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WANL-TME-2689

September 1970

EVALUATION OF THE WANL
INTEGRATED NUCLEAR,
RADIATION, AND SHIELDING
STANDARD DESIGN METHOD
(WISDM) (U)

VOLUME 2

MASTER

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MASTER

VOLUME 2

SPECIAL REVIEW DETERMINATION	Reviewers <u>DBW</u>	Class. <u>U</u>	Date <u>3-2-82</u>
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ABSTRACT

The WANL Integrated Nuclear, Radiation and Shielding Standard Design Method (WISDM) used at the Westinghouse Astronuclear Laboratory in nuclear and radiation design and analysis of the NERVA Nuclear Subsystem is described in this report. An evaluation of the accuracy of the WISDM methods and techniques is made by comparison with experimental results. WISDM is an integral part of an overall Design Engineering Method which is being developed to automate the mechanical, thermal, structural, nuclear, and radiation analyses and design of the NERVA Nuclear Subsystem.

Methods related to predictions in the following nuclear, radiation, and shielding analysis areas are discussed herein: 1) absolute reactivity (for component sizing or fuel loading), 2) control drum worth, 3) fission distribution (for fuel zoning or coolant allocation) 4) material reactivity worth (for evaluation of the effect of non-nominal compositions or conditions), 5) shield performance, 6) radiation heating rates (for component cooling requirements), and 7) radiation environment (for radiation damage).

This report is separated into two volumes. Volume 1 describes the WISDM techniques, evaluates the accuracy of the techniques by comparison with applicable experimental data, and discusses areas requiring improvement. Detailed statistical evaluation of the comparison of experimental and calculated results is presented for the methods used in calculating control drum worth, fission distribution, shield performance, radiation heating rate, and radiation environment. Volume 2, which describes the reactor systems evaluated by WISDM, is published as a separate volume since it contains Confidential Restricted Data.

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Attention: P. P. Ventura

Subject: Transmittal of WANL-TME-2689, "Evaluation of the WANL Integrated Nuclear, Radiation and Shielding Standard Design Method (WISDM)", Vol. I and II (U)

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APPENDIX A-1

NRX-A6 REACTOR

A detailed description of the NRX-A6 reactor can be found in Reference 5, the "NRX-A6 Nuclear Subsystem - Thermal and Nuclear Design Data Book." The information presented here is essentially limited to that directly pertinent to the analysis. To orient the reader, Figures A1-1 to A1-4 have been included. These show various trimetric and cross-sectional reactor views. Table A1-1 summarizes the specification to which the NRX-A6 fuel elements were manufactured. Table A1-2 summarizes the "as-built" material mass inventory of the reactor core. Companion Table A1-3 summarizes this information for each non-core region/component. For the NRX-A6 analytical work appearing in the main body of this report (Section 5), the reactor was subdivided radially into the regions listed in Table A1-4. Table A1-5 shows the detailed "as built" material distribution in the core regions defined in Table A1-4. Based on the masses in Tables A1-5 (core) and A1-3 (non-core) and the volumes in Table A1-4, the atom densities for one-dimensional calculations were developed. The results, presented in Table A1-6, were used in this report only to develop the converged neutron flux and current (see Appendix B). These final spectra were used along with the "two-dimensional" atom densities in Table A1-7* for weighting the fine-group microscopic cross sections in the GAMBIT code. The resulting macroscopic cross sections were used in the control drum worth analysis reported in Section 5. Additional details of the one- and two-dimensional geometrical model may also be found in Section 5.

*See Table A1-8 for NRX-A6 (and PAX-E1) control vane geometrical and mass data.

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TABLE A1-1

(CRD) NRX-A6 FUEL ELEMENT SPECIFICATIONS (REF 5, PG C-15) (U)

MASS SPECIFICATIONS		LOADING CODE										
<u>Item</u>	<u>Unit</u>	<u>21</u>	<u>20</u>	<u>19</u>	<u>18</u>	<u>17</u>	<u>16</u>	<u>15</u>	<u>14</u>	<u>13</u>	<u>12</u>	<u>11</u>
Number of fueled elements		348	246	192	276	78	96	84	60	72	30	102
Coolant channel diameter, as reamed	mils	99	99	99	99	99	99	99	99	99	99	97
Enriched uranium loading per unit length of fueled graphite element	g/inch	2.597	2.444	2.273	2.081	1.719	1.375	1.086	0.879	0.702	0.565	0.469
Enriched uranium loading per fueled graphite element, (+ 2.5 percent tolerance), 1,000 inch unfueled tip ⁽¹⁾	g	132.4	124.6	115.9	106.1	87.7	70.1	55.4	44.8	35.8	28.8	23.9
Graphite loading per fueled element	g	524	526	528	530	534	538	542	544	546	548	549
Graphite loading tolerance per fueled element, includes dimension tolerance (+ 2 percent)	g	11	11	11	11	11	11	11	11	11	11	11
Niobium coating weight per fueled graphite element (bore and nozzle end) ⁽²⁾	g	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Niobium coating weight tolerance per fueled element (bore and nozzle end)	g	± 10	± 10	± 10	± 10	± 10	± 10	± 10	± 10	± 10	± 10	± 10
Maximum allowable external niobium coating weight gain per fuel element	g	NOT APPLICABLE							16.0	16.0	16.0	16.0
Molybdenum coating weight per fueled graphite element	g	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0 ⁽³⁾	3.0	3.0	3.0
Molybdenum coating weight tolerance per fueled element	g	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0 ⁽³⁾	± 1.5	± 1.5	± 1.5

(1) Uranium weight is for 51 inches because of the presence of the one-inch unfueled graphite tip. All other weights and tolerances are for 52 inches.

(2) The average bore and nozzle end niobium weight of all elements may not exceed 60 gms.

(3) Some of the code 14 elements are externally coated. Those elements which are externally coated have a molybdenum weight of 3.0 gms $\pm$ 1.5 gms.

TABLE A1-2

(CRD) NRX-A6 'AS-BUILT' CORE INVENTORY (REF 5, PG C-32) (U)

FUELED ELEMENTS						
<u>Loading Code</u>	<u>Manufacturer</u>	<u>Number of Elements</u>	<u>U Mass⁽¹⁾ Kg</u>	<u>C Mass Kg</u>	<u>Nb Actual⁽²⁾ Mass, Kg</u>	<u>Nb Effective Mass, Kg</u>
21	Y-12	183	24.751	97.027	9.733	9.712
	WNCO	165	22.369	86.675	8.359	7.837
20	Y-12	147	18.762	78.052	7.680	7.665
	WNCO	99	12.705	52.286	5.107	4.785
19	Y-12	82	9.739	43.629	4.279	4.282
	WNCO	110	13.163	58.213	5.543	5.131
18	Y-12	195	21.329	104.172	9.767	9.790
	WNCO	81	9.117	42.957	4.082	3.793
17	Y-12	50	4.698	26.918	2.448	2.417
	WNCO	28	2.659	15.033	1.426	1.358
16	Y-12	60	4.510	32.441	2.967	2.945
	WNCO	36	2.704	19.430	1.772	1.670
15	Y-12	52	3.045	28.312	2.563	2.551
	WNCO	32	1.869	17.420	1.586	1.489
14	Y-12	33	1.561	17.987	1.734	1.717
	WNCO	27	1.265	14.686	1.321	1.275
13	WNCO	72	2.709	39.064	3.669	3.585
12	WNCO	30	0.899	16.366	1.552	1.518
11	WNCO	102	2.535	55.624	5.148	5.050
TOTALS		1,584	160.389	846.292	80.730	78.570

UNFUELED ELEMENTS

<u>Loading Code⁽⁴⁾</u>	<u>Manufacturer</u>	<u>Number of Elements</u>	<u>Ta Mass Kg</u>	<u>C Mass Kg</u>	<u>Nb Actual⁽²⁾ Mass, Kg</u>	<u>Nb Effective⁽³⁾ Mass, Kg</u>
00	Y-12	38	2.827	23.037	0.266	0.258
01	Y-12	185	0.0	112.864	1.350	1.313
02	Y-12	66	0.0	39.548	0.457	0.444
03	WNCO	42	0.0	20.477	0.0	0.0
TOTALS		331	2.827	195.926	2.073	2.015

OTHER COMPONENTS

<u>Component</u>	<u>Quantity</u>	<u>Material</u>	<u>Mass, Kg</u>
Pyrographite Sleeve	289	Carbon	27.413
Positive Shims ⁽⁵⁾	89	Carbon	1.017
Tie Rod	289	Inconel-718	23.647
Liner Tubes	289	Stainless Steel	8.044

(1) Mass of uranium calculated on the basis of a 52-inch fueled length.

