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Released 1994

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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DUN-645

HANFORD CODE C-65

2-10-66

MECHANICAL PROPERTIES
IRRADIATED ALUMINUM REACTOR PROCESS TUBING

FEBRUARY 10, 1966

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MECHANICAL PROPERTIES
IRRADIATED ALUMINUM REACTOR PROCESS TUBING

During CY-1962, the mechanical properties of irradiated process tubes were needed for proper design of replacement tools. A literature search revealed no information concerning the properties of 1100 alloy aluminum with irradiation as high as that being experienced in the Hanford Production Reactors. Samples from six process tubes were sent to the Radiometallurgy Laboratory for determination of the mechanical properties. This document presents the results obtained.

SUMMARY AND CONCLUSIONS

Samples from four irradiated and two unirradiated process tubes were sent to the Radiometallurgy Laboratory for measurement of the ultimate strength, 0.2% yield strength, percent elongation, and Rockwell H hardness. The results obtained are summarized on Tables I to V. Summaries and charts of the data are presented on Tables VI to VIII and Figures 1 to 8. Descriptions of the process tubes, the tube operating histories, and sampling procedures are presented in the Appendix.

In general, the data show that the strength and hardness of the portion of the tubes exposed to radiation increases immediately after installation in the reactors (within the first six months). The strength increases by approximately twenty-five percent and the hardness by about ten percent. During subsequent irradiation (up to ten years), the hardness increases gradually and the strength appears to remain essentially constant.

The maximum integrated flux for the samples was approximately 10^{22} nvt for fast as well as for thermal neutrons. Thermal neutrons are defined as having energies equal or less than 0.25 ev. Fast neutrons are defined as having energies larger than 0.18 Mev.

DISCUSSION

During CY-1962, considerable difficulty was experienced during splitting of process tubes prior to replacement. The problem was believed due partly to softening of the tubes after long irradiation. A literature search revealed no data for aluminum irradiation as long as that being experienced by the process tubes.

Samples from irradiated process tubes were sent to the Radiometallurgy Laboratory for determination of the mechanical properties (yield strength, ultimate strength, percent elongation, and Rockwell H hardness). Descriptions of the

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sampling procedures, the tubes sampled, and the operating conditions for these tubes are presented in the Appendix. The data obtained is presented on Tables I to V.

The data was analyzed by graphing the relative yield strength, hardness, and elongation versus the sample position in the tubes (see Figures 1 to 3). Also, the relative yield strength was plotted versus integrated fast neutron flux (Figure 4).

A word of caution is necessary before discussion of the curves and data. The samples came from irradiated process tubes which had up to ten years reactor residence. As a result, the surfaces of the samples were uneven because of corrosion. The samples were selected such that they appeared to have a smooth surface, but they undoubtedly had some unevenness. In addition, normal variation in measurements for presumably identical samples is about ten percent (+ 5 percent - see Table V). Too much emphasis should not be placed on the value obtained for a particular sample. Instead, the general story told by the samples for a tube should receive primary emphasis. The curves are comparable by family relationship - i.e., general trend - instead of by absolute value because of the variation in as-fabricated properties.

The curves are plotted as relative yield strength, etc., versus sample position in order to permit comparison between tubes of the change in properties along the length of the tubes. The actual values of yield strength, etc., for the unirradiated portions of the tubes vary by forty percent. This is a normal variation for tubes fabricated at different times. Graphs of absolute values show widely separated curves which are difficult to compare. The unirradiated properties for a tube were assumed to have been the average of the properties measured at distances of one foot and forty-one feet from the rear Van Stone flange (i.e., at the outer edges of the reactor shields). The relative values of the physical properties of each sample were obtained by dividing the average measured value for that sample by the unirradiated properties obtained as above for that tube (see Tables VI to VIII).

