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REPORT NO. RP-TR-0007

MASTER

PHOEBUS-2 NOZZLE DEVELOPMENT
NUCLEAR ANALYSIS (U)

MAY 1966

CONTRACT SNPC-35

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Space Nuclear Propulsion Office
Cleveland Extension
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland, Ohio 44135

Attention: A. A. Medeiros

Subject: Phoebus-2 Nozzle Development Nuclear Analysis
Report No. RP-TR-0007 (U) dated May 1966,
Contract SNPC-35

Gentlemen:

In partial compliance with Tasks J and N of the subject contract, we are submitting as Enclosure (1) three (3) copies of the Phoebus-2 Nozzle Development Nuclear Analysis, Report No. RP-TR-0007 (U) dated May 1966. This analysis is a sequel to that described in AGC Report RP-SR-0001, Volume II.

Distribution is being made to the same personnel as that of the Phoebus-2 Nozzle Design Program, Preliminary Design Phase, Summary Report, RP-SR-0001 (U) dated August 1965, as shown by Enclosure (2).

Very truly yours,

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H. E. Pharr
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REPORT NO. RP-TR-0007

PHOEBUS-2 NOZZLE DEVELOPMENT
NUCLEAR ANALYSIS (U)

ROCKET ENGINE OPERATIONS - NUCLEAR

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ABSTRACT

This analysis is a sequel to that described in Aerojet Report No. RP-SR-0001 (Volume II). Updated nuclear heating rates are given for the modified configuration of the Phoebus-2 nozzle and a comparison is provided of the QAD-P5 point kernel predictions of gamma heating with Monte Carlo predictions as well as with measured data.

In addition, primary gamma heating rate data are provided for the LH_2 inlet line and manifold as well as along the divergent section of the nozzle.

This report was prepared by A. D. Wilcox, Physicist and K. O. Koebberling, Nuclear Engineer.

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FOREWORD

This topical report describes the radiation analysis performed early in the Preliminary Design Phase of the Phoebus-2 nozzle program. The objectives of this analysis during the Development Phase were to update and extend the Preliminary Design Phase work which was based on the point kernel method (Ref. 1) and to evaluate prediction accuracy by comparing point kernel method results with both Monte Carlo method results and experimental measurements.

During the Preliminary Design Phase detailed specifications were generated for the nuclear heating rate distributions within the jacket, interface flange, and skirt of several preliminary nozzle configurations. In addition, data were provided which define both the nozzle region radiation environment during full power operation and the neutron-induced activity in the reference nozzle as a function of time after a 20 minute full power firing.

The Preliminary Design Phase calculations were relatively complete with consideration given to the following contributors to nuclear heating:

1. Primary gammas from the reactor core after 20-minutes at full power;
2. Secondary gammas from the nozzle jacket, flange, and skirt;
3. Secondary gammas from the Al/H₂O side shield;
4. Secondary gammas from non-core components of the reactor;
5. Fast neutron elastic scattering;
6. Scattered gammas from the Al/H₂O side shield.

However, some design changes, relatively significant to nuclear heating, were adopted early in the development phase. The significant element of this design change consisted of an increase in nozzle skirt thickness from 0.4-in. to 0.6-in. Moreover, there were two aspects of the Preliminary Design Phase analysis that needed correction. The secondary gammas produced in the nozzle were based on an unperturbed distribution of neutrons, thus neglecting the beneficial effect of self-absorption in the nozzle. Also, the primary gamma source terms used in

the Preliminary Design Phase effort were 6% lower than those recently recommended by LASL (Ref. 2). Hence, there existed a need to complete a second iteration on prediction of nuclear heating.

Parallel with the Aerojet Preliminary Design Phase work were some gamma heating calculations performed by ACFI. These ACFI results were used during the Preliminary Design Phase thermal and stress analyses of the interface region for the Aerojet nozzle and the ACFI pressure vessel. All the Development Phase calculations were performed by Aerojet for use by both Aerojet and ACFI.

The overall uncertainty assigned to the Preliminary Design Phase predictions was +25% and -50%, which is additional to the conservatism associated with the use of unperturbed neutron distributions in predicting the nozzle secondary gammas. For a better understanding of these uncertainty factors, Monte Carlo calculations were performed for the heating rates caused by primary gammas. On the basis of this analysis, the point kernel results for primary gammas are believed to be high by about 2% in the high heating rate zones and by about 30% in the low heating rate zones.

This report consists of two separate parts. Part I describes the point kernel work that updates and extends the Preliminary Design Phase results. Part II describes the comparisons of point kernel predictions with both Monte Carlo results and with experimental data as obtained from the NRX-A2 and NRX-A3 tests. In addition, there are three appendixes that provide the following information:

- (1) Analytical description of the reference configuration,
- (2) Graphical displays of the energy and angular biases,
- (3) Additional primary gamma heating rate data.

PART I

RADIATION HEATING CALCULATIONS

I. INTRODUCTION TO PART I

Part I of this topical report provides nuclear heating rate data for use in temperature and stress analyses on the final design configuration of the Phoebus-2 pressure vessel/nozzle interface assembly. The original data used for the interface analysis are contained in an ACFI publication (Ref. 3). In addition to configuration changes, these new data reflect both a 16 percent increase in primary gamma source strength and the inclusion of heating rate contributions from secondary gamma rays. Moreover, these new data are based on 12-group calculations whereas the earlier work used a 9-group representation.

At a meeting held in Los Alamos (References 4 and 5) Aerojet agreed to provide nuclear heating data for use in temperature and stress analyses on the final design configuration. The analysis methods, models, and source terms used are given in this report along with the heating rate results at nominal values and at 25% above nominal values.

Nuclear heating analyses in support of the Phoebus-2 nozzle and pressure vessel design activities are performed by both Aerojet and ACFI. The preliminary nuclear heating analysis previously used by the Interface Task Force Group was principally an ACFI activity (Ref. 3). The Preliminary Design Phase nuclear heating analysis performed by Aerojet is reported in Reference 1 as summarized below.

A. SUMMARY OF PHASE I RADIATION HEATING ACTIVITY

The Preliminary Design Phase of the Phoebus-2 nozzle design study by Aerojet included calculation of the nuclear heating rates in both the nozzle and pressure vessel for use in temperature and stress analyses. In the course of this design study, a number of candidate configurations were considered. These include a flat-flange model with a 45° nozzle jacket and with both 0.4-in. and 0.6 in. skirt thicknesses; a canted flange model with 45° nozzle jacket and 0.6-in. skirt; and a series of flat flange models with 0.6-in. skirts having

nozzle jacket angles of 30°, 35°, and 40°. The heating rates from primary gammas for these configurations are reported in Reference 1.

The flat flange, 45° nozzle jacket model with a 0.4-in. skirt, as shown in Figure 1, was the selected reference design for the Preliminary Design Phase study. This figure was drawn by GECOP (Ref. 6), a computer program for plotting the configurations defined by the input coefficients for the QAD program. For this configuration the contributions to nuclear heating caused by nozzle secondaries, non-core reactor secondaries, clamshell secondaries, and fast neutrons were calculated and combined with the primary gamma heating rate to obtain the total nuclear heating rate. A detailed discussion of this activity and a tabulation of results are reported in Reference 1.

B. DEVELOPMENTS SINCE THE PHASE I STUDY

On the basis of the results from the Preliminary Design Phase study, the flat flange, 45° nozzle model but with the 0.6-in. skirt thickness (see Figure 2) was selected as the Development Phase Reference design model. As noted, only the primary gamma heating rates had been calculated for this model during the Aerojet Preliminary Design Phase effort.

Also, since the end of the Preliminary Design Phase study, the primary gamma source power has been reported to be 86 megawatts per 1000 megawatts of reactor power (Ref. 2). This corresponds to the gamma yield, including fission product decay gammas, after about 6 minutes of reactor operation at constant power. This new value represents a primary gamma source 6% greater than that used by Aerojet and 16% greater than that used by ACFI during the Preliminary Design Phase study.

The nozzle secondary gamma source terms used by Aerojet in the Preliminary Design Phase study were based on absorption of the unperturbed neutron flux. Further studies during the Development Phase with the TDC transport code, using a discrete representation of the nozzle, established the fact that the

Figure 1

Phobus-2, Preliminary Design Phase Reference Design Nozzle
(with a 0.4 in. thick skirt) (u)

Figure 2

Phoebus-2, Development Phase Reference Design Nozzle
(with a 0.6 in. thick skirt) (u)

Preliminary Design Phase nozzle secondary gamma source terms were excessive and should be reduced by 50%.