(2) Bore coating only. See C. 2.3 for external coating weights.

(3) Mass of uniform Nb equivalent in reactivity to actual bore Nb mass.

(4) Unfueled loading codes are defined in Figure E. 1. 3.

(5) This number represents the carbon in 8 positive shims and 81 thermal capsule families.

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TABLE A1-3

NRX-A6 'AS-BUILT' REFLECTOR REGION INVENTORY (REF 5, PG C-33)

REFLECTOR REGION WEIGHTS⁽¹⁾

<u>Region</u>	<u>Material</u>	<u>Mass, Kg</u>
Filler Strip	Graphite	95.48
	Niobium	0.76
	Paraffin	0.012
	Silicone Grease	0.069
Lateral Support	Graphite	115.08
	Niobium	0.001
Beryllium Reflector Hardware	Graphite	5.30
	Inconel-718	37.11
	Stainless Steel	0.69
	Nispan	1.99
	Titanium	2.94
	Copper	1.54
	Aluminum	11.93
Reflector	Beryllium	884.50
	Titanium	14.67
Control Drums	Beryllium	199.85
	Aluminum	18.11
	Boron-10	1.03
Cluster Plate	Ag-In-Cd	11.47
	Stainless Steel	20.32
	Aluminum	2.49
	Inconel	0.52
Support Block	Graphite	27.53
	Niobium	7.69
	Stainless Steel	0.21
	Molybdenum	1.47
	Tungsten	4.29
	ThO ₂	0.07
	Inconel	1.27
Support Plate	Aluminum	212.29
Pressure Vessel	Aluminum	239.24
	Copper	16.09

(1) Weight for 52.0 inch active core length.

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TABLE A1-4

NRX-A6 REGION IDENTIFICATION AND VOLUMES (REF 5. PG E-6)

REGION DEFINITION FOR ONE-DIMENSIONAL CALCULATIONS
(At Room Temperature)

<u>Region</u>	<u>Outer Radius, cm</u>	<u>Volume, cc</u>
Core 1 (1) Fuel Loading Codes 18, 19	15.747	1.02892×10^5
Core 2 Fuel Loading Codes 19, 20	20.445	0.70552×10^5
Core 3 Fuel Loading Codes 19, 20, 21	25.391	0.94069×10^5
Core 4 Fuel Loading Codes 20, 21	32.491	1.70525×10^5
Core 5 Fuel Loading Codes 19, 20, 21	34.294	0.49964×10^5
Core 6 Fuel Loading Codes 16, 17, 18	36.689	0.70542×10^5
Core 7 Fuel Loading Codes 15, 16, 17	39.480	0.88211×10^5
Core 8 Fuel Loading Codes 13, 14	41.719	0.75438×10^5
Core 9 Fuel Loading Codes 11, 12, 13	43.804	0.7399×10^5
Filler Strip	45.174	0.50581×10^5
Lateral Support 1	46.478	0.49592×10^5
Lateral Support 2	47.831	0.52947×10^5
Beryllium Reflector 1	49.736	0.77123×10^5
Beryllium Reflector 2	50.876	0.47593×10^5
Beryllium Reflector 3	62.814	5.63173×10^5
Void	63.183	0.19291×10^5
Pressure Vessel	64.884	0.90434×10^5

(1) See E. 1, 3 for a more detailed description of the core regions.

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(At Room Temperature)

Region Identification	1	2	3	4	5	6	7	8	9	Total
Radius, cm	<u>15.747</u>	<u>20.445</u>	<u>25.391</u>	<u>32.491</u>	<u>34.294</u>	<u>36.689</u>	<u>39.480</u>	<u>41.719</u>	<u>43.804</u>	
<u>Material</u>										
Carbon										
Fueled Elements	115.097	76.361	104.856	174.215	57.264	80.446	94.324	68.482	75.246	846.291
Unfueled Elements	22.419	14.587	18.259	36.373	7.298	21.834	7.288	40.102	7.288	175.448
Pyrographite Sleeves	4.020	2.607	3.259	6.518	1.304	3.911	1.304	7.170	1.304	31.397
Positive Shims	0.185	0.077	0.062	0.231	0.0	0.139	0.046	0.231	0.046	1.017
Partial Elements	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.477	20.477
Total Carbon	141.721	93.632	126.436	217.337	65.866	106.330	102.962	115.985	104.361	1074.630
Uranium ⁽¹⁾	23.908	17.284	25.414	44.637	13.438	14.831	11.908	5.308	3.660	160.388
Niobium ⁽²⁾										
Bore										
Fueled Elements	10.603	7.054	9.986	16.647	5.427	7.354	8.352	6.279	6.867	78.569
Unfueled Elements	0.256	0.168	0.211	0.415	0.083	0.250	0.084	0.463	0.084	2.014
Matrix	0.194	0.316	0.366	0.939	0.009	0.122	0.0	0.179	0.0	2.125
External										
Fueled Elements	0.003	0.002	0.003	0.005	0.002	0.002	0.002	0.522	1.031	1.572
Unfueled Elements	0.758	0.493	0.619	1.241	0.254	0.743	0.246	1.354	0.246	5.954
Partial Elements	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.150	0.150
Total Niobium	11.814	8.033	11.185	19.247	5.775	8.471	8.684	8.797	8.378	90.384
Molybdenum ⁽²⁾	0.949	0.635	0.819	1.449	0.446	0.645	0.721	0.513	0.528	6.705
Tantalum	0.446	0.0	0.0	1.339	0.446	0.595	0.0	0.0	0.0	2.826
Stainless Steel ⁽³⁾	1.030	0.668	0.835	1.670	0.334	1.002	0.334	1.837	0.334	8.044
Inconel-718 ⁽⁴⁾	3.027	1.964	2.455	4.909	0.982	2.946	0.982	5.400	0.982	23.647
Hydrogen ⁽⁵⁾	0.0014	0.0009	0.0013	0.0022	0.0007	0.0011	0.0010	0.0012	0.0010	0.0108

(1) Uranium masses based on a 52 inch length.

(2) Niobium is reactivity-weighted.

(3) Tube liner weights only; does not include orifice jets.

(4) Weight for entire length of tie rod.

(5) Hydrogen weight assumed to be 10 ppm of the total carbon weight

TABLE A1-5

(CRD) NRX-A6 'AS BUILT' WEIGHTS BY CORE RADIAL REGIONS (REF 5, PG E-8) (U)

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TABLE A1-6

(CRD) NRX-A6 ATOM DENSITIES* FOR ONE-DIMENSIONAL CALCULATIONS (U)

Region	H	C	U-235	U-238	Cr	Fe	Ni	X	Nb	Be	Al
	X10-5	---	X10-3	X10-4	X10-4	X10-3	X10-3	X10-4	X10-3	---	---
Core 1	0.8	0.068843	0.554	0.41	0.88	0.141	0.168	0.63	0.754	---	---
Core 2	0.8	0.066337	0.585	0.43	0.84	0.133	0.159	0.62	0.748	---	---
Core 3	0.8	0.067202	0.645	0.47	0.78	0.125	0.149	0.60	0.780	---	---
Core 4	0.8	0.063689	0.625	0.46	0.86	0.138	0.164	0.59	0.742	---	---
Core 5	0.8	0.065961	0.642	0.47	0.59	0.094	0.112	0.60	0.756	---	---
Core 6	0.9	0.075258	0.502	0.37	1.25	0.200	0.238	0.65	0.793	---	---
Core 7	0.7	0.058456	0.322	0.24	0.33	0.053	0.063	0.53	0.642	---	---
Core 8	0.9	0.076519	0.168	0.12	2.15	0.343	0.408	0.56	0.780	---	---
Core 9	0.8	0.070640	0.117	0.09	0.40	0.640	0.076	0.47	0.739	---	---
Filler Strip		0.094690							0.097		
Lateral Support-1		0.052473									
Lateral Support-2		0.059882									
Be Reflector-1										0.095526	
Be Reflector-2										0.109079	
Be Reflector-3										0.106411	0.000718
Pressure Vessel											0.060573
Axial Buckling			$0.450 \times 10^{-3} \text{ cm}^{-2}$								
Radial Buckling			0.10076×10^{-2}								

*Units are atoms per barn centimeter.