The reactor flux that these tubes experienced is assumed to have had a chopped cosine distribution along the length of the tube. The actual reactor flux distribution varies continuously in accordance with the control rod positions, fuel loading patterns, etc. During long periods of time (greater than two years), the average is normally a cosine. The maximum flux occurs at the reactor center (about 21 feet from the rear Van Stone flange) and drops to about one-eighth of the maximum at the ends of the fuel charge (about nine and 33 feet from the rear Van Stone flange). The location of the ends of the charge cannot be stated exactly because the length and location of the charge change to accommodate flow, corrosion, reactivity, and graphite problems.

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0.2% Yield Strength (Figures 1 and 4)

The yield strength of the tubes increases immediately with irradiation. The data for tube 1786-D shows that during the initial irradiation (7×10^{20} nvt integrated fast flux in five months), the yield strength increases approximately twenty-five percent at the point of maximum flux. The yield strength at this point in the tube then remains essentially constant with increased irradiation (up to 10^{22} nvt integrated fast flux - ten years residence).* The yield strength in the lower flux regions (e.g., samples from nine to 15 feet from the rear Van Stone flange) increases throughout the first ten years.

The data reflects the effect of temperature on strength. The samples from the front half of the tube had higher strength than samples experiencing the same flux in the back half of the tube. Over long periods of time, the strength of 1100 alloy aluminum is sensitive to the environmental temperatures.¹

Ultimate Strength

The change in ultimate strength with irradiation is essentially identical to the change in yield strength. The ultimate strength usually is about five percent higher than the yield strength (see Tables I to IV and Figures 5 to 8).

Percent Elongation (Figure 2)

The percent elongation appears to increase up to one-half with irradiation. This is an unexpected result since the elongation normally decreases as the strength increases. However, the scatter in the data makes conclusions difficult.

Rockwell Hardness H (Figure 3)

The hardness increases approximately ten percent immediately in the central high flux region of the reactor and decreases almost ten percent at the low flux downstream end of the fuel charge. The hardness then increases gradually with time, particularly at the downstream end of the fuel charge.

* The samples at the 21, 30, and 42 foot locations of tube 2758-C (ten years residence) still had the 7072 internal clad. This cladding is assumed to have a negligible effect on the strength measurements.

1. Alcoa Aluminum Handbook, Aluminum Company of America.

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The hardness data must be considered only as indicative of the general change in hardness. The measurements were made with the Rockwell "H" scale (1/8" ball, 60 KG load), because it was the best measurement available. Superficial hardness equipment was not available.

ACKNOWLEDGEMENT

Appreciation is expressed to G. W. Riedeman for assistance in analysis and interpretation of the data and to D. E. Strege for collection, preparation, and shipment of the samples.

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FIGURE 1
PROCESS TUBE YIELD STRENGTH

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FIGURE 2
PROCESS TUBE ELONGATION

FIGURE 3
PROCESS TUBE HARDNESS

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FIGURE 4
EFFECT OF IRRADIATION ON PROCESS TUBE YIELD STRENGTH

FIGURE 5
STRENGTH OF TUBE 1786-D
(7×10^{20} Maximum nvt)

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FIGURE 6
STRENGTH OF TUBE 4274-H
(3×10^{21} Maximum nvt)

FIGURE 7
STRENGTH OF TUBE 2661-H
(6×10^{21} Maximum nvt)

FIGURE 8
STRENGTH OF TUBE 2758-C
(1×10^{22} Maximum nvt)

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Table IPhysical Properties of Tube 1786-D