A meeting was held between Aerojet and LASL personnel during the Development Phase for discussion of the Phoebus-2 radiation heating calculations performed during the Preliminary Design Phase (References 4 and 5). The preliminary radiation heating rates used by the Interface Task Force Group during the Preliminary Design Phase were found to be low by as much as 25 to 35 percent depending on location. Moreover, these rates were restricted to primary gamma sources only. It was decided that new radiation heating rates should be calculated at the detector locations used by ACFI (Ref. 3) and at the detector locations used by Aerojet (Ref. 1). Both of these sets of calculations would be performed by Aerojet, using the best current inputs, including the current reference nozzle configuration. With respect to the Aerojet Preliminary Design Phase calculations (Ref. 1) this would include increasing the primary gamma source strength by 6% and decreasing the nozzle secondary source strength by 50%. These new total heating rates, as calculated and as increased by the uncertainty factor of 25%, would then be used in temperature and thermal stress calculations to represent both the nominal and the "worst case" conditions.

Subsequent to this meeting with LASL personnel, the QAD mathematical model was compared with the current nozzle layout drawing and found to agree well in all significant details.

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II. POINT KERNEL METHOD ANALYSIS

A. COMPUTER PROGRAMS

The TDC neutron transport computer program was used in determining the secondary source strength and its relative spatial distributions. The QAD-P5 point kernel radiation analysis program was used in computing the nuclear heating rates just as in the Preliminary Design Phase study.

B. ANALYTICAL MODEL

The current reference design of the nozzle differs from that used in the Preliminary Design Phase study principally in that the skirt thickness has been increased from 0.4-in. to 0.6-in. This model is shown in Figure 2 as drawn by the GECOP computer program (Ref. 4). The QAD geometrical description is included as Appendix A to this document.

C. SOURCE TERMS

The primary gamma source terms used are given in Table I (increased by the 6% discussed earlier). The primary gamma source distribution is unchanged from that used in the Preliminary Design Phase study. The axial distribution used is given in Figure 3 while the radial and azimuthal distributions were assumed to be flat. It is assumed that the 6% change in source strength results in negligible changes in its relative energy distribution.

The nozzle secondary source spectrum is included in Table I. This spectrum was obtained using the TDC transport code to determine the neutron absorption rates and distributions and by using the gamma yield per absorption from Reference 7. The secondary source spatial distribution, as shown in Figure 4, was input to QAD-P5 using the point source option.

Figure 3
Primary Gamma Source Axial Distribution (u)

TABLE I
Radiation Source Spectra

<u>Group No.</u>	<u>Group Energy Range (Mev)</u>	<u>Source Terms (Mev/sec)</u>		
		<u>Primary*</u>	<u>Nozzle Sec.</u>	<u>Interface Cyl. Sec.</u>
1	7.0 - 8.0	7.807×10^8	3.614×10^{18}	2.567×10^{19}
2	6.0 - 7.0	4.516×10^9	1.078×10^{18}	6.265×10^{18}
3	5.0 - 6.0	8.385×10^9	1.078×10^{18}	6.265×10^{18}
4	4.0 - 5.0	2.272×10^{10}	1.649×10^{18}	1.532×10^{19}
5	3.0 - 4.0	4.876×10^{10}	1.649×10^{18}	1.532×10^{19}
6	2.6 - 3.0	2.83×10^{10}	9.254×10^{17}	5.172×10^{17}
7	2.2 - 2.6	3.795×10^{10}	9.254×10^{17}	5.172×10^{17}
8	1.8 - 2.2	4.83×10^{10}	1.218×10^{18}	5.172×10^{17}
9	1.35 - 1.8	6.678×10^{10}	1.7×10^{18}	5.818×10^{17}
10	0.9 - 1.35	9.13×10^{10}	1.48×10^{18}	4.526×10^{17}
11	0.4 - 0.9	1.217×10^{11}	8.225×10^{16}	0.0
12	0.26 - 0.4	5.68×10^{10}	2.205×10^{17}	0.0

*Units for this column are (Mev/watt-sec)

NOTE: 1. POWER IN WATTS

2. THESE POINT SOURCES ARE INPUT WITH AZIMUTHAL ANGLES ϕ OF 22.5° , 67.5° , 112.5° AND 157.5° TO MAINTAIN A SEPARATION DISTANCE OF AT LEAST 10 CM FROM THE DETECTORS (INPUT AT $\phi = 0.0^\circ$)

Figure 4

Nozzle Secondary Gamma Source Distribution

The interface cylinder secondary gamma spatial distribution and spectrum were obtained in the same manner as the nozzle secondaries: i.e., using the TDC transport code and the gamma yield data from Reference 7. The source terms are included in Table I and the axial and radial source distributions are given in Figures 5 and 6.

The fast neutron heating rates were obtained with the QAD-P5 program using moments method data. A more accurate value could be obtained with the use of the neutron transport code; but since the fast neutrons contribute only about 1% to 5% of the total heating rate, use of a more complex routine could not be justified.

These represent all the secondary sources considered in heating rates calculated for the ACF detector locations. It was possible, for the Aerojet detector locations, to use heating rate data obtained during the Phase I study with suitable adjustments. This, in effect, considered several additional but small sources of nuclear heating such as the clamshell secondaries and other minor secondaries from non-core components of the reactor.

D. DETECTOR LOCATIONS

The detector locations used are unchanged from Figure 6, Reference 3, and from Table 12, Reference 1. The Figure 6, Reference 3, data were originally calculated by ACFI and the Table 12, Reference 1, data by AGC during the Preliminary Design Phase. The calculations reported herein use both of these sets of detector locations. The detector locations are given with the data in Table II and II-A. They are shown in Figure 7, for the detectors originally specified in Table 12, Reference 1; and in Table II and Figure 8 for the detectors initially designated in Figure 6, Reference 3.

E. CALCULATIONS

The basic heating rate calculations for the Development Phase reference model appeared in the Preliminary Design Phase report for those detector locations

Figure 5

Interface Cylinder Secondary Source Axial Distribution

Figure 6

Interface Cylinder Secondary Gamma Source Radial Distribution

Figure 7

Detector Locations in Table II

Figure 8

Detector Locations in Table III

TABLE II

Total Radiation Heating in the Reference Design Nozzle
(Aerojet Detector Locations)

(Flat Flange, 0.6 in. Skirt, 45° Nozzle)*

<u>Detector Number</u>	<u>Detector R (in.)</u>	<u>Location Z (in.)</u>	<u>Nominal Heating Rate (Btu/in.³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in.³-sec)</u>
1	30.0	15.0	0.6659	0.8323
2	30.18	15.0	0.5976	0.7470
3	30.45	15.0	0.5385	0.6731
4	30.0	12.0	0.6826	0.8532
5	30.18	12.0	0.5425	0.6781
6	30.45	12.0	0.3958	0.4948
7	30.0	9.0	0.6031	0.7538
8	30.18	9.0	0.4744	0.5930
9	30.45	9.0	0.3434	0.4293
10	30.0	6.0	0.5812	0.7265
11	30.18	6.0	0.4577	0.5721
12	30.45	6.0	0.3319	0.4148
13	30.0	3.0	0.5658	0.7073
14	30.18	3.0	0.4428	0.5535
15	30.45	3.0	0.3209	0.4011
16	30.0	0.0	0.4425	0.5531
17	30.18	0.0	0.3984	0.4980
18**	30.45	0.0	0.2886	0.3608
30	31.15	-0.01	0.2393	0.2991
31	31.70	-0.01	0.1894	0.2367
32	32.37	-0.01	0.1619	0.2023
33	33.0	-0.01	0.1468	0.1835

* These detector locations were initially specified in Table 12, Reference 2.

** Detectors 19 thru 29 are located in the aluminum pressure vessel and are included in Table II-A.

TABLE II (cont.)

<u>Detector Number</u>	<u>Detector R (in.)</u>	<u>Location Z (in.)</u>	<u>Nominal Heating Rate (Btu/in.³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in.³-sec)</u>
34	33.62	-0.01	0.1336	0.1670
35	34.05	-0.01	0.1136	0.1420
36	34.45	-0.01	0.1084	0.1355
37	30.6	-0.62	0.2365	0.2956
38	31.15	-0.62	0.1596	0.1995
39	31.70	-0.62	0.1205	0.1506
40	32.37	-0.62	0.0957	0.1196
41	32.96	-0.62	0.0854	0.1067
42	33.62	-0.62	0.0771	0.0963
43	34.05	-0.62	0.0715	0.0894
44	34.45	-0.62	0.0665	0.0831
45	29.6	-1.18	0.5587	0.6984
46	30.0	-1.25	0.3544	0.4430
47	30.5	-1.30	0.1969	0.2461
48	31.1	-1.28	0.1119	0.1399
49	31.7	-1.25	0.0823	0.1028
50	32.37	-1.18	0.0651	0.0814
51	32.95	-1.13	0.0585	0.0731
52	33.5	-1.10	0.0553	0.0691
53	29.4	-1.65	0.5685	0.7231
54	29.75	-1.78	0.3878	0.4848
55	30.18	-1.95	0.2341	0.2926
56	30.65	-1.95	0.1458	0.1823
57	29.15	-2.12	0.5914	0.7393
58	29.45	-2.35	0.3665	0.4581
59	29.75	-2.60	0.2708	0.3385
60	29.95	-2.72	0.2171	0.2713

TABLE II (cont.)