A-7

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TABLE A1-7

(CRD) NRX-A6 ATOM DENSITIES**FOR TWO-DIMENSIONAL CALCULATIONS (U)

Region	H	C	U-235	U-238	Cr	Fe	Ni	X	Nb	Be	Misc.
	X10-5	---	X10-3	X10-4	X10-4	X10-3	X10-3	X10-4	X10-3	---	---
Core 1	0.8	0.068843	0.554	0.41	0.88	0.141	0.168	0.63	0.754	---	---
Core 2	0.8	0.066337	0.585	0.43	0.84	0.133	0.159	0.62	0.748	---	---
Core 3	0.8	0.067202	0.645	0.47	0.78	0.125	0.149	0.60	0.780	---	---
Core 4	0.8	0.063689	0.625	0.46	0.86	0.138	0.164	0.59	0.742	---	---
Core 5	0.8	0.065961	0.642	0.47	0.59	0.094	0.112	0.60	0.756	---	---
Core 6	0.9	0.075258	0.502	0.37	1.25	0.200	0.238	0.65	0.793	---	---
Core 7	0.7	0.058456	0.322	0.24	0.33	0.053	0.063	0.53	0.642	---	---
Core 8	0.9	0.076519	0.168	0.12	2.15	0.343	0.408	0.56	0.780	---	---
Core 9	0.8	0.070640	0.117	0.09	0.40	0.064	0.076	0.47	0.739	---	---
Filler Strip		0.094690							0.097		
Lateral Support-1		0.052473									
Lateral Support-2		0.059882									
Be Reflector-1										0.90549	
Be Reflector-2										0.11065	
Be Reflector-3										0.11122	0.000831†
Plunger		0.042360								0.09448	
Spring					13.0	1.23	3.17			0.08568	
Tie Bolt											0.033320 ⁺
Vane											0.044707†
											0.030458*

†Aluminum

+Titanium

*Boron 10

**Units are atoms per barn centimeter.

TABLE A1-8

NRX-A6 AND PAX-E1 CONTROL VANE DATA*

VANE GEOMETRY:

Inner Radius of Control Drum	4.7625 cm
Outer Radius of Control Drum	4.8895 cm
Thickness of Vane	0.050 in.
Length of Plates	17.266 in.
Plates per Vane	3
Total Vanes, NRX-A6 and PAX-E1	12
Total Azimuthal Coverage of Vane	120 degrees
Radial Distance from Center of Core to Center of Control Drum	56.8325 cm

VANE MASSES:

Total Control Vane Mass	5146.434 grams
Total Mass Boron-10	1029.36 grams
Weight Fraction Boron-10 in Boron	0.9576

*Source:

(a) WANL-TME-1642, NRX-A6 Nuclear Subsystem Thermal and Nuclear Design Data Book, November 15, 1967. (Reference 5)

(b) Drawing Number 909E267, Plate Control Drum.

Figure A1-1. Trimetric View of NRX-A6 Reactor (Ref 5, PG C-4)

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(CRD) Figure A1-2. Trimetric View of NRX-A6 Reflector (U)

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THIS DRAWING SHOWS CORE CROSS SECTION AS VIEWED
IN THE DIRECTION OF CORE PROPELLANT FLOW

Figure A1-3. Core Orientation and Cluster Identification (Ref 5, PG C-7)

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NOTES: 1) CORE VIEWED IN THE DIRECTION OF PROPELLANT FLOW.
2) ALL PARTIAL ELEMENTS IN NRX-A6 ARE UNFUELED.

Figure A1-4. Peripheral Clusters and Filler Strip Identification (Ref 5, PG C-8)

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APPENDIX A-2

PAX-E1 REACTOR

A detailed description of the PAX-E1 reactor can be found in References 2, 3, and 12. The reader is also referred to Appendix A-1 for illustrations of general NRX features and Figure A3-1 in Appendix A-3 for a photograph of the PAX assembly and test stand. The information presented in this Appendix is limited to that directly pertinent to the analytical work described in Sections 4 and 6 of this report. Table A2-1 gives the one-dimensional atom density description of PAX-E1 used for the spectrum convergence calculations performed with the geometric model summarized in Table A2-2 and Figure A2-1. (The result of these calculations appears in Appendix B.) The one-dimensional atom densities were also used directly in the computation of reactivity coefficients. The PAX-E1 fission density calculations were based on the atom densities summarized in Table A2-3. The location of the various regions noted in this table appears in Section 6.

TABLE A2-1

(CRD) PAX-E1 ATOM DENSITIES FOR ONE-DIMENSIONAL CALCULATIONS* (U)

Region	C	U235	U238	Cr	Fe	Ni	Nb	Be	Al
	---	$\times 10^{-3}$	$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-3}$	$\times 10^{-4}$	$\times 10^{-3}$	---	---
Core-1	0.066441	0.5347	0.393	0.71	0.248	0.33	0.674		
Core-2	0.066207	0.5662	0.416	0.71	0.248	0.33	0.674		
Core-3	0.066007	0.6103	0.449	0.71	0.248	0.33	0.674		
Core-4	0.065810	0.6645	0.489	0.71	0.248	0.33	0.674		
Core-5	0.066109	0.6051	0.445	0.71	0.248	0.33	0.674		
Core-6	0.066679	0.4917	0.362	0.71	0.248	0.33	0.674		
Core-7	0.067425	0.3219	0.237	0.71	0.248	0.33	0.674		
Core-8	0.070315	0.1743	0.128	1.31	0.456	0.61	0.693		
Core-9	0.071535	0.1099	0.081	0.50	0.175	0.23	0.778		
Filler Strip	0.092590								
Lateral Support-1	0.057189								
Lateral Support-2	0.057189								
Be Reflector-1								0.095526	
Be Reflector-2								0.109079	
Be Reflector-3								0.106411	0.000718
Pressure Vessel									0.060573

*Core atom densities are for NRX-A6 quadrant of PAX-E1.

TABLE A2-2

ONE-DIMENSIONAL PAX-E1 MODEL WITH RING VANE PRESCRIPTION AT 105°

<u>Radial Mesh Line</u>	<u>Zone</u>	<u>Radius</u> (cm)	<u>ΔR</u> (cm)	<u>Region</u> <u>Description</u>
1	1	0.0	7.0	Core Region-1
2	1	7.0	5.0	Core Region-1
3	1	12.0	3.747	Core Region-1
4	2	15.747	4.698	Core Region-2
5	3	20.445	4.946	Core Region-3
6	4	25.391	3.559	Core Region-4
7	4	28.950	3.541	Core Region-4
8	5	32.491	1.803	Core Region-5
9	6	34.294	2.395	Core Region-6
10	7	36.689	1.411	Core Region-7
11	7	38.100	1.380	Core Region-7
12	8	39.480	0.746	Core Region-8
13	8	40.226	0.747	Core Region-8
14	8	40.973	0.746	Core Region-8
15	9	41.719	0.516	Core Region-9
16	9	42.235	0.515	Core Region-9
17	9	42.750	0.527	Core Region-9
18	9	43.277	0.527	Core Region-9
19	10	43.804	0.685	Filler Strip
20	10	44.489	0.685	Filler Strip
21	11	45.174	0.652	Lateral Support-1
22	11	45.826	0.652	Lateral Support-1
23	12	46.478	0.6765	Lateral Support-2
24	12	47.1545	0.6765	Lateral Support-2
25	13	47.831	0.9525	Be-1
26	13	48.7835	0.9525	Be-1
27	14	49.736	1.140	Be-2
28	15	50.876	1.124	Be-3
29	15	52.0	1.2	Be-3
30	15	53.2	1.2	Be-3
31	15	54.4	1.2	Be-3

TABLE A2-2 (Continued)

<u>Radial Mesh Line</u>	<u>Zone</u>	<u>Radius (cm)</u>	<u>R (cm)</u>	<u>Region Description</u>
32	15	55.6	0.764	Be-3
33	16	56.364	0.101	Vane
34	16	56.465	0.101	Vane
35	17	56.566	0.934	Be-3
36	17	57.5	1.4	Be-3
37	17	58.9	1.4	Be-3
38	17	60.3	1.3	Be-3
39	17	61.6	1.214	Be-3
40	18	62.814	0.369	Void
41	19	63.183	0.8505	Pressure Vessel
42	19	64.0335	0.8505	Pressure Vessel
43		64.884		

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TABLE A2-3

(CRD) PAX-E1 ATOM DENSITIES FOR TWO-DIMENSIONAL CALCULATIONS (U)