<u>Specimen</u>	<u>Sample Location*</u>	<u>Ultimate Strength</u> (psi)	<u>0.2% Yield Strength</u> (psi)	<u>Percent Elongation</u>	<u>Rockwell H Hardness</u>
1D-1	1	22,800	21,500	4.7	81.6
1D-2		22,600	19,100	5.7	86.8
1D-3		22,000	21,000	3.4	82.9
Average 1D		22,500	20,500	4.6	83.8
2D-1	9	18,100	17,200	2.8	76.3
2D-2		20,600	20,000	3.9	81.7
2D-3		20,600	17,700	4.3	60.2**
Average 2D		19,800	18,300	3.7	79.0
3D-1	15	24,500	20,600	5.4	89.0
3D-2		24,000	19,300	3.8	75.9
3D-3		24,400	22,300	8.3	85.4
Average 3D		24,300	20,700	5.8	83.4
4D-1	22	30,900	27,500	6.0	95.7
4D-2		27,900	24,800	5.3	87.3
4D-3		30,900	25,900	6.1	97.1
4D-4		30,600	26,300	6.4	96.0
Average 4D		30,100	26,100	6.0	94.0
5D-1	41	20,400	16,900	4.0	87.3
5D-2		22,000	21,400	3.3	86.5
5D-3		22,800	18,400	3.9	84.5
Average 5D		21,700	18,900	3.7	86.1

* Approximate feet from rear Van Stone flange.

** Abnormal value. Not included in average.

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Table II
Physical Properties of Tube 4274-H

<u>Specimen</u>	<u>Sample Location*</u>	<u>Thickness</u> (In.)	<u>Width</u> (In.)	<u>Ultimate Strength</u> (psi)	<u>0.2% Yield Strength</u> (psi)	<u>Percent Elongation</u>	<u>Rockwell H Hardness</u>
7-A		.067	.234	26,000	24,800	6.7	89.8
7-B		.065	.231	29,700	28,300	6.0	91.8
Average 7	1			27,800	26,600	6.4	90.8
8-A		.069	.234	26,300	25,200	6.5	90.5
8-B		.064	.207	32,800	31,400	5.9	88.1
8-C		.064	.242	23,900	23,000	6.5	86.3
Average 8	10			27,700	26,500	6.3	88.3
9-A		.058	.249	27,800	26,900	6.0	89.5
9-B		.059	.249	25,200	24,000	4.8	91.9
9-C		.058	.249	26,900	25,400	8.4	54.2**
Average 9	15			26,600	25,400	6.4	90.7
10-A		.062	.268	37,100	35,200	6.9	74.3**
10-B		.060	.241	35,200	33,100	10.4**	95.8
10-C		.063	.260	35,200	33,500	6.8	94.4
Average 10	21			35,800	33,900	6.8	95.1
11-A		.067	.249	38,400	36,800	6.1	97.0
11-B		.065	.240	40,500	39,700	6.7	102.5
Average 11	30			39,400	38,200	6.4	99.8
12-A		.065	.252	29,800	28,600	5.4	78.1**
12-B		.067	.232	29,900	29,000	5.7	89.8
12-C		.066	.255	28,200	27,500	6.9	88.2
Average 12	41			29,300	28,400	6.0	89.0

* Approximate feet from rear Van Stone flange.

** Abnormal value. Not included in average.

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Table IIIPhysical Properties of Tube 2661-H

<u>Specimen</u>	<u>Sample Location*</u>	<u>Thickness</u> (In.)	<u>Width</u> (In.)	<u>Ultimate Strength</u> (psi)	<u>0.2% Yield Strength</u> (psi)	<u>Percent Elongation</u>	<u>Rockwell H Hardness</u>
1-A	1	.052	.234	23,800	23,100	5.0	84.8
2-A**		.051	.242	23,600	23,300	8.5	88.8
2-B**		.046	.202	26,900	25,900	5.0	85.2
2-C**		.059	.245	24,900	23,800	6.0	89.2
Average 2	12			25,100	24,300	6.5	87.7
3-A		.056	.236	6,700	6,600	.5	92.7
3-B		.058	.238	17,200	16,700	5.5	91.1
3-C		.058	.239	22,200	21,500	4.7	88.4
Average 3	15			***	***	***	90.7
4-A		.062	.236	31,000	30,100	8.4	94.7
4-B		.059	.240	33,300	31,200	7.6	95.4
Average 4	21			32,200	30,600	8.0	95.0
6-A		.060	.239	26,200	25,500	6.0	91.0
6-B		.063	.238	28,300	26,800	6.2	91.7
6-C		.061	.237	31,800	31,000	6.3	94.1
Average 6	38			28,800	27,800	6.2	92.3

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* Approximate feet from rear Van Stone flange.