<u>Detector Number</u>	<u>Detector R (in.)</u>	<u>Location Z (in.)</u>	<u>Nominal Heating Rate (Btu/in.³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in.³-sec)</u>
61	28.8	-2.78	0.5757	0.7196
62	29.0	-3.0	0.4254	0.5317
63	29.3	-3.28	0.2886	0.3608
64	26.6	-5.0	0.6680	0.8350
65	26.83	-5.2	0.4787	0.5983
66	27.15	-5.5	0.3304	0.4130
67	23.62	-8.0	0.6891	0.8614
68	23.82	-8.25	0.4372	0.5460
69	24.02	-8.50	0.3682	0.4602
70	20.59	-11.0	0.6996	0.8745
71	20.83	-11.2	0.5062	0.6327
72	21.06	-11.4	0.3815	0.4769
73	17.56	-14.0	0.6710	0.8387
74	17.75	-14.2	0.5257	0.6571
75	17.95	-14.4	0.4029	0.5036
76	14.6	-17.0	0.6586	0.8232
77	14.76	-17.2	0.5065	0.6331
78	14.92	-17.4	0.4001	0.5001
79	11.55	-20.0	0.6387	0.7984
80	11.69	-20.16	0.5396	0.6745
81	11.85	-20.32	0.4313	0.5391

in Table II, i.e., in the nozzle itself. Thus, to obtain the updated heating rates at these locations, the primary gamma heating rates from Table 12, Reference 1, were increased by 6%. These were then combined with the heating rates caused by the nozzle secondaries as decreased by 50%, the non-core reactor secondaries, the fast neutrons and the clamshell secondaries as obtained from Table 12, Reference 1.

The heating rates for those detectors in Table 12, Reference 1, located in the aluminum pressure vessel were obtained by calculating new data for interface cylinder secondaries and the nozzle secondaries. These heating rates were then combined with the fast neutron heating rates from the original QAD calculations and with the primary heating rates from Table 12, Reference 1, as increased by 6%. The total values are given in Table II-A.

The heating rates for the detector locations from Figure 6, Reference 3, were all new data calculated for this effort. These data included the contributions from nozzle secondaries, interface cylinder secondaries, and fast neutrons as well as from core primaries.

TABLE II-A

Total Radiation Heating in Aluminum Pressure Vessel
(Aerojet Detector Locations)

(Flat Flange, 0.6 in. Skirt, 45° Nozzle)*

<u>Detector Number</u>	<u>Detector Location R (in.) Z (in.)</u>	<u>Nominal Heating₃ Rate (Btu/in.-sec)</u>	<u>1.25 x Nominal Heating₃ Rate (Btu/in.-sec)</u>
19	33.4 2.45	0.0963	0.1204
20	32.48 1.7	0.0972	0.1215
21	34.15 1.7	0.0698	0.0873
22	31.75 1.2	0.1001	0.1251
23	31.95 1.07	0.0914	0.1143
24	32.2 1.0	0.0849	0.1061
25	33.32 0.95	0.0679	0.0849
26	33.05 0.7	0.0670	0.0838
27	31.15 0.4	0.0963	0.1204
28	31.95 0.35	0.0750	0.0938
29	32.8 0.33	0.0633	0.0791

*These detector locations were initially specified in Table 12, Reference 2.

III. RESULTS

A. HEATING RATE TABLES

The heating rates at those detector locations used in Table 12, Reference 1, are given in detail in Table II. Because these numbers were obtained in two different ways, they are separated with the heating rates at the detector locations in the nozzle. being in the main body of the Table and the heating rates at detector locations in the aluminum pressure vessel contained in its supplement, Table II-A.

The new heating rates of those detector locations from Figure 6, Reference 3, are given in Table III.

B. RESIDUAL DIFFERENCES IN TABULATED DATA

The total heating rates in Table II include several small sources of secondary gammas not included in Table II-A and in Table III. The contributions from these sources are generally negligible with respect to the total heating rate. The clamshell secondaries, for example, contribute about 0.2% at most nozzle locations. This contribution increases to 6% in outboard locations of the nozzle in the vicinity of detectors 35 and 43 and where the total heating rate is relatively low.

The non-core reactor secondaries, additional to the interface cylinder secondaries, are the unfueled core tip secondaries, the graphite cookie secondaries, and the reflector secondaries. These contribute about 0.5% to the total nozzle heating with extreme values in the range of 1%.

TABLE III

Total Radiation Heating in the Reference Design Nozzle
(ACFI Detector Locations)

(Flat Flange, 0.6 in. Skirt, 45° Nozzle)*

Detector Number	Detector Location R (cm.) Z (cm.)		Nominal Heating ₃ Rate (Btu/in -sec)	1.25 x Nominal Heating ₃ Rate (Btu/in -sec)
1	100.8	135.2	.0953	.1191
2	101.1	135.2	.0911	.1139
3	101.4	135.1	.0865	.1081
4	102.4	135.1	.0746	.0933
5	100.3	141.3	.1143	.1429
6	100.5	141.3	.1111	.1389
7	100.9	141.4	.1050	.1313
8	101.8	141.5	.0919	.1149
9	99.1	146.2	.1186	.1483
10	99.4	146.2	.1140	.1425
11	99.7	146.3	.1090	.1363
12	100.8	146.6	.0930	.1163
13	97.5	150.8	.1139	.1424
14	97.7	150.9	.1104	.1380
15	98.1	151.0	.1046	.1308
16	99.1	151.4	.0905	.1131
17**				
18	95.4	155.5	.1046	.1308
19	95.8	155.8	.0978	.1223
20	96.8	156.2	.0858	.1073
21	92.6	159.5	.1009	.1261
22	92.8	159.6	.0984	.1230
23	93.2	159.6	.0948	.1185
24	94.3	160.7	.0784	.0980
25	89.5	163.3	.0976	.1220
26	89.7	163.5	.0943	.1179

* These detector locations were initially specified in Table 6, Reference 1.

** These points were not included in the original ACF data.

TABLE III (cont.)

<u>Detector Number</u>	<u>Detector R (cm.)</u>	<u>Location Z (cm.)</u>	<u>Nominal Heating₃Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating₃Rate (Btu/in³-sec)</u>
27	90.1	163.8	.0886	.1108
28	91.2	164.7	.0751	.0939
29	85.3	167.2	.0974	.1218
30	85.5	167.4	.0937	.1171
31	86.0	167.8	.0865	.1081
32	87.2	169.0	.0712	.0890
33	82.5	169.3	.1005	.1256
34	82.7	169.5	.0961	.1201
35	83.3	170.0	.0860	.1075
36	84.6	171.0	.0712	.0890
37	81.1	170.1	.1020	.1275
38	81.5	170.4	.0975	.1219
39	82.4	170.4	.0889	.1111
40	84.1	171.6	.0696	.0870
41	79.7	171.4	.1006	.1258
42	80.3	171.7	.0931	.1164
43	81.5	171.8	.0827	.1034
44	83.6	172.3	.0675	.0844
45	79.1	173.3	.0948	.1185
46	79.9	173.2	.0829	.1036
47	81.3	173.2	.0725	.0906
48	83.6	173.3	.0593	.0741
49	86.6	173.3	.1355	.1694
50	76.8	168.5	.4971	.6214
51	76.7	174.2	.3755	.4694
52	79.1	174.3	.2117	.2646
53	79.7	174.2	.1890	.2363
54	81.4	174.3	.1445	.1806
55	83.7	174.3	.1218	.1522

TABLE III (cont.)