Region	C	U ²³⁵	U ²³⁸	Cr	Fe	Ni	Nb	Be	Al	Ti	B ¹⁰	H
	---	x10 ⁻³	x10 ⁻⁴	x10 ⁻⁴	x10 ⁻³	x10 ⁻⁴	x10 ⁻³	---	---	---	---	x10 ⁻³
Core-1	0.066441	0.5347	0.393	0.71	0.248	0.33	0.674					
Core-2	0.066207	0.5662	0.416	0.71	0.248	0.33	0.674					
Core-3	0.066007	0.6103	0.449	0.71	0.248	0.33	0.674					
Core-4	0.065810	0.6645	0.489	0.71	0.248	0.33	0.674					
Core-5	0.066109	0.6051	0.445	0.71	0.248	0.33	0.674					
Core-6	0.066679	0.4917	0.362	0.71	0.248	0.33	0.674					
Core-7	0.067425	0.3219	0.237	0.71	0.248	0.33	0.674					
Core-8	0.070315	0.1743	0.128	1.31	0.456	0.61	0.693					
Core-9	0.071535	0.1099	0.081	0.50	0.175	0.23	0.778					
Filler Strip	0.092590											
Lateral Support-1	0.057189											
Lateral Support-2	0.057189											
Be Reflector-1								0.09549				
Be Reflector-2								0.11065				
Be Reflector-3								0.11122	0.000831			
Plunger								0.09448				
Spring				13.0	1.23	31.7		0.08568				0.5744
Titanium Tie Bolt										0.03332		
Control Vane**									0.024184		0.016476	

* Core atom densities are for NRX-A6 quadrant of PAX-E1.

** Based on 100 mil control vane

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Figure A2-1. One-Dimensional (Radial) Model of PAX-E1 Reactor Configuration

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APPENDIX A-3

PAX-E5 REACTOR

A-3.1 PAX REACTOR DESCRIPTION

A-3.1.1 PAX Assembly

The Permanent Assembly Experiment (PAX) critical assembly, shown in Figure A3-1, is a nuclear and mechanical mock-up of the NRX reactor which is a part of the development program for the NERVA engine. The PAX-E5 assembly consists primarily of NRX components which are nuclearly equivalent to the NRX-A6 reactor.

The basic PAX assembly consists of the reactor subassembly, the radiation shield mock-up, pressure vessel, control drum drives, and test stand. The PAX reactor subassembly includes the core assembly, graphite inner reflector, beryllium outer reflector, and the lateral support. Clusters of graphite-uranium fuel elements, which constitute the core assembly, rest upon an aluminum core support plate which, in turn, is supported by the pressure vessel dome via a transition ring and the outer reflector support ring. A typical NRX-type dummy aluminum shield rests beneath the core support plate. Immediately surrounding the core assembly are three band and pulley mechanisms which provide lateral support for the PAX core. The beryllium outer reflector consists of twelve 30-degree sectors which are held vertically between the reflector support ring and the lower (forward) support ring by means of through-bolts. Each sector contains one rotating control drum. Surrounding the reactor subassembly is a dummy aluminum pressure vessel and NRX-type dummy shield which is comprised of three sections: the dome, which contains the core support plate, the cylinder body which contains the reactor subassembly, and a removable section at the nozzle end of the pressure vessel. The nozzle end mechanically supports either a protective cover, the dummy nozzle, or the components of end-on experiments. During these experiments a special adapter ring was used to support the shield mock-up in place of the usual nozzle adapter section. That is, the nozzle end of the PAX was utilized and effectively converted into the inlet end of the reactor for these shield measurements.

A-3. 1. 2 PAX-E5 REACTOR

The reactor configuration used for the NRX-A6 radiation environment experiments was designated the PAX-E5 reactor. In one quadrant of the reactor, three NRX-A3 type 30-degree beryllium sectors were modified to closely simulate the NRX-A6 reflector. NRX-A6 reject fuel was used in this quadrant as well as the central circle. In the remaining 270 degrees, the reflector consisted of 9 KIWI sectors augmented on the inner diameter with removable beryllium liner plates as shown in Figure A3-2 to provide the equivalent NRX-A6 beryllium area density. Since not enough NRX-A6 type fuel was available for the remaining 270 degree portion of the core, a mix of fueled and unfueled elements was used with the material atom densities adjusted on a per element and per cluster basis by means of various types of wires placed in specified coolant channels. Hence, the PAX fuel elements are nuclearly equivalent to those in the NRX-A6 design and are mechanically identical. (See Appendix A-1 for more details.) Although the majority of the fuel elements in the PAX core are elements that have been rejected in manufacture, the causes for rejection are related to the mechanical or thermal specifications and do not affect their use in a reactor as a radiation source. Reactor power calibrations were derived from a fission flux map of the core and radiochemistry of selected fuel samples.

A-3. 1. 3 SHIELD MOCK-UPS

Two different configurations of materials on the end of the bare PAX-E5 reactor were employed in these experiments and analyzed. These configurations are described as follows:

Shield Configuration Designation	Area Density (gm/cm ²)	Description
4B	59.05	A bare PAX reactor with a mock-up of a typical core support plate, plenum region, and pressure vessel on a NERVA type reactor.
7D	139.70	Configuration 4B with six BATH (Boron-Aluminum-Titanium-Hydride) shield modules interposed between the core support plate and the plenum-pressure vessel region.

The materials* and area densities are given in Table A3-1. It should be noted that all three configurations contained the 3/8-inch thick Boral cluster plate mock-up. Figures A3-3 and A3-4 show a breakdown of shield Configuration 4B, while Figures A3-5 and A3-6 contain the corresponding information for shield Configuration 7D.

Small aluminum spacer bars were placed between the shield materials at points of interest to permit measurements of neutron flux and dose rate inside the shield mock-ups by means of passive dosimeters. Two aluminum bars (3 feet x 1/2 inch x 1/4 inch) or rods (3 feet x 1/4 inch diameter) two inches apart were sandwiched centrally between two sheets of material in order to leave quarter-inch gaps. In addition, one-inch square aluminum bars, one-quarter-inch thick, were also inserted at some of the corners and edges of these layers so that the materials could be kept as flat as possible. In all, 22 sets of spacers were used.

A-3.2 PAX-E5 ANALYTICAL MODEL

From the mechanical design layout and detailed parts drawings for the PAX-E5 critical assembly, a basic cylindrical (r,z) geometry model was developed for use in the various computer codes employed in this evaluation. Presented in this section are the geometrical models and associated material data applied in the discrete ordinate transport analyses.

*All aluminum used in the construction of the shield, dome and plenum region mock-up was 2219 alloy to correspond to the actual alloy proposed for use in the R-1 reactor. All Inconel was type 718 and Boral contained 23 w/o B₄C (of the total sheet).

A-3. 2. 1 Material Data

As indicated in Section A-3. 1. 2, the PAX-E5 assembly is not azimuthally uniform either in material composition or dimensions, but consists of a 270 degree PAX core sector with a KIWI type reflector, and a 90 degree NRX-A6 core sector with a modified NERVA reflector. However, the measurements and calculations were made above the reactor assembly where azimuthal variation is of secondary importance. In addition, power measurements recorded as a function of radial distance for traverses in both sectors indicated only minor differences in fission rate distributions. The effect of differences in reflector composition and dimensions is minimal and radiation levels in the shields are representative of sources in the 270 degree sector. Therefore, material and geometrical data for the 270 degree sector were used in the analytical models presented in this section to describe the entire assembly. Table A3-2 lists the various materials and their associated masses in the core region of the PAX-E5, and Table A3-3 lists the materials and their masses in the non-core regions of the critical assembly. In Table A3-2, the masses of the fueled and unfueled elements have been subdivided to show the mass in the 90 degree A6 portion of the core and the mass in the 270 degree rezoned PAX portion of the core. Table A3-4 provides a list of the atom densities for the material compositions in the PAX-E5 reactor, shield Configuration 4B, and shield Configuration 7D. The location of each composition is shown in the geometrical description of each shield configuration which is discussed in the next section.

The neutron transport cross sections for Composition 31 contain data to represent the PAX-E5 control drums at an operating angle of 90 degrees. The twelve control vanes, which are 120 degree plates fastened to the exterior of each of the beryllium control drums, are treated in a special manner in (r,z) geometry calculations. By empirical techniques, the control vane cross sections for the PAX-E5 have been developed such that the radial fission distribution and absorptions in the control vanes for (r,z) calculations agree with explicit, (r,θ) calculations and measurements. In the (r,z) model, an annular zone which is 0.254 cm thick is located with an inner radius of 57.72 cm and contains these special vane cross sections to mock up the control drum vanes.