** Samples taken from bottom of tube.

*** Too much variation in measured properties. Data not used in correlations.

Table IV

Physical Properties of Tube 2758-C

<u>Specimen</u>	<u>Sample Location*</u>	<u>Thickness</u> (In.)	<u>Width</u> (In.)	<u>Ultimate Strength</u> (psi)	<u>0.2% Yield Strength</u> (psi)	<u>Percent Elongation</u>	<u>Rockwell H Hardness</u>
1C1		0.072	0.264	20,630	19,740	12.2	77.7
1C2		0.072	0.264	20,260	19,210	13.0	72.7
1C3		0.057	0.267	22,700	21,780	10.6	66.4
Average 1C	1			21,200	20,200	11.9	72.3
2C1		0.067	0.268	22,670	21,500	10.2	76.1
2C2		0.056	0.269	21,320	20,930	11.8	46.7**
2C3		0.070	0.268	20,640	19,790	19.1**	87.2
Average 2C	10			21,500	20,700	11.0	81.6
3C1		0.059	0.271	23,380	22,310	10.6	82.2
3C2		0.052	0.273	23,730	22,750	11.0	76.7
Average 3C	15			23,600	22,500	10.8	79.4
4C1		0.069	0.267	23,260	21,850	14.1	86.4
4C2		0.065	0.267	25,720	24,570	16.6	87.2
4C3		0.068	0.271	26,370	25,380	12.3	87.0
Average 4C	21			25,100	23,900	14.3	86.9
5C1		0.072	0.276	21,210	20,960	21.5	76.1
5C3		0.071	0.292	25,850	25,850	20.3	91.3
Average 5C	30			23,500	23,400	20.9	83.7
6C1		0.068	0.257	19,660	19,260	10.3**	65.4
6C2		0.072	0.269	18,080	17,880	20.2	73.6
6C3		0.066	0.270	18,480	18,030	18.4	38.4**
Average 6C	41			18,700	18,400	19.3	69.5

* Approximate feet from rear Van Stone flange.

** Abnormal value. Not included in average.

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Table V

Typical Physical Properties of Unirradiated Tubes

<u>Tube Number</u>	<u>Specimen</u>	<u>Thickness</u> (In.)	<u>Width</u> (In.)	<u>Ultimate Strength</u> (psi)	<u>0.2% Yield Strength</u> (psi)	<u>Percent Elongation</u>	<u>Rockwell H Hardness</u>
5	1	.069	.239	21,800	21,400	5.9	85.7
	2	.068	.238	24,000	23,300	6.0	85.9
	3	.067	.238	22,500	22,000	6.8	87.0
	4	.068	.238	23,100	22,700	6.2	84.8
	5	.063	.238	22,200	22,000	5.9	80.7
	6	.067	.238	23,600	23,100	5.5	80.9
	7	.064	.237	24,000	23,400	5.8	83.9
	8	.065	.238	22,400	22,100	5.3	85.1
	Average			23,000	22,500	5.9	84.2
6	A-1	.061	.230	24,600	23,800	5.7	90.0
	A-2	.062	.235	25,000	24,100	5.5	88.4
	A-3	.064	.237	24,000	23,400	5.1	86.1
	A-4	.061	.248	22,000	21,200	5.6	85.0
	A-5	.069	.249	21,500	20,800	5.6	-
	Average			23,400	22,700	5.5	87.4

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Table VI

Summarized Strength Data

Sample Position (Ft. from Rear Van Stone Flange)	Average Yield Strength (psi)							
	Tube 1786-D		Tube 4274-H		Tube 2661-H		Tube 2758-C	
	Average	Relative	Average	Relative	Average	Relative	Average	Relative
1	20,500	1.041	26,600	0.967	23,100	1.000	20,200	1.047
9	18,300	0.929	-	-	-	-	-	-
10	-	-	26,500	0.964	-	-	20,700	1.073
12	-	-	-	-	24,300	1.052	-	-
15	20,700	1.051	25,400	0.924	-	-	22,500	1.166
21	-	-	33,900	1.233	30,600	1.325	23,900	1.238
22	26,100	1.325	-	-	-	-	-	-
30	-	-	38,200	1.389	-	-	23,400	1.212
38	-	-	-	-	27,800	1.203	-	-
41	18,900	0.959	28,400	1.033	-	-	18,400	0.953
Average Front and Rear	19,700	1.000	27,500	1.000	23,100	1.000	19,300	1.000