<u>Detector Number</u>	<u>Detector R (cm.)</u>	<u>Location Z (cm.)</u>	<u>Nominal Heating₃ Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating₃ Rate (Btu/in³-sec)</u>
56	86.7	174.3	.0802	.1003
57	76.5	175.5	.3759	.4699
58	78.3	175.4	.1826	.2282
59	79.1	175.5	.1527	.1909
60	79.9	175.4	.1305	.1631
61	81.3	175.4	.1020	.1275
62	83.8	175.5	.0783	.0979
63	86.6	175.6	.0618	.0773
64	76.2	176.9	.3696	.4620
65	78.2	177.0	.1432	.1790
66	79.1	177.0	.1070	.1338
67	79.8	177.0	.0910	.1138
68	81.4	177.0	.0664	.0830
69	83.8	177.0	.0493	.0616
70	76.0	178.2	.3256	.4070
71	78.2	178.2	.1270	.1588
72	79.1	178.2	.0908	.1135
73	79.8	178.2	.0737	.0921
74	81.3	178.2	.0520	.0650
75	75.7	179.2	.3207	.4009
76	78.2	179.2	.1146	.1433
77	79.1	179.2	.0812	.1015
78**				
79	71.5	183.8	.4709	.5886
80	66.6	188.6	.5051	.6314

** These points were not included in the original ACF data.

PART II

EVALUATION OF ACCURACY

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IV. INTRODUCTION TO PART II

Part II of this topical report describes an accuracy evaluation of the QAD-P5 point kernel method which was the principal analysis method used in Part I. This accuracy evaluation is based on comparisons with Monte Carlo method predictions as well as with measured data from the recent NRX-A2 and NRX-A3 tests.

The Monte Carlo calculations were performed for primary gammas only since these constitute about 80% of the total heating. The comparisons with measured data included both gamma rays and neutrons. These comparisons were made with data taken at the meridian and equatorial rings about the reactor rather than in the vicinity of the nozzle-pressure vessel interface region. Suitable data at the interface region were not available. However, the meridian and equatorial ring data did provide a general measure of the accuracy that can be expected from the analysis methods used in Part I of this report.

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V. MONTE CARLO ANALYSIS

A. GAMMA RAY DATA FOR USE WITH FMC-G

A limited study was conducted to determine applicability of certain gamma ray data for use in the Monte Carlo code FMC-G (Ref. 8). The data in question were generated by the authors of FMC and are presented in Ref. 8 as part of a sample problem. Since the data were generated primarily to illustrate use of the code, apparently little or no concern was given to ascertaining their validity in solving actual problems. This is evidenced by the fact that the tabulated pair production cross-sections of lead are obviously fictitious, thus casting doubt on the remaining gamma ray data in the above report.

In the present study, particular scrutiny was given to the data on the scattering angular distributions and the cross-sections. A new set of angular distribution data has been generated and was used in this analysis.

1. Gamma Ray Scattering Angular Distribution

In FMC-G, the scattering angle of a photon on collision is determined from the Klein-Nishina scattering distribution. Input data are in the form of probability tables, each uniquely associated with a gamma energy group. If the energy group bounds are selected so that they are spaced sufficiently close, a simple numerical average (over an energy group) should yield an adequate description of the gamma scattering process for that group. In any case, whatever weighting scheme is employed, an angular distribution data set should result which is bracketed by the distributions evaluated at the energy group bounds. This, apparently, is not the case for most of the angular distribution data of Reference 8, which are hereafter denoted as Data 1.

A complete set of angular distribution data was therefore generated and the results are presented in Table IV. These data are hereafter denoted as Data 2. Program 20-4 was used to average the raw data over each energy group with no weighting factor. The point values (in energy and angle) of the angular distributions were taken

TABLE IV

Gamma Scattering Distribution

(For a given energy group, a tabulated value is probability of scattering at corresponding μ or less)

	<u>Energy Group</u>							
μ	.1 - .15 Mev	.15 - .2 Mev	.2 - .3 Mev	.3 - .4 Mev	.4 - .5 Mev	.5 - .6 Mev	.6 - .8 Mev	.8 - 1 Mev
- 1	0	0	0	0	0	0	0	0
-.906	.04762	.04354	.03833	.03301	.02092	.02787	.02659	.02407
-.643	.1663	.1536	.1377	.1202	.1070	.1037	.09982	.09169
-.259	.3132	.2931	.2686	.2388	.2159	.2123	.2080	.1948
.259	.5081	.4843	.4543	.4353	.4268	.4050	.3785	.3617
.643	.7048	.6842	.6588	.6443	.6379	.6113	.5793	.5596
.906	.9069	.8985	.8880	.8799	.8741	.8605	.8432	.8288
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

	<u>Energy Group</u>							
μ	1 - 1.5 Mev	1.5 - 2 Mev	2 - 3 Mev	3 - 4 Mev	4 - 5 Mev	5 - 6 Mev	6 - 8 Mev	8 - 10 Mev
- 1	0	0	0	0	0	0	0	0
-.906	.02160	.01916	.01705	.01526	.01422	.01354	.01263	.01170
-.643	.08332	.07532	.06770	.06109	.05694	.05414	.05089	.04753
-.259	.1799	.1661	.1517	.1393	.1305	.1237	.1172	.1106
.259	.3411	.3222	.3006	.2814	.2672	.2553	.2445	.2325
.643	.5343	.5091	.4831	.4587	.4395	.4242	.4091	.3918
.906	.8083	.7853	.7588	.7318	.7106	.6927	.6724	.6498
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

from Reference 9. Significant differences were found between Data 1 and Data 2, especially below 3 Mev. In this energy domain, the probability for scattering into the angular increment $0^\circ - 25^\circ$ as obtained from Data 1 is as high as much as a factor of 1.25 relative to the corresponding probability obtained from Data 2. The nature of this difference is such that deeper gamma ray penetration would result with the use of Data 1 than would result with the use of Data 2.

A typical contrast between Data 1 and Data 2 is shown in Figure 9. Also drawn in Figure 9 are the values reported in Reference 10. One should place more confidence on the data of Reference 10 than on Data 1 inasmuch as the former is given in a report devoted to a compilation of gamma ray data. A complete comparison of Data 2, as generated by Aerojet, with those tabulated in Reference 10 cannot be made because of differences in the energy group structure. However, where a direct comparison can be made, almost perfect agreement is noted. It is therefore recommended that the values given in Table IV be used in future calculations for which the group structure indicated is acceptable.

2. Adjusted Cross Sections

The tabulated cross-sections in Reference 8, with the exception noted in the introduction, are the actual values at the energy group bounds. (FMC approximates the cross-section at intermediate energy points by connecting straight lines between the values at the group bounds). With such a representation it is reasonable to suspect that if the cross-section for an important event varied with strong nonlinearities then a significant error may result in calculations involving deep penetrations (depth of ~ 3 mfp).

The photoelectric cross-section for lead varies between the functions E^{-3} at 0.1 Mev to E^{-1} at 10 Mev. Since the energy variation is such that its curvature is uniformly concave upward, the selection of the actual values at the group energy bounds results, except at a finite number of points, in an overestimate of cross-section,

Angular Scattering Distribution for Energy Group 0.2 - 0.3 Mev

and hence an underestimate of penetration. Because the total cross-section enters into the argument of an exponential, a given error in total cross-section magnifies the error in the calculation of gamma penetration. A suitable averaging procedure for the selection of cross-section for Monte Carlo calculation is described in Reference 11. In this method the cross-sections at the group bounds are adjusted so that the area under the actual cross-section curve is equal to that of the straight line connection between the adjusted values. The shape of the actual curve is approximated by requiring the straight line to pass through the average cross-section values for each half of the energy group in question. The effects of the photoelectric cross-sections as determined by the two methods are shown in some of the results described in the next section.

3. Point Source Calculations

To study the effects of changes in angular distributions and cross-sections, the problem of a point isotropic source in separate, infinite media of water and lead was considered. Flux at a point was approximated by the flux within spherical shells of less than 0.1 cm thickness which surround the source. A source of 1000 particles at 3 Mev was processed for each problem run, requiring less than 2-1/2 minutes of IBM 7094 computing time per run.

The effects on energy flux* caused by changes in angular distribution are shown in Figure 10 for a water medium. Also plotted in Figure 10 for comparison are the moments method results of Goldstein (Ref. 12). As expected, the Data 1 angular distributions, in general, yielded fluxes that are higher than those of Data 2. A comparison of the total Monte Carlo flux (uncollided plus scattered) is shown in Figure 11. It is to be noted that the uncollided component does not include the effects of angular distribution and that the observed contrast in total flux reflects, among others, the statistical error inherent in the uncollided flux.

*The energy flux is not an actual output of FMC-G. An examination of the energy flux of Reference 12, however, shows that the mid-point energy of the group bounds is very close to the average energy for the problems under study. The error introduced by assuming the group energy flux to be given by the product of group number flux and group mid-point energy should therefore be insignificant compared to statistical errors.

Figure 10
Scattered Energy Flux in Water

Figure 11

Total Energy Flux in Water

In the initial calculation for a lead medium, the table of photoelectric cross-sections was represented by the actual values at the energy group bounds. The resulting fluxes are unduly low when compared to Goldstein's data. Subsequent calculations therefore were performed with the adjusted cross-section following the scheme of Reference 11. A considerably improved comparison with Goldstein's data was obtained with these new cross-sections.