Composition 32 is a dummy composition whose cross sections contain response functions to obtain threshold fluxes and dose rates, using the activity calculation option in the DOT code as a function of mesh cell. Compositions 33, 34, and 35 are mixtures of other compositions which are obtained internal to the DOT code.

A-3.2.2 GEOMETRICAL MODEL

The analysis of a complex reactor geometry combined with the inclusion of slabs of shielding material atop the aft end of the system as existed in the PAX-E5 assembly experiments presents a formidable task for discrete ordinate transport analysis. As shown in Figures A3-4 and A3-6, slabs of Boral, polyethylene, steel, Inconel, titanium, and aluminum were combined in specific arrangements to simulate the cluster plate, support plate, flight shield, plena, and pressure vessel. For this analysis, it was necessary to represent the Boral slabs explicitly to avoid numerical inaccuracies and to homogenize together by conserving mass those materials such as aluminum, polyethylene and void, steel and Inconel, and titanium and void to conserve mesh in the transport model.

In addition, it was necessary to split Configuration 7D into two neutron transport problems, employing a total of 6,591 mesh cells. Problem 7D-1 represented the reactor assembly and slabs of mock-up material up to and including one shield module. Problem 7D-2 represented all six shield modules, the plena, and pressure vessel mock-up materials. The use of two problems provided the geometrical detail necessary for an accurate radiation and shielding analysis. The approach of "splitting" the geometry was possible because the WANL version of the two-dimensional discrete ordinate transport code, DOT, contains provisions for automatically performing a fixed boundary source calculation using as input either data cards or an angular flux tape from a previous DOT calculation. The latter approach was employed for analysis of Configuration 7D-2. One shield module was included in problem 7D-1 so that when the fixed boundary source was obtained in the void zone between the core support plate mock-up and the first flight shield mock-up module, an accurate representation of the returning neutrons from the shield would be included.

The mesh spacing used in the DOT problems was determined empirically from the largest total and corresponding scatter cross section as well as prior knowledge of the source of transported particles. Particles at any point in a region are produced by either fission sources or slowing down sources from higher groups or particles transported from neighboring points. If fission or slowing down sources are predominant, then the mesh spacing was relaxed.

A-3.2.2.1 Shield Configuration 4B

Figure A3-7 shows the PAX-E5 assembly geometry that was employed in the DOT analysis of shield Configuration 4B. Figure A3-7 is not drawn to scale, but is expanded to include a legible region description. The atom density composition numbers presented in Table A3-4 correspond to the numbers in parentheses shown in Figure A3-7. The mesh line coordinates presented in Table A3-5 correspond to the indices shown in Figure A3-7.

A-3.2.2.2 Shield Configuration 7D

Figure A3-8 shows the PAX-E5 assembly geometry that was employed in the DOT two-dimensional (r,z) neutron transport analysis of Configuration 7D-1. This figure is not drawn to scale, but is expanded to include a legible region description. The atom density composition numbers presented in Table A3-4 correspond to the numbers in parentheses shown in Figure A3-8. The mesh line coordinates presented in Table A3-6 correspond to the indices shown in Figure A3-8.

Figure A3-9 shows the PAX-E5 assembly geometry that was employed in the DOT analysis of Configuration 7D-2. As explained in Section A-3.2.2, this calculation was a fixed boundary source calculation. Figure A3-9 is not drawn to scale, but is expanded to include a legible region description. The atom density composition numbers presented in Table A3-4 correspond to the numbers in parentheses shown in Figure A3-9. The mesh line coordinates presented in Table A3-7 correspond to the indices shown in Figure A3-9.

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TABLE A3-1

SHIELD COMPOSITIONS

Configuration 48

Region Mockup Description	Material Thickness		Material	Density (gms/cc)	Area Density (gms/cm ²)
	(Inch)	(cm)			
Cluster Plate	0.375	0.95	Boral 80 w/o Al 20 w/o B ₄ C	2.59	2.47
Support Plate	4.50	11.43	Al-2219	2.76	31.49
Hydrogen	1.25	3.18	(CH ₂) ⁿ	0.914	3.00
Plenum Support	0.75	1.91	Steel	8.35	15.91
Boral	0.25	0.64	Boral 80 w/o Al 20 w/o B ₄ C	2.59	1.64
Pressure Vessel	0.625	1.59	Al-2219	2.86	4.54
Total Material Thickness	7.75	19.70		Total Area Thickness	59.05

Configuration 7D

Region Mockup Description	Material Thickness		Material	Density* (gms/cc)	Area Density (gms/cm ²)
	(Inch)	(cm)			
Cluster Plate, Support Plate, H ₂ , Plenum, Boral, PV	7.75	19.70	Configuration 48 (See Above)	3.00 (avg)	59.05
Shield	0.75	1.91	Inconel-718	8.75	16.71
Shield	1.50	3.81	Titanium	4.84	18.44
Shield	3.75	9.52	Al-2219	2.86	27.23
Shield	1.50	3.81	Polyethylene	0.914	3.48
Shield	2.25	5.71	Boral 80 w/o Al 20 w/o B ₄ C	2.59	14.79
Total Material Thickness	17.5	44.46		Total Area Density	139.70

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TABLE A3-2
(CRD) PAX-E5 CORE INVENTORY (U)

<u>Material Description</u>	<u>270 Degree Rezoned PAXD Mass (KG)</u>	<u>90 Degree NRX-A6 Mass (KG)</u>
<u>Fueled Elements</u>		
Uranium	109.315	43.812
Carbon	522.310	233.110
Niobium		
Coating	46.148	21.404
Wires	12.260	-
Molybdenum		
Coating	-	1.709
Wires	10.048	
<u>Unfueled Elements</u>		
Carbon		
Central	124.380	50.850
19-Hole	93.738	-
Partials	15.062	5.021
Tantalum	3.807	1.581
<u>Hardware</u>		
Pyrographite Sleeves	20.800	6.930
Steel Tie Rods	14.490	4.830
Steel Tube Liners	6,170	2.050

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TABLE A3-3
(CRD) PAX-E5 NON-CORE INVENTORY (U)

<u>Region</u>	<u>Material Description</u>	<u>Mass (KG)</u>
Filler Strip	Carbon (filler strips)	93.37
	Steel (lat. support bands)	1.66
Lateral Support	Carbon (liner plates)	109.96
	Steel (banding device)	4.24
	Steel (retainer screws)	1.29
	Aluminum (shutdown can)	1.98
Beryllium Reflector	<u>NRX-A6 Quadrant</u>	
	Carbon (plungers)	1.45
	Inconel (springs)	13.24
	Aluminum (caps)	2.98
	Titanium (tie bolts)	6.78
	Beryllium	
	$r < 51$ cm (plates)	48.84
	$r > 51$ cm (reflector body)	168.02
	<u>270 degree KIWI Sectors</u>	
	Aluminum (alignment shrouds)	13.53
	Titanium (tie bolts)	20.36
	Beryllium	
Control Drums	$r < 51$ cm (plates)	209.25
	$r > 51$ cm (reflector body)	453.59
Support Block	Beryllium	200.14
	Aluminum (shrouds)	20.11
	Carbon (support blocks)	35.86
	Carbon (cups, spacers, and washers)	1.76
	Molybdenum (cones)	1.46
	Steel (tie rod ends)	0.88

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(CRD) TABLE A3-3 (CONTINUED) (U)

<u>Region</u>	<u>Material Description</u>	<u>Mass (KG)</u>
Cluster Plate	Niobium (wires)	0.71
	Molybdenum (wires)	0.58
	Gd-SS (cluster plates)	8.50
	Steel (orifice mockups)	13.60
	Steel (springs)	6.70
	Steel (split bushings)	1.42
	Aluminum (cluster plate bushings)	2.00
	Steel (tie rod holder and nut)	11.51
	Steel (tie rod ends)	2.40

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TABLE A3-4

(CRD) COMPOSITION ATOM DENSITIES FOR TRANSPORT ANALYSIS OF PAX-E5 (ATOMS/BARN-CM) (U)