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Table VII

Summarized Elongation Data

Sample Position (Ft. from Rear Van Stone Flange)	Average Elongation							
	Tube 1786-D		Tube 4274-H		Tube 2661-H		Tube 2758-C	
	Average	Relative	Average	Relative	Average	Relative	Average	Relative
1	4.6	1.11	6.4	1.03	5.0	1.00	11.9	0.76
9	3.7	0.89	-	-	-	-	-	-
10	-	-	6.3	1.02	-	-	11.0	0.71
12	-	-	-	-	6.5	1.30	-	-
15	5.8	1.40	6.4	1.03	-	-	10.8	0.69
21	-	-	6.8	1.10	8.0	1.60	14.3	0.92
22½	6.0	1.45	-	-	-	-	-	-
30	-	-	6.4	1.03	-	-	20.9	1.34
38	-	-	-	-	6.2	1.24	-	-
41	3.7	0.89	6.0	0.97	-	-	19.3	1.24
Average Front and Rear	4.15	1.00	6.20	1.00	5.00	1.00	15.6	1.00

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Table VIII

Summarized Hardness Data

Sample Position (Ft. from Rear Van Stone Flange)	Average Hardness							
	Tube 1786-D		Tube 4274-H		Tube 2661-H		Tube 2758-C	
	Average	Relative	Average	Relative	Average	Relative	Average	Relative
1	83.8	0.986	90.8	1.010	84.8	1.000	72.3	1.020
9	79.0	0.930	-	-	-	-	-	-
10	-	-	88.3	0.982	-	-	81.6	1.151
12	-	-	-	-	87.7	1.034	-	-
15	83.4	0.982	90.7	1.009	90.7	1.070	79.4	1.120
21	-	-	95.1	1.058	95.0	1.120	86.9	1.226
22½	94.0	1.107	-	-	-	-	-	-
30	-	-	99.8	1.110	-	-	83.7	1.181
38	-	-	-	-	92.3	1.088	-	-
41	86.1	1.014	89.0	0.990	-	-	69.5	0.980
Average Front and Rear	85.0	1.000	89.9	1.000	84.8	1.000	70.9	1.000

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APPENDIX A

SAMPLING PROCEDURE

The four process tubes selected for sampling were normal production reactor aluminum tubes removed after varying amounts of reactor residence. A description of the tubes and their operating conditions is presented in Appendix B.

It was intended that six samples be obtained from each tube. These samples were to be taken from the top half of the tube at the following locations:

1. Approximately one foot from the rear Van Stone flange.
2. Approximately ten feet from the rear Van Stone flange.
3. Approximately 15 feet from the rear Van Stone flange.
4. Approximately 21 feet from the rear Van Stone flange.
5. Approximately 30 feet from the rear Van Stone flange.
6. Approximately one foot from the front Van Stone flange
(41 feet from the rear Van Stone flange).

Obtaining satisfactory samples was difficult because the samples should have uniform thickness. Corroded reactor process tubes usually have non-uniform internal surfaces with numerous locations of accelerated local corrosion. In addition, the average wall thickness varies rapidly along the length and around the circumference of the tube in the vicinity of the outlet end of the fuel charge (nine to fifteen feet from the rear Van Stone flange). The samples used appeared to have no areas of accelerated local corrosion and were selected such that the measured average wall thickness at each end of the sample did not differ by more than 0.002 inches. In one case, because a satisfactory sample could not be obtained from the top of the tube, the sample was taken from the bottom (Sample 2 of Tube 2661-H). Also, some samples could not be obtained because of process tube damage during removal from the reactor.

