)	8.25 (-3)
TOTAL					9.23 (5)	3.44 (-1)

NOTE: Numbers in parentheses refer to powers of ten, i.e., $1.03 (-2) \equiv 1.03 \times 10^{-2}$.

TABLE 5-5

ESTIMATED HEATING RATES IN CONTROL VANES
LOCATED AT 115° FOR 1515 MW OPERATING CONDITIONS

TYPE	RATIO OF FULL POWER TO AMBIENT HEATING RATES *	WATTS
Neutron ^{10}B (n, α)	1.02	2.60 (6) ± 0.30 (6)
Photon	0.835	4.16 (5) ± 0.62 (5)
TOTAL	0.984	3.00 (6) ± 0.30 (6)

* Ratio of calculated heating at 1515 MW thermal power operating conditions to heating at ambient temperature no hydrogen.

Figure 5-1. Calculation Flowchart for Vane Heating

Figure 5-2. Comparison of the Calculated and Experimental Azimuthal Distribution of the Saturated Activity of ^{164}Dy (Bare Wires) on the Inside Surface of the Vane near the Core Midplane.

Figure 5-3. Comparison of the Calculated and Experimental Azimuthal Distribution of the Saturated Activity of ^{164}Dy (Bare Wires) on the Outside Surface of the Vane near the Core Midplane.

Figure 5-4. The Ratio of the Calculated to Experimental Saturated Activity of the ^{164}Dy as a Function of Azimuthal Angle on the Inside Surface of the Vane near the Core Midplane

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Figure 5-5. The Ratio of the Calculated to Experimental Saturated Activity of ^{164}Dy as a Function of Azimuthal Angle on the Outside Surface of the Vane near the Core Midplane

Figure 5-6

Sketch of Typical Geometry Mockup of Part of the Vane in R- θ Code

Figure 5-7. Comparison of the Experimental (PAX-G1A) Radial Distribution of the Saturated Activity of ^{164}Dy (Bare Foils) at the Core Midplane with DOT (PAX-G1A) and EXTERMINATOR-2 (PAX-G2A) Distribution

Figure 5-8. Axial Distribution of the Saturated Activity of ^{164}Dy (Bare Wires) on the Leading and Trailing Edges of the Vane

Figure 5-9. Axial Distribution of the Saturated Activity of ^{164}Dy (Bare Foils) on the Outside Surface of the Vane 4.65 Degrees from the Leading Edge.

Figure 5-10. Comparison of the Calculated and Experimental Azimuthal Distribution of the ^6Li Absorption Rate on the Inside Surface of the Vane near the Core Midplane.

Figure 5-11. Comparison of the Calculated and Experimental Azimuthal Distribution of the ⁶Li Absorption Rate on the Outside Surface of the Vane near the Core Midplane.

Figure 5-12. The Ratio of the Calculated to Experimental ${}^6\text{Li}$ Absorption Rate as a Function of Azimuthal Angle on the Inside Surface of the Vane near the Core Midplane.

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Figure 5-13. The Ratio of the Calculated to Experimental ${}^6\text{Li}$ Absorption Rate as a Function of Azimuthal Angle on the Outside Surface of the Vane near the Core Midplane.

Figure 5-14. Azimuthal Distribution of the Gamma Kerma Rate for CaF_2 and ^7LiF on the Outside Surface of the Vane near the Core Midplane.

Figure 5-15. Axial Distribution of the Gamma Kerma Rate for ⁷LiF on the Leading and Trailing Edges of the Vane

Figure 5-16. Relative $^{10}\text{B}_{(n,\alpha)}$ Heating Rate Distribution as a Function of Azimuthal Angle on the Surfaces of the Vane

Figure 5-17. Relative Photon Heating Rate Distribution as a Function of Azimuthal Angle

Figure 5-18. Total Heating Rate Distribution of the Vane at the Core Midplane as a Function of Azimuthal Angle

Figure 5-19. Relative Axial Distribution of the Total Heating Rate

6.0 CONCLUSIONS

From the comparisons of the experimental and calculated data presented herein, the following conclusions are made:

