Calvert Cliffs Units #1 and #2
Reactor Vessel Beltline Materials

Revision 02

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FORWARD

In order to comply with the requirements of 10CFR50.61 (b)(1) as advertised in the Federal Register, May 15, 1991, Baltimore Gas & Electric Company has compiled the information necessary to perform the Pressurized Thermal Shock (PTS) rule calculations for RT_{PTS}. The PTS screening criteria will be exceeded for Unit #1 at a fluence of 2.61×10^{19} n/cm² on axial weld 2-203. The PTS screening criteria will not be exceeded on Unit #2 at fluences less than 10^{20} n/cm².

ILLUSTRATIONS

FIGURE

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1.0 History

The reactor vessels for Calvert Cliffs Unit #1 and Unit #2 were fabricated by Combustion Engineering (CE) at Chattanooga Works, Tennessee for Combustion Engineering Power System Division in Windsor, Connecticut. The vessels were fabricated of formed and welded SA 533, Grade B, Class 1 plates. This was the normal fabrication technic at the Chattanooga facility. For the Calvert Cliffs vessels, CE employed a submerged arc welding process using a Mil B-4 Modified (Mn-Mo-Ni) wire with nickel in the range of 0.6 to 1.1 wt%. The Mil B-4 Modified (Mn-Mo-Ni) welds were produced with either a Linde 1092, 0091, or 124 flux. Welding procedures included both single and tandem arc processes. A list of the reactor vessel beltline materials for Calvert Cliffs Unit #1 and Unit #2 appear in Table No. 1-1 and 1-2 respectively (Reference #7 & #8). The location of these materials in the beltline region are shown in Figure No. 1-1

CALVERT CLIFFS UNIT #1 REACTOR VESSEL BELTLINE MATERIALS
TABLE NO. 1-1

WELD MATERIALS (Mil B-4 modified Ni-Mn-Mo):

ID	TYPE	WIRE(S)	FLUX TYPE	LOT NO.
2-203-A,B,C	Longitudinal Tandem Arc	20291 12008	1092	3833
3-203-A,B,C	Longitudinal Tandem Arc	21935	1092	3869
9-203	Girth Single Arc	33A277	0091	3922

PLATE MATERIALS (ASME SA 533, Grade B, Class 1):

ID	LOCATION
D-7206-1,2,3	Intermediate Shell Plate
D-7207-1,2,3	Lower Shell Plate

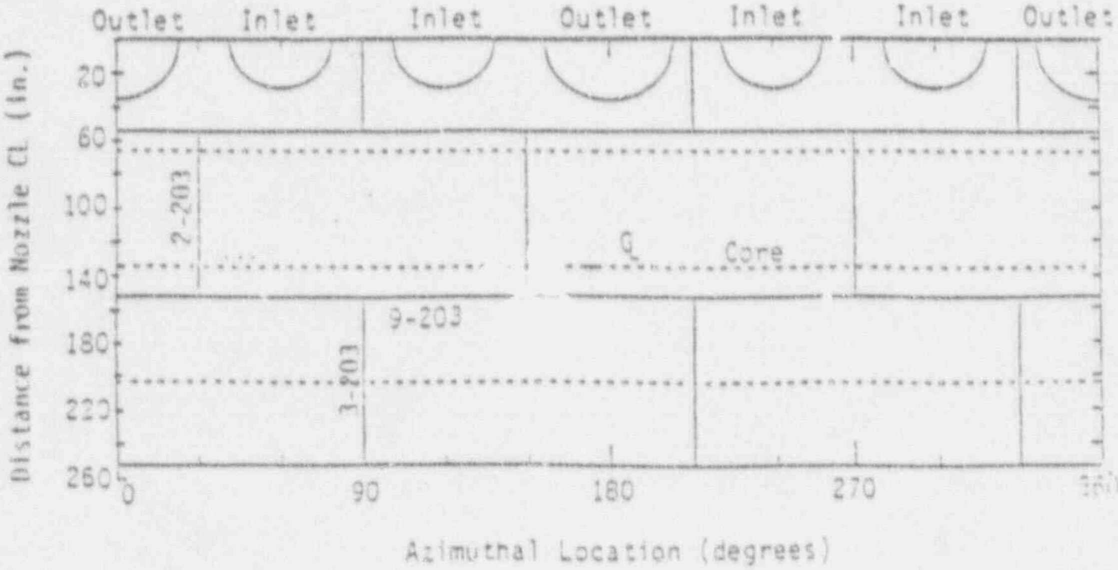
CALVERT CLIFFS UNIT #2 REACTOR VESSEL BELTLINE MATERIALS
TABLE NO. 1-2