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APPENDIX B

DESCRIPTION OF PROCESS TUBES

The aluminum samples described in this document were obtained from normal small Hanford production reactor aluminum process tubes. These tubes are approximately forty-two feet long and one and three-quarters inches in diameter. They have an average wall thickness of approximately 0.065 inches when installed. There are two internal ribs in the bottom half of the tubes. All tubes sampled were fabricated from 1100 H18 alloy aluminum. One tube (2758-C) also had an approximately 0.007 inch internal cladding of 7072 alloy.

The tubes penetrate the reactor horizontally from front to rear. At the two ends, they are supported and protected by gunbarrels penetrating the shields and entering the graphite. The central portion of the tube lies in a graphite channel and contains fuel elements. Each gunbarrel supports a nozzle assembly which has a coolant connection and a cap for access to the tube. A Van Stone flange on each end of the tube is clamped between the nozzle and the gunbarrel to provide a seal for both the coolant and the reactor atmosphere. The single-pass coolant enters the front of the tube, flows down the tube past the fuel elements, and then exits from the rear end of the tube. Distances along the length of the tube normally are referred to the rear Van Stone flange (RVSF) as the base.

During reactor operation, the tubes corrode internally. Since the corrosion rate increases with temperature, the downstream (rear) portion of the tubes corrodes more rapidly than the upstream portion. Essentially no corrosion occurs in the upstream third of the tubes.

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Table IX

Description of Tubes Sampled

Tube number	1786-D	4274-H	2661-H	2758-C
Installation date	1/12/64	8/1/59	7/27/56	11/18/52
Removal date	6/22/64	8/1/62	8/7/62	12/7/62
Heat removal (MWD)*	158	810	1471	2382
Tube composition				
Base metal	1100-H18	1100-H18**	1100-H18**	2S (1100)**
Internal clad	None	None	None	72S
Tube dimensions				
ID (inches)	1.598	1.598	1.598	1.633
OD (inches)	1.729	1.729	1.729	1.764
Length (feet)	42	42	42	42
Internal clad (inches)	0	0	0	0.003 to 0.010

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* Total heat removal by coolant flowing through tubes. Includes heat generated in fuel plus heat conducted to tube from surrounding graphite and shielding.

** Alloy confirmed by spectrographic analysis.

Table X

Process Tube Fuel Charges

<u>Tube No.</u>	<u>Period</u>	<u>Number Fuel Charges</u>	<u>Heat Generation (MWD)</u>	<u>Type Fuel</u>	<u>Charge Length (feet)</u>
1786-D	1/64 to 6/64	2	158	Natural	24
4274-H	8/59 to 8/62	11	810	0.95% enriched	19
2661-H	7/56 to 5/61	16	1177	Natural	24
	5/61 to 1/62	2	174	0.95% enriched plus target elements	24
	1/62 to 8/62	2	<u>120</u>	Natural	24
			1471		
2758-C	11/52 to 12/52	1	3	Natural	24
	12/52 to 10/53	1	128	Natural plus U-235-Al alloy	20
	10/53 to 12/60	33	1655	Natural	24
	12/60 to 2/61	1	54	0.95% enriched	19
	2/61 to 12/62	9	<u>542</u>	Natural	24
			2382		

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APPENDIX C

PROCESS TUBE INTEGRATED NEUTRON FLUX

Objective:

To determine the integrated neutron flux for process tubes removed from the small reactors.

Basic Data and Assumptions:

1. Cosine flux distribution from front to rear.
2. Flux data for 1 kw/foot and natural fuel

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<u>Type Flux</u>	$\frac{nv}{\text{(Volume Averaged)}}$
Thermal ($\bar{E} < 0.25 \text{ ev}$)	0.97×10^{12}
Intermediate ($0.25 \text{ ev} < E_n < 0.18 \text{ Mev}$)	0.81×10^{12}
Fast ($> 0.18 \text{ Mev}$)	0.92×10^{12}

Source: HW-74094, Vol. 2, pp. 22-24, for natural fuel at 400 MWD/T.