- 1) The total experimental heating rate is 0.401 ± 0.041 watts/cc-mw* for an 18 vane system at ambient conditions and 115° drum angle. The ratio of the calculated to experimental total heating rates are 1.10 (+0.13/-0.10) and 1.38 (+0.16/-0.13) with and without effective absorption cross sections, respectively.
- 2) The experimentally derived ^{10}B (n, α) heating rate per cc of vane material, using ^{164}Dy saturated activity, is 0.344 ± 0.41 watts/cc-mw* for an 18 vane system at ambient conditions, and 115° drum angle. The ratio of the calculated to experimental total integral ^{10}B (n, α) heating rates are 1.17 (+0.16/-0.13) and 1.49 (+0.20/-0.17) with and without effective absorption cross sections, respectively.
- 3) The experimentally derived photon heating rate per cc of vane material is 0.0672 ± 0.010 watts/cc-mw for an 18 vane system at ambient conditions and 115° drum angle. The ratio of the calculated to experimental photon heating rate is 0.61 (+0.11/-0.08).
- 4) The use of effective absorption cross sections for the vane, rather than using the infinitely dilute cross sections used for fission distribution and drum worth predictions, greatly improves the comparison of the calculated and experimental ^{164}Dy saturated activity and ^6Li absorption rates on the surfaces of the vane. Using effective absorption cross sections, the calculated ^{164}Dy saturated activity on the surfaces of the vane are factors of 1.1 to 2.7 greater than the measured data. Similar differences are observed when the experimental ^6Li absorption rates are compared with experiment.

* Thermal power

- 5) The experimental ^7LiF photon Kerma rate for the G2A is a factor of 1.8 greater than the DOT (R,Z) reactor calculations for the similar G1A reactor as shown in Figure 5-14. The reason for the large difference is not totally understood, but is attributed in part to small differences in G1A and G2A reactors, neutron response of TLDs and difference in Rads (LiF) (experimental data) and Rads (Carbon) (calculated data).
- 6) The azimuthal distribution of the heating rate is significantly effected by the photon heating rate and is approximately 12 percent of the neutron heating at the leading edge and a maximum of 30 percent at an azimuthal angle of 1.3 radians.
- 7) The ratio of the calculated total heating at full power operating conditions with hydrogen to the ambient temperature - no hydrogen condition was estimated to be 0.984. This ratio for neutron heating was 1.02, while the photon heating ratio was 0.835.
- 8) From a comparison of the DOT (PAX-G1A) and EXTERMINATOR - 2 (PAX-G2A) calculated radial distribution of the saturated activity of ^{164}Dy at the core midplane with experiment (PAX-G1A), it is concluded that there may be a discrepancy in the ^{164}Dy cross sections and that examination of the ring prescription used to simulate the control vane should be made to determine if an improvement in the prediction of low energy neutron flux can be made.

The conclusions presented above are strictly valid only for the 115° drum position analyzed and must be used with caution for other vane angles.

The following recommendations are made to improve the prediction of the vane heating:

- 1) The use of a finer mesh in the EXTERMINATOR - 2 to mockup the geometry of the vane.

- 2) The improvement in the cross sections for the vane. These could be made by obtaining spectrally weighted cross sections for the vane by analyzing the vane in a simple geometry using 1) transport theory, 2) fine mesh in the vane, and 3) the Be reflector spectra.
- 3) The use of (R, θ) neutron and photon transport calculations performed with an (R, θ) DOT using fine mesh in the vane and improved spectrally weighted cross sections for the vane.
- 4) The improvement in the ^6Li data which would be a direct indication of the $1/v$ absorption of ^{10}B .
- 5) The conduction of experiments similar to those made at the 115° drum angle for other drum positions, e.g., 15, 30, 60, 90, and 145 degrees to determine the validity of calculational methods at various drum positions.

APPENDIX A

DY-AL FOIL CALIBRATION REPORT

Table A-1 presents the report on absolute activity of dysprosium-aluminum foils and wires which was used in the absolute calibration of the Dy-Al measurements.