The flux calculations for lead are summarized in Figures 12 and 13. Again, the Data 1 angular distribution, in general, resulted in higher fluxes. The unusual result at 4 mfp on Figure 13 is a statistical manifestation, caused by an overestimate of the uncollided Monte Carlo flux. Note in these figures the effect of changes in the photoelectric cross-section.

The deviations of the Monte Carlo flux values relative to the moments method data are tabulated below for the two sets of angular distributions considered:

DATA 1 Results

	H_2O			Pb		
	$\mu r=1$	$\mu r=2$	$\mu r=4$	$\mu r=1$	$\mu r=2$	$\mu r=4$
Total Flux	+3.7%	+22.5%	+18%	+1.8%	+7.5%	+6.2%
Scattered Flux	+1.9%	+0.09%	+27%	+5.2%	+5.1%	+4.5%

DATA 2 Results

	H_2O			Pb		
	$\mu r=1$	$\mu r=2$	$\mu r=4$	$\mu r=1$	$\mu r=2$	$\mu r=4$
Total Flux	-2.8%	-3.1%	-7.1%	-0.06%	+3.6%	+9.0%
Scattered Flux	+4.2%	-7.3%	-9.9%	-14%	-2.8%	-7.7%

* The energy flux is not an actual output of FMC-G. An examination of the energy flux of Reference 12, however, shows that the mid-point energy of the group bounds is very close to the average energy for the problems under study. The error introduced by assuming the group energy flux to be given by the product of group number flux and group mid-point energy should therefore be insignificant compared to statistical errors.

Figure 12

Scattered Energy Flux in Lead

Figure 13

Total Energy Flux in Lead

Except for Pb at $\mu_r=1$, the Data 2 results are within 10% of the moments method results. The overall comparison appears to favor the use of Data 2 angular distributions, but admittedly not by a conclusive margin; the statistical uncertainties could explain the deviations of either result relative to the moments method result. Nevertheless, since definite errors exist in Data 1, and since the use of the proper angular distributions assumes greater importance in actual problems where spherical symmetry rarely exists, the use of Data 2 distributions instead of Data 1 is recommended.

The energy distributions as obtained with use of Data 2 are compared with moments method results in Figures 14 and 15 for water and lead, respectively. General spectral shapes are predicted but clearly, if accurate details are sought, statistical errors must be reduced either by processing a larger number of particles or by resorting to some variance reduction techniques.

B. FMC-G BIASING TECHNIQUES

Because of the large amount of machine time required to generate good statistics in a "brute force" Monte Carlo calculation of the Phoebus-2 nozzle heating rates, it is necessary to consider several biasing techniques to obtain reliable data with a reasonable expenditure of computer dollars. Because of schedule limitations, biasing methods for only the source regions were considered.

1. Discussion

During the Preliminary Design Phase of the Phoebus-2 nozzle study, it was found that the probability for a particle originating more than two mean free paths from the nozzle end of the core to react in the nozzle was very small. Neglecting these contributions would have no significant effect on results but would represent a significant savings in machine running time. By dividing the Phoebus-2 core into five axial regions, each approximately one mean free path in length, one is able to limit consideration to only the first two regions of the core. At the same time, a radial division of the core into four increments in order to keep the thickness of each region less than a mean free path results in a twenty region core as shown in Figure 16. Keeping region thicknesses at about one mean free path avoids some difficulties inherent in the FMC-G code.

Figure 14

Energy Spectrum of Scattered Flux in Water

Figure 15

Energy Spectrum of Scattered Flux in Lead

Figure 16

Computer Plot of the FMC-G Model (45° - Nozzle) (u)

By considering the spatial distribution of the gamma source in the core, one can arrive at the number of particles born in each core region. Table V gives this information based on a total of 1×10^5 particles. Also given is the position-biased source where we now consider only 26% of the total source. This represents a 74% reduction in running time with equivalent statistical validity in results.

From the Preliminary Design Phase and the Development Phase studies it was found that particles with initial energies below certain values, which vary with the source position, and particles with initial velocities directed away from the nozzle have negligible probabilities for reacting in the nozzle. Based on this information, cutoff values for both energy and direction were selected in each core region. Table VI gives the selected values.

As a check on the selected cut-off values, a series of runs was made with 1000 particles from each of the eight remaining core regions. Figures B-1 through B-16 of Appendix B depict the results of these runs as histograms. Shown on each figure is its selected cutoff value. As can be seen, these cut-off values are appropriate for all but one case (Figure B-13). However, the deviation shown is a low probability event.

Using the data from Table VI for the initial axial angles, and considering an isotropic source, one can readily compute that 50% of the particles will start in the range 90° - 180° and 62.94% in the range 75° - 180° . Applying these factors one arrives at the number of particles from each source region as given in Table V for inclusion of direction biasing.

These calculations are based on 62.94 photons per watt-second in the energy band 0-8 Mev. Figure B-17 depicts this source spectrum in accumulative photons as a function of energy. By reading the number of photons per watt-second corresponding to an energy cut-off value and dividing by 62.94 photons per watt-second one is able to arrive at that fraction of the source that can be neglected. Application of these fractions to the core regions yield the last column of data in Table V. Accumulative probability tables can then be computed for the different cutoff energies and these are shown in Figure B-18.

TABLE V

Number of Particles from the Various Core Regions
(After Inclusion of Several Biasing Techniques)

<u>Core Region</u>	<u>Particles in Each Region per 10⁵ Total Particles</u>	<u>Consideration of First 2 Mean Free Paths only</u>	<u>Inclusion of Direction Biasing</u>	<u>Inclusion of Energy Biasing</u>
1	400			
2	480			
3	640			
4	400	400	200	115
5	140	140	88	51
6	3,200			
7	3,860			
8	5,100			
9	3,160	3,160	1,580	1,040
10	1,120	1,120	705	613
11	6,420			
12	7,740			
13	10,200			
14	6,320	6,320	3,160	2,387
15	2,240	2,240	937	814
16	9,480			
17	11,420			
18	15,060			
19	9,320	9,320	4,660	3,520
20	3,300	3,300	1,650	1,435
TOTAL	<u>100,000</u>	<u>26,000</u>	<u>12,980</u>	<u>9,975</u>

TABLE VI

Energy and Angle Biases Selected for Gamma Sources

<u>Region</u>	<u>Starting Axial Angle Range*</u>	<u>Cut-off Energy</u> (Mev)
4	90° - 180°	0.4
5	75° - 180°	0.1
9	90° - 180°	0.3
10	75° - 180°	0.1
14	90° - 180°	0.2
15	75° - 180°	0.1
19	90° - 180°	0.2
20	90° - 180°	0.1

* 0° is in the forward direction

2. Results

The biasing techniques considered here have resulted in better than a factor of ten reduction in machine running time relative to the "brute force" technique. Thus for comparable cost, a far greater number of histories can be considered in order to arrive at statistically adequate nozzle heating rate results. These calculations have been performed and are reported in the following section.

C. FMC-G RESULTS

Using the biasing techniques described in the previous section, a total of 2×10^6 equivalent histories were examined with the FMC-G code in order to obtain the primary gamma heating rates in the Phoebus-2 nozzle.

1. Discussion

The nozzle was divided into three subassemblies: the skirt, the flange, and the jacket. In order to keep the thickness of a zone less than a mean free path and to remove any surface-region ambiguity, it was considered necessary to divide each subassembly into several regions. Figure 17 depicts the geometry of the nozzle with the location of the various regions as shown.

FMC-G calculates the heating in these regions for a specified number of histories in units of Mev. It is necessary to scale these values to full power and then convert to the desired units, using Equation (1).

$$HR_{ACT} = \frac{HR_{FMC-G} PSC}{VN} \quad (1)$$

where:

$$\begin{aligned} HR_{ACT} &= \text{Heating rate in the desired units (Btu/in}^3\text{-sec)} \\ HR_{FMC-G} &= \text{Heating from FMC-G (Mev)} \\ P &= \text{Power of reactor source in watts} \\ S &= \text{No. of photons per watt-sec, or} \\ S &= 62.4 \times 10^{10} \text{ photons/watt-sec} \end{aligned}$$

Figure 17

Phoebus-2 Nozzle Assembly

C = Conversion factor to desired units
 $= 2.49 \times 10^{-15} \text{ Btu-cm}^3/\text{in}^3\text{-Mev}$
 V = Volume of region (cm^3)
 N = Number of histories considered

Assuming $N = 500,000$ photons, then

$$HR_{ACT} = \frac{HR_{FMC-G}}{V} 15.676 \text{ (Btu/in}^3\text{-sec)} \quad (2)$$

The results from FMC-G were grouped into 4 batches of 500,000 equivalent histories in order to perform a statistical evaluation of the results. Based on the four values, a mean is computed for each region by

$$X = \frac{\sum_{i=1}^N x_i}{N}$$

From this mean value one can arrive at a variance for each group of values by

$$S^2 = \frac{\sum_{i=1}^N (x_i - \bar{X})^2}{N-1}$$

where:

S^2 = variance
 N = number of samples
 x_i = the value of the i th sample
 $\bar{X}$ = mean value

The square root of the variance is an approximation of the standard deviation (S.D.) where one S.D. is that envelope about the mean into which 68% of the samples will fall.