WELD MATERIALS (Mil B-4 modified Ni-Mn-Mo):

ID	TYPE	WIRE(S)	FLUX TYPE	LOT NO.
2-203-A,B,C	Longitudinal Tandem Arc	8746	124	3878
3-203-A,B,C	Longitudinal Tandem Arc	33A277	0091	3922
9-203	Girth Single Arc	10137	0091	3999

PLATE MATERIALS (ASME SA 533, Grade B, Class 1):

ID	LOCATION
D-8906-1,2,3	Intermediate Shell Plate
D-8907-1,2,3	Lower Shell Plate



CALVERT CLIFFS REACTOR PRESSURE VESSEL MAP
FIGURE 1-1

2.0 Background Information On Beltline Materials

2.1 Plates

The six plate sections used to fabricate the beltline region have been well characterized with respect to chemistry and mechanical properties by Combustion Engineering (References #1 and #2).

2.2 Welds

The chemical composition and mechanical properties of the wire/flux combinations used in the surveillance programs were well characterized originally (Reference #3). The composition and mechanical properties of other welds have been established by reviews of original fabrication records.

BG&E contracted CE in late 1981 to perform a search of their records at Chattanooga. These results were issued in a transmittal from Kruse (CE) to Titland (BG&E) dated January 11, 1982 (Reference #4). Included were available wire chemistries and chemical analysis of weld deposits for certain wire/flux combinations. Although this information did not provide data necessary for all the welds it was helpful in providing insight into the relationship between weld wire chemistries and weld deposit chemistries. The general conclusions that have been drawn from the available data are the following (Reference #4 and #5).

1. In general, the flux Lot No. has little or no effect on the deposit analysis with respect to copper and nickel contents.

2. The nickel content of the wire is very similar to that of the weld deposit (See Figure No. 2).

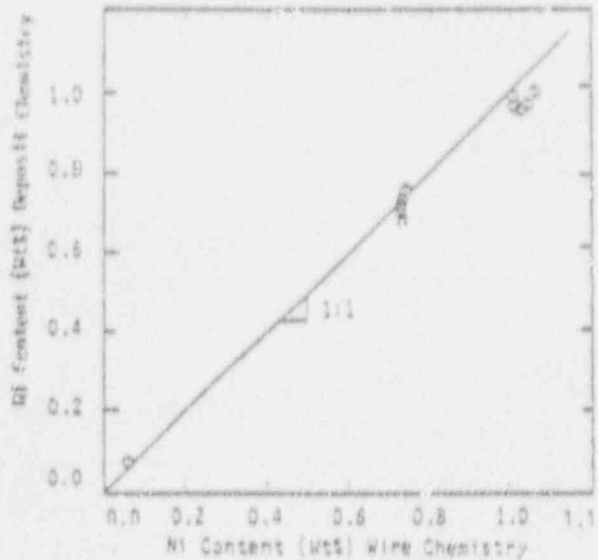
3. The copper content of the weld deposit is not accurately reflected by the copper content of the wire (See Figure No. 3). It is generally higher in the weld deposit than in the weld wire.

4. A review of the data indicated that the composition of the weld deposit made with two different wires (Tandem Arc Process) can be estimated accurately by an arithmetic average of deposit chemistries of individual wires. For a more detailed explanation, see Reference #5.