TABLE A-1
DY-AL ACTIVITY CALIBRATION REPORT

CHEMICAL ANALYSIS REQUEST FORM 54740 A		WESTINGHOUSE ATOMIC POWER DIVISIONS ANALYTICAL SERVICE LABORATORIES WALTZ MILL SITE		ANAL. SERV. REQUEST NO. <div style="text-align: right; font-size: 1.2em;">1782</div>	
ORIGINATOR R Brawdy	DEPT. & GRP. WANEF	EXT. 5226	INITIATING DOCUMENT REFERENCES		DATE SUBMITTED 3-11-70
ROOM NO.	FACILITY				REQUESTED COMPLETION DATE 3-13-70
CHARGE NO.			IWR 59-RN-YD-M-08524		
ORIGINATOR'S SIGNATURE & DATE R Brawdy 3-11-70		AUTHORIZING SIGNATURE & DATE [Signature] 3-11-70		ACCEPTANCE SIGNATURE & DATE P. Blackburn 3-11-70	
ORIGINATOR'S SAMPLE NO.	ANAL. SERV. LAB NO.	ANALYSIS			
DY-AL WIRE #1	70-430	QUANTITATIVE FOR			
" " #2	" 431	QUALITATIVE FOR ABSOLUTE COUNT RATE @ T₀*			
DY-AL FOIL #1	" 432	APPROX. CONCENTRATION (S)			
" " #2	" 433	RESULTS IN UNITS OF ☐ Wt. % ☐ PPM ☐ Other (specify)			
		DISPOSITION OF SAMPLE ☐ Discard ☒ Return to Requestor ☐ Other (specify)		MATERIAL CLASSIFICATION ☒ Unclassified ☐ Confidential ☐ Secret	
SAMPLE DESCRIPTION					
APPROX. WT. AND/OR VOL.		ENRICHMENT			
MATERIAL FORM AND COMPOSITION, SPECIAL HANDLING, ETC. Wire = 10% Dy -030Y-5, Foil = 4% Dy -005A-25					
RADIOACTIVITY Content and Level 5 M.R./hr. @ contact 2X in					
PREVIOUS HISTORY (IRRADIATIONS, PHYSICAL TREATMENT, ETC., WHICH COULD INFLUENCE SAMPLE TREATMENT) 100 WT-HR IRRADIATION					
REMARKS * T₀ = 1432 H-05 3-11-70 (WANEF clock)					
ANALYTICAL SERVICE LABORATORY USE ONLY					
REMARKS:					

CAB.

Spec ☐	Gas ☐	Radio Chem. ☒	Chem ☐	Na ☐	Mass ☐	Pu ☐
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ANAL. SERV. REQUEST NO. <div style="font-size: 1.2em;">1782</div>	CHECK COPIES FOR LEGIBILITY <div style="text-align: right;">ORIGINATOR COPY</div>
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APPENDIX B
THE R-1 MOCKUP CONTROL VANE DOSIMETRY
EXPERIMENTAL PROCEDURE

In accordance with WANEF procedures*, an Experimental Details Checklist (EDC) was written to set forth the details of experimental procedures to be used in making the control vane dosimetry measurements in the PAX-G reactor as well as evaluating any nuclear hazards resulting from such an operation. Those portions of the experimental procedure applicable to the TME may be found in Parts 1 through 12 of the EXPERIMENTAL DETAILS section of EDC-76. The body of EDC-76 is contained in this appendix.

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

WANEF
EXPERIMENTAL DETAILS CHECKLIST*

No. 76

Date 4/22/69

TITLE OF EXPERIMENT: R-1 Mockup Control Vane Dosimetry

OBJECTIVES:

1. Measure the thermal neutron flux distribution across an R-1 mockup drum control vane with Dy-Al wires and foils with particular emphasis at the leading edge. The vane angle will be 115° for all three R-1 mockup drums.
2. Repeat Item 1 with the three R-1 mockup drums at 80° for comparison with previous measurements performed on the PAX NRX-A6 mockup.
3. Determine the feasibility of using Li^6F and Li^7F to measure (n, α) heating in the vane.

EQUIPMENT REQUIREMENTS:

1. The PAX-G reactor with the 60° R-1 mockup reflector in place.
2. R-1 mockup control vanes of CuB^{10} , or AlB^{10} if CuB^{10} are not available.
3. Counting room foils and instrumentation.