Since the small number of samples in this case tends to limit the validity of the S.D., it was considered important to perform another type of evaluation. The "T test" derived from the Students-t distribution was used in order to arrive at confidence limits for the mean based on the number of samples (Reference 13). The Students-t distribution approaches a normal distribution as the number of samples approaches infinity. The confidence limits are expressed as a probability that the actual value (μ) will lie within the limits. Continuing with the notation from above:

$$\bar{X} \pm \frac{t_{\gamma/2} S}{\sqrt{N}} \quad \mu < \bar{X} \pm \frac{t_{\gamma/2} S}{\sqrt{N}}$$

where:

$1 - \sigma$ = the confidence level

$$t = \frac{\bar{K} - \mu}{S} \sqrt{N-1}$$

2. Results

For this study it was decided to use 90% confidence limits for the four samples. Then $t_{.05}$ is found to be 2.353 from Table VII of Reference 13. The FMC-G results with one S.D. and 90% confidence limits are given in Table VII for the various regions and for the average for the subassemblies of the nozzle. Also shown are the QAD volume-averaged heating rates for most of the regions for comparison.

TABLE VII

Comparison of FMC-G and QAD-P5 Results

<u>Sub-Assembly</u>	<u>Region</u>	FMC-G Heating Rate (Btu/in ³ -sec)	90% Confidence Limits (Btu/in ³ -sec)		QAD Volume Averaged Heating Rate (Btu/in ³ -sec)	Percentage Difference (FMC-G)-(QAD) (FMC-G)
			<u>Upper</u>	<u>Lower</u>		
Skirt	62	0.4850 $\pm$ 0.0372	0.5287	0.4412	0.4414	8.99
	63	0.3160 $\pm$ 0.0225	0.3424	0.2896	0.3217	-1.80
	64	0.2615 $\pm$ 0.0239	0.2896	0.2334	0.3036	-16.10
	Ave.	0.3401 $\pm$ 0.0154	0.3583	0.3220	0.3533	-3.88
Flange	79	0.0676 $\pm$ 0.0313	0.1045	0.0308	0.0914	-35.21
	81	0.0927 $\pm$ 0.0130	0.1080	0.0775	0.1046	-12.84
	82	0.1214 $\pm$ 0.0206	0.1457	0.0972	0.1561	-28.58
	83	0.0450 $\pm$ 0.0126	0.0599	0.0301	0.0636	-41.33
	84	0.0365 $\pm$ 0.0113	0.0487	0.0222	0.0456	-28.81
	86	0.0608 $\pm$ 0.0125	0.0755	0.0461	0.0829	-36.35
	Ave.	0.0722 $\pm$ 0.0109	0.0850	0.0594	0.0946	-31.02
Jacket	87	0.2386 $\pm$ 0.0261	0.2693	0.2079	--	--
	88	0.3472 $\pm$ 0.0125	0.3619	0.3326	0.3233	6.88
	89	0.3188 $\pm$ 0.0208	0.3433	0.2942	0.3356	-5.27
	90	0.2935 $\pm$ 0.0287	0.3273	0.2598	0.3229	-10.02
	91	0.1082 $\pm$ 0.0348	0.1491	0.0672	--	--
		0.2977 $\pm$ 0.0157	0.3162	0.2793	--	--
3-Region Jacket (88-89-90)	Ave.	0.3277 $\pm$ 0.0156	0.3411	0.3043	0.3276	-1.52

Based on the results of this study it is found that QAD tends to over-estimate the heating rates in the Phoebus-2 nozzle. These over-estimates in the skirt and the jacket are quite small ($\approx 2\%$), with the QAD value falling within the 90% confidence limits of the FMC-G value. In the flange area, on the other hand, where the heating rates are smaller in magnitude, the percent difference is much larger ($\approx 30\%$). These results indicate that the QAD code can predict primary gamma heating rates for the nozzle with relatively small ($\approx 4\%$) uncertainties at in-board regions and moderate uncertainties ($\approx 30\%$) in the outboard regions.

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VI. COMPARISON WITH EXPERIMENT

As part of a continuing effort to improve analysis methods for radiation environment, numerous comparisons have been made between analysis results and measured results. These comparisons include analysis vs analysis, analysis vs experiment, and experiment vs experiment. Parallel analyses are performed with different methods on those problems requiring accurate predictions and for which suitable experimental data are not available.

Much like analysis, development of techniques is also required for the acquisition of suitable experimental data. The large amount of measured data taken from the series of NERVA and Kiwi tests require comparison and evaluation to determine the validity of techniques used for calibration and normalization.

A considerable amount of data are available for the radiation environment about the NERVA reactors. These include gamma ray dose rates, neutron fluxes, and neutron spectra. These data were measured with dosimeters located on the meridian ring (MR) and on the equatorial ring (ER). The meridian ring is a semicircle in the plane of the reactor axis with 5-foot radius originating from the center of the reactor core. The equatorial ring is a 5-foot radius circle concentric with the reactor and located at the core midplane.

A. GAMMA RAY DOSE RATES

Comparisons of gamma ray dose rates predicted by QAD-P5 and measured from NRX-A are shown in Figure 18. The comparison data shown are obtained from the expression: $(D_m - D_c)/D_m$. In this expression D_m is the measured dose rate and D_c is the calculated dose rate.

Note that the agreement is within 10% at the nozzle end and within 34% at the reactor midplane.

Figure 18

Comparison of QAD Calculated Gamma Dose Rates with NRX-A2 Data

B. FAST NEUTRON FLUX

Comparisons of fast neutron flux as predicted with TDC and QAD-P5 against measured values are shown in Figures 19 and 20, respectively. The differences between TDC predictions and measured data range from a high of -59.5% to a low of +61.5%. The differences between QAD-P5 (water moments data) range from a high of -87.2% to a low of +34.8%. Use of QAD-P5 results with beryllium moments data or carbon moments data lead to significantly larger differences.

C. NEUTRON SPECTRA

Comparisons of neutron spectra as predicted with TDC and QAD-P5 against measured data are shown in Figures 21 and 22, respectively. TDC is shown to be in good agreement with measured spectra with some small deviations for neutrons below 2.5 Mev. QAD-P5 spectra are best when the results with beryllium moments data are used. Note that the water moments data provided the best QAD-P5 agreement with measurements for fast neutrons.

Figure 19

Comparison of TDC Calculated Fast Neutron Flux with NRX-A2 Data

Figure 20

Comparison of QAD Calculated Fast Neutron Flux with NRX-A2 Data

Figure 21

Comparison of TDC Calculated Neutron Spectrum with NRX-A2/A3 Data

Figure 22
Comparison of QAD Calculated Neutron Spectra with NRX-A3 Data

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VII. CONCLUSION

This report provides nuclear heating data for the Phoebus-2 reference nozzle as modified early in the Development Phase. The calculations were performed principally with the QAD-P5 point kernel code. However, the secondary gamma sources were predicted with the TDC transport theory code.

Heating rate data were generated for the entire nozzle assembly as well as for the interface region between nozzle and pressure vessel. These data were used by both Aerojet and ACFI in thermal and stress analyses of both the nozzle and pressure vessel.

The uncertainty in these predictions is difficult to define. It appears to have a strong dependence on location with the best accuracy for those regions with high heating rates. The QAD-P5 code, when used with water buildup factors, will generally tend to overestimate the gamma ray environment. This overestimate is believed to be small ($\approx 2\%$) for the high heating rate regions and moderate ($\approx 30\%$) for the low heating rate regions.

The TDC code, with Mill's 18-group cross sections, appears to underestimate the fast neutron environment by between 12% and 60% in the nozzle region. This appears to be within the validity range of the measured data. The adequacy of the secondary gamma sources produced in the nozzle depends on the ability of TDC to define the thermal neutron environment. Thus, while the available data seem to show that the QAD-P5 code provides conservative results, appropriate data for a conclusive demonstration was not available. Hence a nominal uncertainty factor of +25% is recommended for use with the total heating rate data provided in Part I of this report. This means that design calculations performed with nominal heating rate values should be repeated with values that are increased by 25% to ensure that adverse conditions do not occur.

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APPENDIX A

ANALYTICAL DESCRIPTION OF THE REFERENCE CONFIGURATION

The detailed description of the input data for the QAD-P5 code is given for the reference design. The zone description is given in Table A-1, the boundary description is given in Table A-2, and the material composition in Table A-3.