Description	Composition No.	1 H	2 Be	4 C	5 AL	6 Ti	7 Cr	8 Fe	9 Cu	10 Nb	11 MO	12 U ²³⁵	13 U ²³⁸	14 Ni	15 Mn	16 Ta	Others
Core (1)	1	8.125-6		6.864-2	6.272-6	9.715-6	7.457-5	9.790-5	1.331-6	7.473-4	1.201-4	5.409-4	3.977-5	2.139-4	5.323-6	3.246-5	
Core (2)	2	7.623-6		6.613-2	5.934-6	9.188-6	7.054-5	9.260-5	1.259-6	7.058-4	1.201-4	5.701-4	4.189-5	2.0235-4	5.035-6	2.210-5	
Core (3)	3	8.257-6		6.693-2	5.563-6	8.615-6	6.614-5	8.684-5	1.180-6	7.493-4	1.201-4	6.134-4	4.508-5	1.897-4	4.721-6	1.674-5	
Core (4)	4	7.707-6		6.382-2	6.137-6	9.505-6	7.296-5	9.577-5	1.302-6	6.994-4	1.201-4	5.639-4	4.146-5	2.093-4	5.208-6	9.695-6	
Core (5)	5	8.370-6		6.583-2	4.190-6	6.490-6	4.979-5	6.531-5	8.897-7	7.661-4	1.201-4	6.298-4	4.629-5	1.429.4	3.553-6	1.561-5	
Core (6)	6	9.314-6		7.551-2	8.903-6	1.379-5	1.058-4	1.388-4	1.889-6	6.059-4	1.201-4	4.709-4	3.460-5	3.036-4	7.553-6	1.328-7	
Core (7)	7	6.775-6		5.861-2	2.373-6	3.676-6	2.820-5	3.699-5	5.039-7	4.687-4	1.201-4	3.095-4	2.275-5	8.096-5	2.012-6	3.537-8	
Core (8)	8	8.711-6		7.621-2	1.526-5	2.363-5	1.813-4	2.380-4	3.239-6	4.252-4	1.201-4	1.626-4	1.195-5	5.205-4	1.294-5	2.274-7	
Core (9)	9	8.077-6		7.079-2	2.830-6	4.383-6	6.226-5	1.416-4	6.008-7	4.800-4	1.201-4	1.146-4	8.427-6	1.0918-4	5.252-6	4.220-8	
Filler Strip	10			8.619-2			4.282-4	1.458-3						1.897-4	4.259-5		
Lateral Support	11			6.117-2	1.221-3		1.829-4	6.232-4						8.111-5	1.819-5		
Beryllium Liner	12		1.23-1														
Beryllium Reflector	13		9.455-2			5.964-4			3.329-4								
Pressure Vessel	14				5.916-2				1.611-3								GD (17)
Cluster Plate	15				2.099-4	6.286-7	2.970-3	1.012-2	9.478-8					1.316-3	2.959-4	6.416-8	1.534-5
Support Plate	16				2.665-2	8.593-6	8.683-4	2.795-3		3.741-6				5.972-4	8.116-5	6.007-4	
Plenum	17						3.089-4	1.051-3						1.369-4	3.1000-5		
Aluminum Shield	18				5.507-2				1.491-3								
VOID	19																
Shaft-Shield	20				3.911-2	1.767-3	2.319-4	7.906-4	1.059-3					2.320-4	2.300-5		
Dome End Reflector	21				3.572-4	3.294-3	2.014-4	6.867-4						1.420-4	2.018-5		
Nozzle End Reflector	22				1.626-2	6.426-3	3.468-4	1.149-3		4.147-5				9.315-5	3.332-5		
Nozzle End Lateral Support	23			1.277-1	1.230-3		1.660-4	5.839-4						7.302-5	1.278-5		
Support Blocks	24			5.685-2			9.328-5	3.177-4			2.5157-4			4.133-5	9.795-6		(3) 10
Cluster Plate Mockup (Boral)	25			6.82-2	4.688-2												5.4058-3
Support Plate Mockup (Al)	26				5.916-2				1.61-3								
Plena Mockup (CH ₂)	27	7.850-2		3.954-2													
Inconel	28				1.845-3	2.858-3	1.532-2	6.240-3	3.920-4					5.996-2	9.060-4	2.750-4	
Titanium	29					5.658-2											
Stainless Steel	30						1.779-2	6.060-2						7.880-3	1.770-3		
Vane	31																
Activities	32																
Flight Shield Mockup																	
Boral	25			6.820-2	4.688-2												
Aluminum-Polyethylene-Void	33	2.415-2		1.216-2	2.276-2				6.19-4								
Aluminum	34				3.287-2				8.945-4								
Inconel-Titanium	35				6.143-4	3.869-2	5.101-3	2.077-3	1.305-4					1.996-2	3.016-4	9.156-5	

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TABLE A3-5

MESH COORDINATES FOR THE DOT NEUTRON TRANSPORT PROBLEM
FOR THE PAX-E5 ASSEMBLY GEOMETRY, CONFIGURATION 4B

<u>Radial Mesh No.</u>	<u>R (cm)</u>	<u>Axial Mesh No.</u>	<u>Z (cm)</u>	<u>Axial Mesh No.</u>	<u>Z (cm)</u>
1	0.0	1B	0.0	41B	212.669
2	7.0	2B	0.848	42	216.30
3	12.0	3B	5.239	43B	219.971
4B *	15.742	4	11.2	44B	223.781
5B	20.445	5	18.7	45B	224.416
6B	25.391	6	27.3	46B	228.226
7	28.95	7	34.8	47B	228.861
8B	32.491	8B	40.835	48B	232.671
9B	34.294	9	48.0	49B	233.306
10B	36.689	10B	55.349	50	233.95
11	38.1	11	60.0	51B	234.576
12B	39.480	12	65.0	52B	235.211
13	40.226	13B	70.519	53	236.16
14	40.973	14	70.70	54B	237.116
15B	41.719	15	71.75	55	237.50
16	42.235	16	73.20	56	238.07
17	42.75	17	73.40	57	238.62
18	43.277	18B	73.921	58B	239.021
19B	43.804	19	78.0	59	239.08
20	44.40	20	84.0	60	239.18
21B	45.127	21	92.0	61	239.27
22	46.277	22	101.0	62B	239.338
23B	47.427	23	110.0	63	240.125
24	48.67	24	120.0	64B	240.926
25	49.90	25	130.0		
26B	51.118	26	140.0		
27	52.3	27	150.0		
28	54.0	28	160.0		
29	56.0	29	170.0		
30B	57.722	30	179.0		
31	57.849	31	188.0		
32B	57.976	32	196.0		
33	59.0	33	202.0		
34	61.0	34B	206.001		
35B	63.185	35	208.85		
36B	64.033	36B	211.716		
37	66.4	37	211.77		
38B	68.786	38	212.02		
39	71.65	39	212.369		
40B	74.518	40	212.62		

* "B" Indicates a composition
boundary mesh line

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TABLE A3-6.

**MESH COORDINATES FOR THE DOT NEUTRON TRANSPORT PROBLEM
FOR THE PAX-E5 ASSEMBLY GEOMETRY, CONFIGURATION 7D-1**

<u>Radial Mesh No.</u>	<u>R (cm)</u>	<u>Axial Mesh No</u>	<u>Z (cm)</u>	<u>Axial Mesh No.</u>	<u>Z (cm)</u>
1	0.0	1B	0.0	41B	212.669
2	7.0	2B	0.848	42	216.30
3	12.0	3B	5.239	43B	219.971
4B*	15.742	4	11.2	44B	223.781
5B	20.445	5	18.7	45B	224.416
6B	25.391	6	27.3	46B	228.226
7	28.95	7	34.8	47B	228.861
8B	32.491	8B	40.835	48B	232.671
9B	34.294	9	48.0	49B	233.306
10B	36.689	10B	55.349	50	233.95
11	38.1	11	60.0	51B	234.576
12B	39.480	12	65.0	52B	235.211
13	40.226	13B	70.519	53B	236.163
14	40.973	14	70.70	54B	237.592
15B	41.719	15	71.75	55	237.65
16	42.235	16	73.20	56	237.75
17	42.75	17	73.4	57	237.85
18	43.277	18B	73.921	58B	237.909
19B	43.804	19	78.0	59	238.30
20	44.40	20	84.0	60	239.50
21B	45.127	21	92.0	61B	239.973
22	46.277	22	101.0	62	240.02
23B	47.427	23	110.0	63	240.17
24	48.67	24	120.0	64	240.41
25	49.90	25	130.0	65	240.56
26B	51.118	26	140.0	66B	240.608
27	52.3	27	150.0	67B	241.243
28	54.0	28	160.0		
29	56.0	29	170.0		
30B	57.722	30	179.0		
31	57.849	31	188.0		
32B	57.976	32	196.0		
33	59.0	33	202.0		
34	61.0	34B	206.001		
35B	63.185	35	208.85		
36B	64.033	36B	211.716		
37	66.4	37	211.77		
38B	68.786	38	212.02		
39	71.65	39	212.369		
40B	74.518	40	212.62		