HAZARDS CONSIDERATIONS:

This experiment involves the removal and disassembly of an R-1 mockup control drum in order to affix detectors directly to the vane. The reactivity effect of these detectors will be negligible and undoubtedly, negative. Because the detectors are inside of the aluminum drum housing, even if they should come loose, they will be contained and the drum will not be prevented from rotating in. In any event, the Operating Limits permit the reactor to be operated with only 10 of the 12 PAX drums, providing that the minimum shutdown of \$3.40 is maintained. It is estimated that with one R-1 mockup drum stuck at its operating position of 115° , the shutdown will be around \$4.30. Thus, neither hazard nor violation would exist if the drum did jam. The procedure for removing and replacing a drum is covered in the Reactor Operations Manual, Section 5.4.2.2.3. Briefly, it requires adding 60¢ worth of poison wires before the drum is removed, making a reactivity check after the drum is replaced and removing the poison wires in increments no larger than 50¢.

The experiment will be carried out in accordance with SOP 5.2, Reactor Operating Procedures, and SOP 5.4, Manual Reactivity Change Procedures, as well as with the rules of paragraph 5.5.5 of the Reactor Operations Manual covering PAX Out-of-Reactor Experiments.

* For execution of T/S 59DW-269-0.

When the experiments are carried out in accordance with the rules and limitations stated in the above paragraphs of the Reactor Operations Manual, they do not introduce the possibility of an accident not analyzed in the Safety Report nor do they increase either the probability or the consequence of the accidents analyzed in the Safety Report.

EXPERIMENTAL DETAILS:

The procedure for performing this experiment will include the following sequence of steps:

1. Insert poison wires in the central channels of the elements given in Appendix A. These will be worth -61¢.
2. Remove R-1 mockup control drum number B and disassemble to remove vanes. A schematic of the R-1 sector is presented in Figure 1.
3. Load Dy-Al foils, wires and TLD's on vanes as given in Figures 2, 3, and 4.
4. Reassemble vane and control drum, and reinsert drum in reflector.
5. Check operation of the drum.
6. Run reactor to check reactivity, but do not exceed 10 watts reactor power on a period. If it is necessary to attain a delayed critical condition, do not exceed a power level of 1 watt.
7. Remove about 30¢ worth of wire and check reactivity, but do not exceed 10 watts reactor power on a period. If it is necessary to attain a delayed critical condition, do not exceed a power level of 1 watt.
8. Remove remainder of wires, check reactivity, and make foil irradiation at a reactor power of 200 watts for 1/2 hour with the three R-1 mockup control drums at 115°.
9. Repeat steps 1 and 2.
10. Unload Dy-Al foils, wires, and TLD's from the vane.
11. Repeat steps 4 through 7.
12. Remove remainder of poison wires and check reactivity.

When time and schedule*permit:

13. Repeat steps 1 through 12 for the three R-1 mockup drums at 80° with Dy-Al wires and foils only.

* Not required for NSS-PDR

DATA REQUIRED:

1. Bare and Cd-covered saturated activity per watt of power in the R-1 mockup sector of the Dy-Al detectors with estimate of accuracy.
2. Position of dosimeters on the vane.
3. Gamma dose rate in Rads(C)/Hr-watt of Li^7F TLD's vs. position on vane.
4. Li^6 Captures/Gm-Hr-watt vs. position on vane.
5. B^{10} Captures/Gm-Hr-watt vs. position on vane obtained from data presented in Item 4.
6. Relative Dy-Al foil activity vs. position for case of drums at 80° .
7. Photographs of detectors on foils and wires on the drum vane.
8. Details of detector calibration procedures.

WRITTEN BY: J. S. Frantz

Date 4/22/69

SCIENTIST-IN-CHARGE F. S. Frantz
F. S. Frantz, Manager, WANEF

Date 4/22/69

MANAGER, NUCLEAR AND RADIATION DESIGN W. P. Kovacic
W. P. Kovacic

Date 4/23/69

FIGURE 1
EXPERIMENTAL TEST GEOMETRY

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VIEW LOOKING FORWARD

- 1) Not to scale.
- 2) All dimensions in inches.
- 3) All foils 0.25 in. dia. x 0.005 in. thick Dy-Al
- 4) All foils near edges are placed with the center of the foils 0.125 in. from the vane edge

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- Bare foils.
- ◐ Cd-covered foils (on foil side away from vane only).
- Bare foils on outside surface of vane only.
- ⊗ Bare foils that are placed tangent to each other.
- ⊠ Cd-covered foils that are placed tangent to each other.