The boundaries are defined by the general quadratic expression $A(X-X_0)^2 + B(Y-Y_0)^2 + C(Z-Z_0)^2 = K^2$. The QAD-P5 code is programmed to recognize six specialized forms of this general equation. The three of these equation types that are used in the boundary description in Table A-2 are:

$$(2) \quad A(X-X_0)^2 + B(Y-Y_0)^2 + C(Z-Z_0)^2 = K$$

$$(3) \quad X^2 + Y^2 = K$$

$$(6) \quad Z = K$$

TABLE A-I

Referenced Design Model Zone Description

Zone No.	No. of Bound- aries	Compo- sition No.	Zone Boundaries with Crossing Sense (+ Bnd) and Probable Zone Entered (Pk)											
			<u>Bnd #1</u>	<u>Pk</u>	<u>Bnd #2</u>	<u>Pk</u>	<u>Bnd #3</u>	<u>Pk</u>	<u>Bnd #4</u>	<u>Pk</u>	<u>Bnd #5</u>	<u>Pk</u>	<u>Bnd #6</u>	<u>Pk</u>
1	1	1	-1	2										
2	3	2	1	1	5	6	-2	3						
3	3	12	2	2	5	6	-3	4						
4	3	4	3	3	5	6	-4	5						
5	3	11	4	4	15	17	-29	28						
6	4	3	1	1	8	9	-4	5	-5	2				
7	4	11	42	35	14	15	-26	21	-19	36				
8	4	13	34	29	36	43	-31	33	-35	37				
9	4	11	1	1	9	10	-4	5	-8	6				
10	4	9	1	1	10	11	-3	16	-9	9				
11	4	11	1	1	11	12	-3	18	-10	10				
12	4	7	1	1	12	13	-2	19	-11	11				
13	4	11	1	1	13	14	-2	19	-12	12				
14	4	9	1	1	14	15	-2	20	-13	13				
15	3	11	1	1	-31	33	-14	14						
16	4	11	3	10	15	17	-4	5	-9	9				
17	4	13	3	10	16	18	-28	27	-15	5				
18	4	11	3	10	18	19	-25	23	-16	17				
19	3	11	2	12	20	20	-18	18						
20	6	9	2	14	14	15	41	35	-42	34	-18	18	-20	19
21	4	13	26	45	40	39	-27	26	-19	22				
22	4	9	26	23	19	21	-27	26	-17	25				

TABLE A-1 (cont.)

Zone No.	No. of Boundaries	Composition No.	Zone Boundaries with Crossing Sense ($\pm$ Bnd) and Probable Zone Entered (Pk)											
			Bnd #1	Pk	Bnd #2	Pk	Bnd #3	Pk	Bnd #4	Pk	Bnd #5	Pk	Bnd #6	Pk
23	5	9	25	18	18	34	-26	22	-17	25	-21	24		
24	3	11	25	18	21	23	-17	25						
25	4	11	25	18	17	23	-27	38	-16	17				
26	4	13	27	21	40	39	-28	27	-22	38				
27	5	13	28	17	40	39	39	40	-38	41	-15	28		
28	5	13	29	5	15	27	34	43	-30	29	-23	30		
29	4	13	30	28	34	43	-35	44	-24	31				
30	3	11	29	5	23	28	-30	31						
31	3	11	30	30	24	29	-35	44						
32	4	11	2	12	18	19	-3	18	-11	11				
33	1	11	31	15										
34	5	9	42	20	19	45	32	36	-26	22	-18	23		
35	3	11	-41	20	14	15	-42	45						
36	3	9	19	45	-26	22	-32	34						
37	3	11	33	44	35	46	-31	33						
38	4	11	27	25	22	26	-28	27	-16	17				
39	4	11	26	45	14	15	-31	33	-40	21				
40	3	11	40	39	-38	42	-39	27						
41	3	13	38	27	37	42	-15	28						
42	5	11	38	27	40	39	-31	33	-15	43	-37	41		
43	4	11	34	29	15	42	-31	33	-36	46				
44	3	11	30	30	35	31	-33	37						

TABLE A-II

Reference Design Analytical Model Boundary Description

<u>Boundary No.</u>	<u>Boundary Type</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>X_o</u>	<u>Y_o</u>	<u>Z_o</u>	<u>K</u>
1	6							173.89
2	6							41.808
3	6							38.316
4	6							31.966
5	3							4861.3
6	3							4950.2
7	3							5040.0
8	3							5130.8
9	3							5295.5
10	3							6140.3
11	3							6200.0
12	3							9812.9
13	3							10161.0
14	3							10677.0
15	3							5767.8
16	3							6001.6
17	3							6240.0
18	3							6606.4
19	3							7294.4
20	2	1.0	1.0	2.4196	0.0	0.0	41.808	10161.0
21	2	1.0	1.0	-2.7312			-52.197	
22	2	1.0	1.0	-1.0163			-78.357	
23	2	1.0	1.0	4.9986			2.54	5767.8
24	2	1.0	1.0	-0.98599			-8.0704	
25	6							3.3
26	6							0.79375
27	6							
28	6							0.9525

TABLE A-II (cont.)

<u>Boundary No.</u>	<u>Boundary Type</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>X_o</u>	<u>Y_o</u>	<u>Z_o</u>	<u>κ</u>
29	6							2.54
30	6							-8.255
31	6							-70.66
32	2	1.0	1.0	-1.108			-79.629	
33	6							-62.852
34	2	1.0	1.0	-1.0555			-81.092	
35	3							447.23
36	3							503.69
37	2	1.0	1.0	-3.8025			-46.046	
38	6							-4.064
39	2	1.0	1.0	-2.8435			-53.925	
40	3							7723.6
41	2	1.0	1.0	2.1701			41.808	10816.0
42	6							1.6

TABLE A-III

Material Composition

Compo- sition	Material							
	H (g/cm ³)	U (g/cm ³)	Ni (g/cm ³)	Cr (g/cm ³)	Fe (g/cm ³)	Nb (g/cm ³)	C (g/cm ³)	Mn (g/cm ³)
1								
2	0.0001845	0.13833			0.08	0.153	1.192	
3							1.80	
4	0.000116				0.08	0.27	0.192	
5	0.00488		0.0634	0.0127	0.0476		1.22	0.00133
6	0.00479		0.0294	0.0589	0.222		1.51	0.00618
7	0.000938							
8	0.00985		0.0279	0.0075	0.00965	0.000359		0.00022
9								
10					7.6			
11								
12	0.00184				0.08	0.218	1.192	
13			3.984	1.769	1.623		0.008229	0.0535
14							0.00094	
15							0.00192	

	Material						
	Mo (g/cm ³)	Pb (g/cm ³)	Al (gm/cm ³)	Be (g/cm ³)	B (g/cm ³)	Cu (g/cm ³)	H ₂ O (g/cm ³)
1							
2							
3							
4							
5			0.112				
6			0.149				
7	0.0492		0.0434	1.695	0.00185		
8	0.380		0.0815	0.596	0.00058		
9			2.70				
10							
11							
12							
13	0.740						
14			1.0035		0.0034		0.6611
15			0.8795		0.0069		0.6866

APPENDIX B

GRAPHICAL DISPLAYS OF ENERGY
AND ANGULAR BIASES

Figure B-1

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 4 (Based on 1000 Particles)

Figure B-2

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 5 (Based on 1000 Particles)

Figure B-3

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 9 (Based on 1000 Particles)

Figure B-4

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 10 (Based on 1000 Particles)

Figure B-5

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 14 (Based on 1000 Particles)

Figure B-6

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 15 (Based on 1000 Particles)

Figure B-7

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 19 (Based on 1000 Particles)

Figure B-8

Number of Particles Reaching The Flange
As a Function of The Particles Initial Axial Direction
From Source Region 20 (Based on 1000 Particles)

Figure B-9

Number of Particles Reaching The Flange
As a Function of The Particles Initial Energy From
Source Region 4 (Based on 1000 Particles)

Figure B-10

Number of Particles Reaching The Flange
As a Function of the Particle Initial Energy From Source
Region 5 (Based on 1000 Particles)

Figure B-11

Number of Particles Reaching the Flange as
a Function of the Particles Initial Energy From
Source Region 9 (Based on 1000 Particles)

Figure B-12

Number of Particles Reaching the
Flange as a Function of the Particles Initial Energy
From Source Region 10 (Based on 1000 Particles)

Figure B-13

Number of Particles Reaching the Flange
As a Function of the Particles Initial Energy From
Source Region 14 (Based on 1000 Particles)

Figure B-14

Number of Particles Reaching the Flange
As a Function of the Particles Initial Energy From
Source Region 15 (Based on 1000 Particles)

Figure B-15

Number of Particles Reaching the
Flange As a Function of the Particles Initial
Energy From Source Region 19 (Based on 1000 Particles)

Figure B-16

Number of Particles Reaching The Flange
As a Function of the Particles Initial Energy From
Source Region 20 (Based on 1000 Particles)

Figure B-17

Phoebus II Accumulative Direct
Gamma Source As a Function of Energy

Figure B-18

Energy Biased Gamma Source
As a Function of Cutoff Energy

APPENDIX C

ADDITIONAL GAMMA HEATING CALCULATIONS

As part of an effort to complete the design analysis for the Phoebebus-2 nozzle assembly during the Development Phase, gamma heating rates were determined for three subassemblies of the nozzle. These include the divergent section of the nozzle, the nozzle inlet manifold, and the nozzle inlet pipe. The QAD-P5 point kernel code was used for this analysis using the source terms described in Part I of this report.