* "B" indicates a composition boundary
mesh line

TABLE A3-7

MESH COORDINATES FOR THE DOT NEUTRON TRANSPORT PROBLEM
FOR THE PAX-E5 ASSEMBLY GEOMETRY, CONFIGURATION 7D-2

<u>Radial Mesh No.</u>	<u>R (cm)</u>	<u>Axial Mesh No.</u>	<u>Z (cm)</u>	<u>Axial Mesh No.</u>	<u>Z (cm)</u>
1	0.0	1B	0.0	41	15.398
2	7.0	2	0.794	42	16.827
3	12.0	3B	1.588	43B	17.779
4B*	15.742	4	1.63	44	18.414
5B	20.445	5	1.746	45	18.462
6B	25.391	6	1.85	46	18.612
7	28.95	7B	1.905	47	18.852
8B	32.491	8	2.30	48	19.002
9B	34.294	9	2.86	49	19.049
10B	36.689	10	3.40	50	19.522
11	38.10	11B	3.810	51	20.722
12B	39.480	12	4.762	52	21.113
13	40.226	13B	5.715	53	21.172
14	40.973	14	6.35	54	21.272
15B	41.719	15	6.398	55	21.372
16	42.235	16	6.548	56	21.43
17	42.75	17	6.788	57	22.859
18	43.277	18	6.938	58B	23.811
19B	43.804	19	6.985	59	24.446
20	44.40	20	7.458	60	24.494
21B	45.127	21	8.658	61	24.644
22	46.277	22	9.049	62	24.844
23B	47.427	23	9.108	63	25.034
24	48.67	24	9.208	64	25.081
25	49.90	25	9.308	65	25.554
26B	51.118	26	9.366	66	26.754
27	52.3	27	10.795	67	27.145
28	54.0	28B	11.747	68	27.204
29	56.0	29	12.382	69	27.304
30B	57.722	30	12.43	70	27.404
31	57.849	31	12.58	71	27.462
32B	57.976	32	12.82	72	28.891
33	59.0	33	12.97	73B	29.843
34	61.0	34	13.017	74	30.478
35B	63.185	35	13.49	75	30.526
36B	64.033	36	14.69	76	30.676
37	66.4	37	15.081	77	30.916
38B	68.786	38	15.14	78	31.066
39	71.65	39	15.24	79	31.113
40B	74.518	40	15.34	80	31.586

*"B" Indicates a composition boundary mesh line

TABLE A3-7

(CONTINUED)

<u>Axial Mesh No.</u>	<u>Z (cm)</u>
81	32.786
82	33.177
83	33.236
84	33.336
85	33.436
86	33.494
87	34.923
88B	35.875
89	36.51
90	36.558
91	36.708
92	36.948
93	37.098
94	37.145
95	37.618
96	38.818
97	39.209
98	39.268
99	39.368
100	39.468
101	39.526
102	40.955
103B	41.907
104B	42.2245

Figure A3-1. The PAX Reactor with Mock-up Nozzle in Place

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Figure A3-2. PAX-E5 Reactor Core and Reflector Configuration

Figure A3-3. Shield Configuration 4B in Position Above PAX Reactor

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Figure A3-4. Schematic of Shield Configuration 4B

Figure A3-5. Shield Configuration 7D in Place Above the PAX Reactor

Figure A3-6. Schematic of Shield Configuration 7D

MESH INTERVAL SPACING

NOTE: NUMBERS IN PARENTHESES ARE COMPOSITION NUMBERS CORRESPONDING TO TABLE A3-4. OTHER NUMBERS ARE REGION NUMBERS.

Figure A3-7. Neutron Transport Analysis Model of Configuration 4B

NOTE: NUMBERS IN PARENTHESES ARE COMPOSITION NUMBERS CORRESPONDING TO TABLE A3-4. OTHER NUMBERS ARE REGION NUMBERS.

Figure A3-8. Neutron Transport Analysis Model of Configuration 7D-1.

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APPENDIX A-4

FCX REACTOR

A-4.1 PHYSICAL DESCRIPTION AND GEOMETRY

The Flexible Critical Experiment (FCX) Reactor is described in detail in References 34 and 40. The information presented here is limited to that directly pertinent to the analysis. The reactor is basically a cylindrical two-region assembly consisting of a central zone with a homogeneous mixture of graphite and fully enriched uranium (graphite matrix with enriched U microsphere beads), and an outer zone (reflector) of graphite. Figure A4-1 gives a trimetric view of the assembly. Figure A4-2 is a cross-sectional view illustrating the arrangement of fueled and unfueled graphite elements in the reactor. Also shown are the core/reflector boundaries and the control rod positions.

Initial criticality of the assembly was attained with a loading of 253 fueled clusters in the core comprised of 1518 fueled and 253 unfueled elements and 320 unfueled clusters in the reflector composed of 2240 unfueled elements. All the elements in FCX are hexagonal in shape, measuring about 0.75 inch across the flats and 52 inches in length. The core clusters contain 6 fueled elements and 1 unfueled element, whereas the reflector clusters contain 7 unfueled elements. The elements are held together in a cluster arrangement with a 0.25-inch thick aluminum "cluster plate" on the top and bottom. This configuration is shown in Figure A4-3.

The control rod mechanisms for FCX are shown in the test stand in Figure A4-1. Figure A4-4 shows the detailed design of an individual FCX control rod assembly. The FCX control rod is a "fuel follower" type approximately twice the length of the core. The upper part of this rod is a 2-inch diameter stainless steel tube with a wall thickness of 53 mils which encases a cadmium-covered polyethylene cylinder. The polyethylene is 1.805 inches in diameter. The cadmium sleeve around it is 32 mils thick. The bottom portion of the rod contains fuel and graphite elements similar to the core constituents.

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(U) When the control rod is lowered into the core, the polyethylene rod acts as a "flux trap" and thermalizes the neutrons that enter it. When these neutrons are scattered out of the polyethylene cylinder, a large fraction are captured in the cadmium sheath.

(U) The core and reflector cluster assemblies in the FCX core are supported by a 1.5 inch thick aluminum support plate in which accurately spaced holes are drilled to locate the cluster plate support stubs.

A-4.2 (CRD) MATERIAL INVENTORY (U)

A-4.2 (CRD) Major Constituents of the Elements (C, U, Nb) (U)

(CRD) The fuel elements in the FCX core are composed primarily of carbon, uranium, and niobium and were manufactured at the WNCO (Westinghouse Astronuclear Core Operations) and at the ORNL Y-12 facility. These fuel elements contain pyrolytic graphite coated UC₂ microspheres distributed uniformly in a graphite matrix. The uranium is fully enriched (93.15 percent U-235). Each element contains 19 coolant channels which are coated with approximately 1.5 mils of niobium carbide. Two types of unfueled elements were used in FCX: those used in the fuel clusters were of the regular NRX type; the elements used for the graphite reflector were made of solid AGOT graphite. All the unfueled elements are threaded for 3/4 of an inch on both ends to receive a one-inch long, 0.5-inch diameter aluminum stud which holds the cluster plate in place.

(U) The FCX fuel elements were primarily elements from the NRX manufacturing process which were not suitable for high temperature testing. Approximately eighty percent of the fuel elements used had complete fuel inventory data available. The fuel content of the remaining 20 percent of the fuel elements was estimated from the known elements. Table A4-1 lists the number and kind of fuel elements used.

A-4.2.2 (U) Atom Densities (U)

(U) The geometrical model developed for the FCX ANISN and DOT calculations conserved in general the total volume envelope of the components assigned to each particular region in the model. Its overall form for the fueled and unfueled elements was that of a

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right circular cylinder of height equal to 132.08 cm (52 inches). An effective radius was computed for the array of elements assigned to the innermost core region. The effective outer radius of each subsequent region in the model was computed from the outer radius of the region it enclosed and the volume of fueled/unfueled elements assigned to it. Axially, the cluster plates, support blocks and void at the bottom of the reactor were homogenized into a single region. The cluster plate on top of the reactor was simulated by a region 1/4-inch thick. The geometrical model is shown in Figure A4-5.

Based on this geometrical model and the material inventory of FCX listed in Table A4-1, the atom densities were computed for each region. These are tabulated in Table A4-2. The values shown were used in the majority of FCX calculations. The mesh cell arrangement for the model in ANISN and DOT calculations is shown in Tables A4-3 and A4-4.