3. The fast flux in the tube is 0.8875 times as high as the volume average fast flux in the fuel.
4. The intermediate flux in the tube is 1.03 times the volume average fast flux in the fuel.
5. The thermal flux in the tube is 1.26 times the volume averaged thermal flux in the fuel.
6. A natural fuel charge is 23.58 feet long.
7. The thermal flux in a lattice containing enriched fuel equals 116 percent of the thermal flux in a lattice operating at the same power with natural fuel.
8. The fast and intermediate flux in a lattice containing enriched fuel is the same as the fast flux in a lattice operating at the same power with natural fuel.
9. The volume average flux at the center of a lattice equals 1.4174 times the volume average flux for chopped cosine front to rear flux.

Calculations:

Basis: 1 MWD of heat generation

If the average heat generation is 1 kw/foot, the total heat generation is 23.58 kw for one lattice unit (or process tube) containing a natural fuel charge.

The time required to generate one MWD would be:

$$\frac{(1,000 \text{ kw})(86,400 \text{ sec.})}{(23.58 \text{ kw})} = 3.6641 \times 10^6 \text{ sec.}$$

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And the nvt for the center of the tube containing a natural fuel charge would be:

a. Thermal

$$(\text{Time}) \left(\frac{\text{Central volume average flux}}{\text{Volume average flux}} \right) (\text{Volume average flux in fuel}) \times$$

$$\left(\frac{\text{Volume average flux in tube}}{\text{Volume average flux in fuel}} \right)$$

$$= (3.6641)(10^6)(1.4174)(0.97)(10^{12})(1.26)$$

$$= 6.35 \times 10^{18} \text{ nvt/MWD}$$

b. Intermediate

$$= 4.33 \times 10^{18} \text{ nvt/MWD}$$

c. Fast (>0.18 MEV)

$$= 4.24 \times 10^{18} \text{ nvt/MWD}$$

The nvt for the center of a tube containing an enriched fuel charge would be:

a. Thermal

$$(\text{nvt for natural charge}) \left(\frac{\text{Thermal flux in natural fuel}}{\text{Thermal flux in enriched fuel}} \right)$$

$$(6.35 \times 10^{18})(1.16) = 7.37 \times 10^{18} \text{ nvt/MWD}$$

b. Intermediate

$$= 4.33 \times 10^{18} \text{ nvt/MWD}$$

c. Fast (>0.18 MEV)

$$= 4.24 \times 10^{18} \text{ nvt/MWD}$$

The neutron exposures for the process tube samples then become:

Sample Location (Ft. from RVSF)	Relative Neutron Flux*	Integrated Neutron Flux (nvt x 10 ²¹)											
		1786-D			4274-H			2661-H			2758-C		
		Fast	Inter.	Thermal	Fast	Inter.	Thermal	Fast	Inter.	Thermal	Fast	Inter.	Thermal
1	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0.12	0.1	0.1	0.1	-	-	-	-	-	-	-	-	-
10	0.26	-	-	-	0.9	0.9	1.6	-	-	-	2.6	2.7	3.9
12	0.49	-	-	-	-	-	-	3.1	3.1	4.6	-	-	-
15	0.75	0.5	0.5	0.8	2.6	2.6	4.5	4.7	4.8	7.0	7.6	7.7	11.3
21	1.00	-	-	-	3.4	3.5	6.0	6.2	6.4	9.3	10.1	10.3	15.1
22	1.00	0.7	0.7	1.0	-	-	-	-	-	-	-	-	-
30	0.49	-	-	-	1.7	1.7	2.9	-	-	-	4.9	5.0	7.4
38	**	-	-	-	-	-	-	**	**	**	-	-	-
41	0	0	0	0	0	0	0	-	-	-	0	0	0

* Chopped cosine front-to-rear flux distribution.

** Location is inside reactor biological shield. Local flux is not known.

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