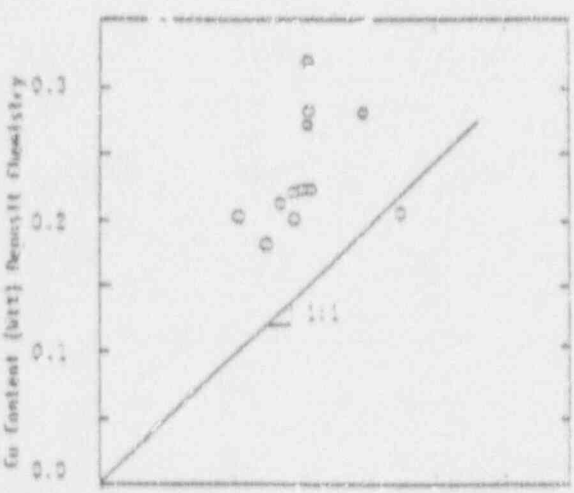
During a review of the material surveillance data base MATSURV (Reference #6) EPRI discovered that some of the weld wire used in the Calvert Cliffs beltline welds was also used in the fabrication of the surveillance blocks for the Cooper Station reactor. Under EPRI Contract #RP 2180-5, the General Electric Company generated chemical composition and mechanical property data on the Cooper weldments removed from archival sections at GE Nuclear Center at Vallecitos, California.

In early 1983, BG&E contracted with CE to compile and reproduce records which document the materials of the Calvert Cliffs Unit #1 and Unit #2 reactor vessels (Reference #7 and #8).

EPRI compiled a reactor vessel surveillance program data base (Reference #9). The data base contains information on irradiated material from surveillance programs. A search of this data base in January, 1986 revealed that a particular wire/flux combination used in Calvert Cliffs beltline welds was also used in the fabrication of surveillance blocks for Duke Power Company's William B. McGuire Unit #1. Since this material was used in the production of surveillance blocks, the chemical composition and mechanical properties were both well characterized (Reference #10).



CORRESPONDENCE BETWEEN Ni CONTENT OF THE WELD WIRE AND Ni CONTENT OF THE DEPOSITED WELD METAL (REFERENCE #5)
FIGURE 2-1



LACK OF CORRESPONDENCE BETWEEN Cu CONTENT OF THE WELD WIRE AND Cu CONTENT OF THE DEPOSITED WELD METAL (REFERENCE #5)
FIGURE 2-2

3.0 Determination Of Chemical Composition and Mechanical Properties

3.1 Chemical Composition

The information compiled in Section 2.0 from various sources has been used to determine the chemical composition of materials in the Calvert Cliffs reactor vessels beltline regions. The following guidelines were used to determine the chemical composition of the welds (see Appendix A):

1. Copper content for a particular wire/flux combination was determined from deposited weld metal chemical analyses using the same wire/flux combination (the flux Lot No. may vary).

2. Nickel content of a weldment was determined from both weld wire chemical analyses and deposited weld metal chemical analyses.

3. For Tandem arc processes the chemical composition from the single wires were averaged to determine the chemical composition of the weldment when tandem deposit chemical analyses were not available.

Chemical compositions for the welds were determined in Appendix A by averaging the data compiled in accordance with the above guidelines. Note that in Appendix A the analysis numbers with an "R" as a prefix indicates a weld wire chemical analysis and the analyses numbers with "D" as a prefix indicates a weld deposit chemical analysis. All remaining alloy determinations (surveillance capsule, EPRI, etc.) are also from weld deposit chemical analyses.

The compositions of the plates are well documented in References #1 and #2.

3.2 Mechanical Properties

Initial RT_{NDT} values for some of the weldments in the beltline region of Calvert Cliffs reactor vessels were determined by measurements made in the Calvert Cliffs surveillance programs for specific wire/flux combinations. Initial RT_{NDT} for wire/flux combinations in some welds at Calvert Cliffs was determined from measurements made in the William B. McGuire Unit #1 Surveillance Program. For all other wire/flux combinations used, the generic mean value was assigned in accordance with 10 CFR, Part 50.61.

The initial RT_{NDT}s for the plates are well documented in Reference #7 and #8.