In order to include the effect of the control rod followers, a second geometrical model of FCX was developed. This model was similar to the initial model except the loss of fuel and graphite in the core due to allowances for insertion of seven circular fuel followers and control rods in the hexagonal array was accounted for. This model is shown in Figure A4-6. The atom densities applicable to this revised model appear in Table A4-5.

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TABLE A4-1

(CRD) FCX INITIAL MATERIAL INVENTORY (U)

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Region	No. of Elements With Data	Total Elements in FCX	Total Weights of Elements with Data, KG			FCX Total Wt. Inventory, KG			Weight, gm Element		
			C	U	Nb	C	U	Nb	C	U	Nb
Core:											
Unfueled Elements	244	253	120.680	--	--	125.131	--	--	494.59	--	--
Fuel Ele- ments Y-12	454	548	243.105	56.002	20.526	293.438	67.596	24.775	535.47	123.35	45.21
Fuel Ele- ments WAFF	<u>760*</u>	<u>970</u>	<u>405.745</u>	<u>97.720</u>	<u>9.8262</u>	<u>517.854</u>	<u>124.810</u>	<u>12.455</u>	<u>533.87</u>	<u>128.67</u>	<u>12.84</u>
Core Total	1458	1771	769.530	153.722	30.352	936.423	192.406	37.230	528.75	126.75	24.53
Reflector:											
Unfueled Elements	--	2240	--	--	---	1603.0	--	--	715.7	--	--

Includes the 7 follower clusters on the control rods, but does not include material inventory removed to allow for cylindrical control rods in a hexagonal array.

* Contains two code 79 elements, included in the actual weights but not in the average weight per element.

TABLE A4-2

(CRD) LIST OF ATOM DENSITIES FOR FCX (U)

Region	Description	Atom Density (atoms/cm ³ x 10 ⁻²⁴)				
		C	U	H	Nb	Al
1	Core	6.19642(-2)	6.49835(-4)	9.22047(-6)	3.47144(-4)	-----
2	Core	5.19642(-2)	6.49835(-4)	9.22047(-6)	3.47144(-4)	-----
3	Core	6.19642(-2)	6.49835(-4)	9.22047(-6)	3.47144(-4)	-----
4	Reflector	8.38634(-2)	-----	-----	-----	-----
5	Reflector	8.38634(-2)	-----	-----	-----	-----
6	Reflector	8.38634(-2)	-----	-----	-----	-----
7	Cluster Plate (Top)	-----	-----	-----	-----	6.025(-2)
8	Cluster Plate and Support Block (Bottom)	-----	-----	-----	-----	4.686(-2)

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TABLE A4-3

RADIAL MESH CELL BOUNDARIES USED FOR ANISN AND DOT CALCULATIONS

Radial Mesh Cell Number	Region Assigned to Cell (No. in Table A4-2 and Figure A4-5)	Inner Radius of Cell, cm
1	Core (1)	0.0
2	Core (1)	4.0
3	Core (1)	8.0
4	Core (1)	11.0
5	Core (1)	14.0
6	Core (1)	17.0
7	Core (1)	19.0
8	Core (1)	21.0
9	Core (1)	23.0
10	Core (1)	25.0
11	Core (1)	27.0
12	Core (1)	28.5
13	Core (1)	30.0
14	Core (1)	31.5
15	Core (1)	33.0
16	Core (1)	34.0
17	Core (1)	35.0
18	Core (2)	36.0
19	Core (2)	36.8
20	Core (2)	37.6
21	Core (2)	38.4
22	Core (2)	39.2
23	Core (2)	39.8
24	Core (2)	40.4
25	Core (3)	41.0
26	Core (3)	41.6
27	Core (3)	42.0
28	Core (3)	42.4
29	Reflector (4)	42.7424
30	Reflector (4)	43.1
31	Reflector (4)	43.9
32	Reflector (5)	45.0
33	Reflector (5)	46.5
34	Reflector (5)	48.5
35	Reflector (5)	50.5
36	Reflector (5)	52.5
37	Reflector (5)	55.0
38	Reflector (5)	57.0
39	Reflector (5)	59.0
40	Reflector (5)	60.5
41	Reflector (6)	62.0
42	Reflector (6)	63.5 64.3251

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TABLE A4-4

AXIAL MESH CELL BOUNDARIES USED FOR DOT CALCULATIONS

<u>Axial Mesh Cell Number</u>	<u>Region Assigned to Cell (No. in Table A 4-2 and Figure A 4-5)</u>	<u>Axial Position of Lower Cell Boundary, cm</u>
1	CP&SB*	0.0
2	CP&SB	2.33
3	CP&SB	4.03
4	CP&SB	5.71
5	Core (1)	8.83
6	Core (1)	12.33
7	Core (1)	16.33
8	Core (1)	20.33
9	Core (1)	25.33
10	Core (1)	30.33
11	Core (1)	36.33
12	Core (1)	42.33
13	Core (1)	49.33
14	Core (1)	56.33
15	Core (1)	64.33
16	Core (1)	71.73
17	Core (1)	80.33
18	Core (1)	88.33
19	Core (1)	95.33
20	Core (1)	102.33
21	Core (1)	108.33
22	Core (1)	114.33
23	Core (1)	119.33
24	Core (1)	124.33
25	Core (1)	128.33
26	Core (1)	132.33
27	Core (1)	135.33
28	Core (1)	136.52
29	CP*	137.79
30	CP	138.09
		138.43

* CP&SB = Cluster Plate and Support Block; CP = Cluster Plate.

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TABLE A4-5

(CRD) LIST OF ATOM DENSITIES FOR MODIFIED FCX MODEL (U)

Region	Description	Atom Density (atom/cm ³ x 10 ⁻²⁴)					
		C	U	H	Nb	Al	Stainless Steel*
1	Stainless Steel Rod	---	---	---	---	---	6.6970(-1)
2	Fuel in Fuel Follower	5.8350(-2)	6.0717(-4)	9.22047(-6)	2.976(-4)	---	---
3	Al and Stainless Steel Tubes	---	---	---	---	1.1600(-2)	7.3680(-2)
4	Core	6.19642(-2)	6.49835(-4)	9.22047(-6)	3.47144(-4)	---	---
5	Core with 6 Fuel Followers	4.52542(-2)	4.56465(-4)	9.22047(-6)	2.5237(-4)	2.1026(-5)	2.0074(-4)
6	Core	6.19642(-2)	6.49835(-4)	9.22047(-6)	3.47144(-4)	---	---
7	Core	6.19642(-2)	6.49835(-4)	9.22047(-6)	3.47144(-4)	---	---
8	Core	6.19642(-2)	6.49835(-4)	9.22047(-6)	3.47144(-4)	---	---
9	Reflector	8.38634(-2)	---	---	---	---	---
10	Reflector	8.38634(-2)	---	---	---	---	---
11	Reflector	8.38634(-2)	---	---	---	---	---
12	Cluster Plate (top)	---	---	---	---	6.025(-2)	---
13	Cluster Plate and Support Block (bottom)	---	---	---	---	4.686(-2)	---

*Volume fraction to be used with macroscopic cross section of pure stainless steel.

Figure A4-1. The FCX Reactor

Figure A4-2. FCX Final Configuration - A Cross-Sectional View

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Figure A4-3. Schematic of Typical FCX Cluster

Figure A4-4. FCX Control Rod Assembly

Figure A4-5. Geometrical Model of FCX Used for Nuclear Analysis
(All of the Dimensions Are in Centimeters)

Figure A4-6. A Modified Geometrical Model of FCX which Includes the Fuel Followers
(All of the Dimensions Are in Centimeters)

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TITLE (WISDM) Evaluation of the WANL Integrated Nuclear, Radiation and Shielding Standard Design Method	
	DOCUMENT NO. WANL-TME-2689, Volume 2	DATE September 1970
ABSTRACT The WANL Integrated Nuclear, Radiation and Shielding Standatd Design Method (WISDM) used at the Westinghouse Astronuclear Laboratory in nuclear and radiation design and analy- sis of the NERVA Nuclear Subsystem is described in this report. An evaluation of the accuracy of the WISDM methods and tech- niques is made by comparison with experimental results. WISDM is an integral part of an overall Design Engineering Method which is being developed to automate the mechanical, thermal, structural, nuclear, and radiation analyses and design of the NERVA Nuclear Subsystem.		
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