All locations shown depict foils on outside surface of vane and a corresponding location on inside surface except as noted above.

TOTAL NUMBER OF FOILS = 64 (36 Outside Surface; 28 Inside Surface).

Figure 2. Dy-Al Foil Location on the Vane of the PAX-R1 Mockup Drum Number B

- 1) All wires placed vertically along vane axis.
- 2) All wires bare.
- 3) All wires 0.030 in. diam. x 0.5 in. long Dy-Al
- 4) All dimensions in inches.
- 5) Not to scale.

- × Wires placed directly on the thin edges of the vane (denotes center of wire location).
- Wires placed at positions corresponding to center of foils placed directly above midplane.
- ⊥ Wire placed at vane ϕ .

□ 10 wires placed tangent to each other starting from the vane edge.

▨ 17 wires placed tangent to each other starting from the vane edge.

All locations except those denoted by x are placed on the outside surface of the vane and at a corresponding location on the inside surface.

TOTAL NUMBER OF WIRES = 85 (37 Inside Surface; 37 Outside Surface; 11 on Edges).

Figure 3. Dy-Al Wire Location on the Vane of the PAX-R1 Mockup Drum Number B

-

- de surface of the vane.
- TOTAL NUMBER OF DOSIMETERS = 127
Li ⁶ F : 42 outside surface; 42 inside surface; 11 on edge
Li ⁷ F : 21 outside surface; 11 on edge

B-8

APPENDIX

SHIPPING POISON WIRE CORE LOCATIONS FOR DRUM REMOVAL

000B	1A1B	2A1B	3A1B	4A1B	5A1B	6A1B
000C	1A1C	2A1C	3A1C	4A1C	5A1C	6A1C
000D	1A1D	2A1D	3A1D	4A1D	5A1D	6A1D
000E	1A1E	2A1E	3A1E	4A1E	5A1E	6A1E
000F	1A1F	2A1F	3A1F	4A1F	5A1F	6A1F
000G	1A1G	2A1G	3A1G	4A1G	5A1G	6A1G
1B1B	2B1B	3B1B	4B1B	5B1B	6B1B	
1B2B	2B2B	3B2B	4B2B	5B2B	6B2B	

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TITLE													
		Control Vane Heating Measurements													
DOCUMENT NO.		DATE													
WANL-TME-1913		August, 1970													
ABSTRACT															
<p>Radiation measurements were made on a Cu¹⁰B R-1 type control vane, (at a 115° drum angle), located in the test sector of the low power critical mockup of the R-1 reactor, PAX-G2A. Dosimeters used consisted of Dy-Al foils and wires and ⁶LiF, ⁷LiF and CaF₂ TLDs. Results were compared with analytical calculations based on the (R, θ) EXTERMINATOR-2 neutron diffusion code. Effective rather than dilute vane absorption cross sections yielded good agreement with the experimental results.</p>															
DATA ITEM NO.		SECURITY CLASSIFICATION OF DOCUMENT													
T-119		UNCLASSIFIED													
CDRL LINE NO.		TOTAL NO. OF PAGES													
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KEY WORDS															
<table border="0"> <tr> <td>Control Vane</td> <td>Heating Rate</td> </tr> <tr> <td>PAX-G2</td> <td>CuB Vane</td> </tr> <tr> <td>R-1 Reactor</td> <td></td> </tr> <tr> <td>Radiation Measurements</td> <td></td> </tr> <tr> <td>Neutron Flux Density</td> <td></td> </tr> <tr> <td>Gamma Dose Rate</td> <td></td> </tr> </table>				Control Vane	Heating Rate	PAX-G2	CuB Vane	R-1 Reactor		Radiation Measurements		Neutron Flux Density		Gamma Dose Rate	
Control Vane	Heating Rate														
PAX-G2	CuB Vane														
R-1 Reactor															
Radiation Measurements															
Neutron Flux Density															
Gamma Dose Rate															
AUTHOR/EDITOR		PREPARING DEPT.													
V. S. Oblock and W. D. Rankin		WANEF													
W Form 59943		DOCUMENT INFORMATION SUMMARY													

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