4.0 Determination of Limiting Fluence

Estimated chemistries from Appendix A were used in conjunction with the requirements of 10CFR, Part 50.61 (b.2.IV) to determine the chemistry factors for each beltline material. Tables 4-1 and 4-2 provide a summary of estimated chemistries, initial RT_{NDT}, initial upper shelf energies and prescribed chemistry factors for Calvert Cliffs Unit #1 and Unit #2 respectively. Using the equation prescribed by 10CRF50.61 (b)(2), $RT_{PTS} = I + M + \Delta RT_{PTS}$, and rearranging to determine the maximum permissable RT_{PTS} (270 °F for plates, forgings, and axial welds, or 300 °F for circumferential welds) the maximum change in RT_{PTS} was calculated for each material.

$$\Delta RT_{PTS}^{(Limiting)} - I - M = RT_{PTS}^{max}$$

Where I = initial RT_{NDT}
M = Margin

The actual ΔRT_{PTS} is calculated using the equation:

$$\Delta RT_{PTS} = (CF) f^{(0.28 - 0.10 \log f)}$$

Where CF is the chemistry factor and f is the neutron fluence in units of 10^{19} n/cm². The value at which the screening criteria is exceeded can be determined by taking the ratio between the maximum RT_{PTS} and the chemistry factor.

i.e., $F_{max} = \Delta RT_{PTS}^{max}/(CF)$

Where $F_{max} = f^{(0.28 - 0.10 \log f)}$

The values for Initial RT_{NDT}, Margin, RT_{PTS}, and limiting values of F are presented in Table 4-3. The lowest value of F in Unit #1 is 1.257 which corresponds to a fluence of 2.61×10^{19} n/cm². The lowest value of F in Unit #2 is 1.615 which corresponds to a fluence greater than 10^{20} n/cm².

TABLE NO. 4-1:

CALVERT CLIFFS UNIT #1 REACTOR VESSEL BELTLINE MATERIAL

ID	Cu (w/o)	Ni (w/o)	INITIAL RT_{NDT} (°F)	CHEMISTRY FACTOR	INITIAL USE (Ft - Lb)
2-203-A,B,C	0.21(a)	0.88(a)	-50.0(b)(g)	210	110.0 (b)(g)
3-203 A,B,C	0.21(a)	0.69(a)	-56.0(c)	179	NA
9-203	0.23(a)	0.23(a)	-80.0(d)	121	158.0 (d)
D-7206-1	0.11(e)(h)	0.55(e)(h)	20.0(f)(h)	74	90.0(f)(h)
D-7206-2	0.12(e)(h)	0.64(e)(h)	-30.0(f)(h)	84	81.0(f)(h)
D-7206-3	0.12(e)(h)	0.64(e)(h)	10.0(f)(h)	84	112.0(f)(h)
D-7207-1	0.13(e)(h)	0.54(e)(h)	10.0(f)(h)	90	77.0(f)(h)
D-7207-2	0.11(e)(h)	0.56(e)(h)	-10.0(f)(h)	74	90.0(f)(h)
D-7207-3	0.11(e)(h)	0.53(e)(h)	-20.0(f)(h)	74	81.0(f)(h)

a. See chemistry data in Appendix for sources.

b. Davidson, J.A. and Yanicko, S.E., "Duke Power Company William B. McGuire Unit #1 Reactor Vessel Radiation Surveillance Program", WCAP-91995, November 1977

c. Generic mean value.

d. Byrne, S.T., Biemilier, E.L., and Ragl, A., "Testing and Evaluation of Calvert Cliffs Unit #1 and Unit #2 Reactor Vessel Materials Irradiation Surveillance Program Baseline Samples", Combustion Engineering, TR-ESS-001, January 31, 1975.

e "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Calvert Cliffs Unit #1 Reactor Vessel Materials", Combustion Engineering, CENPD-34, February 4, 1972.

f. These values have been corrected for the transverse charpy direction in accordance with NRC Branch Technical position MTEB 5-2 when required.

g. "Reactor Vessel Weld Materials for Calvert Cliffs Unit #1 Supplemental Surveillance Program", Combustion Engineering, 02987-MCC-002, November 1989.

h. "Baltimore Gas & electric Unit #1 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Materials Test Reports, and Base Materials Test Reports", Combustion Engineering Contract No. 72167.