The results are shown in Figures C-1, C-2, and C-3 and Tables C-1, C-2, and C-3. The figures identify detector locations and the tables provide the gamma heating rates at the corresponding detector locations.

NOTE: $Z = 0$ AT P.V. - FLANGE INTERFACE

Figure C-1

Detector Locations in the Divergent
Section of the Nozzle

Figure C-2

Detector Locations on the Nozzle Inlet Manifold

Figure C-3

Detector Locations in the Nozzle Inlet Pipe

C-4

TABLE C-I

Primary Gamma Heating in Divergent Section of Nozzle

Detector Number	Detector Location*				Gamma Heating Rate (Btu/in. ³ /sec)
	R (cm)	R (in.)	Z (cm)	Z (in.)	
1	21.3	8.38	-59.4	-23.39	0.4012
2	21.93	8.63	-54.4	-23.39	0.3377
3	22.2	8.74	-54.4	-23.39	0.3134
4	25.1	9.88	-75.0	-29.53	0.1401
5	26.0	10.24	-75.0	-29.53	0.1546
6	26.8	10.55	-75.0	-29.53	0.2032
7	34.2	13.46	-85.0	-33.46	0.1265
8	34.7	13.66	-85.0	-33.46	0.1451
9	35.1	13.81	-85.0	-33.46	0.1785
10	43.0	16.93	-95.0	-37.4	0.1032
11	43.5	17.13	-95.0	-37.4	0.1284
12	44.0	17.32	-95.0	-37.4	0.1663
13	51.8	20.39	-105.0	-41.34	0.0856
14	52.3	20.59	-105.0	-41.34	0.1134
15	52.8	20.79	-105.0	-41.34	0.1430
16	60.2	23.70	-115.0	-45.28	0.0678
17	60.8	23.94	-115.0	-45.28	0.0842
18	61.4	24.17	-115.0	-45.28	0.1238
19	69.0	27.16	-125.0	-49.21	0.0550
20	69.5	27.36	-125.0	-49.21	0.0706
21	70.0	27.56	-125.0	-49.21	0.0987
22	77.8	30.63	-135.0	-53.15	0.0460
23	78.2	30.29	-135.0	-53.15	0.0592
24	78.6	30.94	-135.0	-53.15	0.0781

* The Z=0 reference is at the nozzle-pressure vessel flange interface with positive source in the forward direction.

TABLE C-I (cont.)

<u>Detector Number</u>	<u>Detector Location*</u>				<u>Gamma Heating Rate (Btu/in.³/sec)</u>
	<u>R (cm)</u>	<u>R (in.)</u>	<u>Z (cm)</u>	<u>Z (in.)</u>	
25	86.4	34.02	-145.0	-57.09	0.0359
26	86.9	34.21	-145.0	-57.09	0.0492
27	87.4	34.41	-145.0	-57.09	0.0713
28	95.1	37.44	-155.0	-61.02	0.0288
29	95.6	37.64	-155.0	-61.02	0.0407
30	96.1	37.83	-155.0	-61.02	0.0601
31	104.0	40.94	-165.0	-64.96	0.0271
32	104.5	41.14	-165.0	-64.96	0.0395
33	105.0	41.34	-165.0	-64.96	0.0614
34	112.7	44.37	-175.0	-68.90	0.0224
35	113.2	44.57	-175.0	-68.90	0.0333
36	113.7	44.76	-175.0	-68.90	0.0528
37	119.9	47.2	-183.0	-72.05	0.0234
38	120.4	47.4	-183.0	-72.05	0.0363
39	120.9	47.60	-183.0	-72.05	0.050

* The Z=0 reference is at the nozzle-pressure vessel flange interface with positive source in the forward direction.

TABLE C-II

Nuclear Heating Rates for the Nozzle Inlet Manifold

Number	Detector Location				Heating Rate in Iron (Btu/in. ³ -sec)			Total
	R		Z		Pri	Nozzle	Clamshell	
	(cm)	(in.)	(cm)	(in.)		Sec	Sec	
101	53.02	20.87	-159.42	-62.76	0.0432	0.0118	0.0016	.0566
102	52.69	20.74	-159.53	-62.81	0.0306	0.0101	0.0012	.0419
103	52.36	20.61	-159.64	-62.85	0.0324	0.0095	0.0008	.0427
104	54.87	21.6	-162.82	-64.10	0.0276	0.0076	0.0016	.0368
105	54.3	21.38	-163.01	-64.18	0.0251	0.0078	0.0011	.0340
106	53.74	21.16	-163.2	-64.25	0.0244	0.0079	0.0007	.0330
107	56.76	22.35	-166.2	-65.43	0.0162	0.0042	0.0015	.0219
108	55.94	22.02	-166.48	-65.54	0.0110	0.0041	0.0011	.0162
109	55.11	21.70	-166.76	-65.65	0.0131	0.0050	0.0008	.0189
110	58.61	23.07	-169.4	-66.69	0.0123	0.0041	0.0015	.0179
111	57.54	22.65	-169.96	-66.91	0.0063	0.0023	0.0010	.0096
112	56.44	22.24	-170.31	-67.06	0.0074	0.0032	0.0005	.0111
113	60.57	23.85	-172.95	-68.09	0.0094	0.0036	0.0015	.0145
114	59.22	23.32	-173.41	-68.27	0.0036	0.0024	0.0009	.0069
115	57.86	22.78	-173.87	-68.45	0.0041	0.0036	0.0005	.0082
116	63.09	24.84	-180.14	-70.92	0.0027	0.0013	0.0016	.0056
117	61.53	24.22	-180.14	-70.92	0.0012	0.0010	0.0010	.0032
118	60.1	23.66	-180.14	-70.92	0.0020	0.0018	0.0006	.0044
119	64.648	25.45	-177.93	-70.05	0.0557	0.0070	0.0009	.0636
120	70.75	27.85	-177.61	-69.93	0.0577	0.0092	0.0024	.0693
121	72.0	28.35	-157.4	-61.97	0.0670	0.0148	0.0025	.0843
122	56.0	22.05	-157.4	-61.97	0.0727	0.0151	0.0022	.0900
123	70.76	27.86	-157.91	-62.17	0.0359	0.0180	0.0026	.0565
124	58.735	23.12	-161.97	-63.61	0.0380	0.0212	0.0020	.0612
125	64.807	25.51	-156.8	-61.73	0.0423	0.0226	0.0022	.0671
126	59.41	23.39	-156.8	-61.73	0.0252	0.0126	0.0020	.0398

TABLE C-III

Primary Gamma Heating Rates in the Nozzle Inlet Pipe

Number	Detector Location*				Primary Gamma Heating Rate (Btu/in. ³ -sec)
	R (cm)	R (in.)	Z (cm)	Z (in.)	
1	71.12	28.0	-157.28	-61.92	0.0655
2	76.2	30.0	-157.28	-61.92	0.0793
3	81.28	32.0	-157.28	-61.92	0.0797
4	86.36	34.0	-157.28	-61.92	0.0777
5	91.44	36.0	-157.28	-61.92	0.0752
6	96.52	38.0	-157.28	-61.92	0.0722
7	101.6	40.0	-157.28	-61.92	0.0689
8	103.83	40.875	-157.28	-61.92	0.0682
9	71.12	28.0	-178.24	-70.17	0.0317
10	76.2	30.0	-178.24	-70.17	0.0408
11	81.28	32.0	-178.24	-70.17	0.0496
12	86.36	34.0	-178.24	-70.17	0.0512
13	91.44	36.0	-178.24	-70.17	0.0537
14	96.52	38.0	-178.24	-70.17	0.0522
15	101.6	40.0	-178.24	-70.17	0.0504
16	103.83	40.875	-178.24	-70.17	0.0500

* The Z=0 reference is at the nozzle-pressure vessel flange interface with positive sense in the forward direction.