TABLE NO. 4

CALVERT CLIFFS UNIT #2 REACTOR VESSEL BELTLINE MATERIAL

ID	Cu (w/o)	Ni (w/o)	INITIAL RT_{NDT} (°F)	CHEMISTRY FACTOR	INITIAL USE (Ft - Lb)
2-203-A,B,C	0.12(a)	1.01(a)	-56.0(b)	161	NA
3-203 A,B,C	0.23(a)	0.23(a)	-80.0(c)	121	158.0(c)
9-203	0.22(a)	0.05(a)	-60.0(c)	101	125.0(c)
D-8906-1	0.15(d)(f)	0.56(d)(f)	10.0(e)(f)	108	77.0(e)(f)
D-8906-2	0.11(d)(f)	0.56(d)(f)	10.0(e)(f)	74	74.0(e)(f)
D-8906-3	0.14(d)(f)	0.55(d)(f)	5.0(e)(f)	98	75.0(e)(f)
D-8907-1	0.15(d)(f)	0.60(d)(f)	-8.0(e)(f)	110	83.0(e)(f)
D-8907-2	0.14(d)(f)	0.66(d)(f)	10.0(e)(f)	102	115.0(c)
D-8907-3	0.11(d)(f)	0.74(d)(f)	-16.0(e)(f)	77	84.5(e)(f)

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a. See chemistry data in Appendix for sources.

b. Generic mean value.

c. Byrne, S.T., Biemiller, E.L., and Ragl, A., "Testing and Evaluation of Calvert Cliffs Unit #1 and Unit #2 Reactor Vessel Materials Irradiation Surveillance Program Baseline Samples", Combustion Engineering, TR-ESS-001, January 31, 1975.

d. "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Calvert Cliffs Unit #2 Reactor Vessel Materials", Combustion Engineering, CENPD-48, August 15, 1972.

e. These values have been corrected for the transverse charpy direction in accordance with NRC Branch Technical Position MTEB 5-2, where required.

f. "Baltimore Gas & Electric Unit #2 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Materials Test Reports, and Base Materials Test Reports", Combustion Engineering Contract No. 73167.

TABLE NO. 4-3:

CALVERT CLIFFS REACTOR VESSEL BELTLINE MATERIAL RT_{PTS} PARAMETERS

ID	I (RTNDT)	M (MARGIN)	RTPTS (MAXIMUM)	CF (CHEMISTRY FACTOR)	F Max (RTPTS/CF)
UNIT #1					
2-203-A,B,C	-50	56	264	210	1.257
3-203 A,B,C	-56	66	260	179	1.453
9-203	-80	56	324	121	2.678
D-7206-1	20	34	216	74	2.919
D-7206-2	-30	34	266	84	3.167
D-7206-3	10	34	226	84	2.69
D-7207-1	10	34	226	90	2.511
D-7207-2	-10	34	246	74	3.324
D-7207-3	-20	34	256	74	3.459
UNIT #2					
2-203-A,B,C	-56	66	260	161	1.615
3-203 A,B,C	-80	56	294	121	2.430
9-203	-60	56	304	101	3.010
D-8906-1	10	34	226	108	2.093
D-8906-2	10	34	226	74	3.054
D-8906-3	5	34	231	98	2.357
D-8907-1	-8	34	244	110	2.218
D-8907-2	10	34	226	102	2.216
D-8907-3	-16	34	252	77	3.273

5.0 References

1. "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Calvert Cliffs Unit #1 Reactor Vessel Materials", Combustion Engineering, CENPD-34, February, 1972.

2. "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Calvert Cliffs Unit #1 Reactor Vessel Materials", Combustion Engineering, CENPD-48, August 1972.

3. Byrne, S.T., Biemiller, E.L., and Ragl, A., "Testing and Evaluation of Calvert Cliffs Unit #1 and Unit #2 Reactor Vessel Materials Irradiation Surveillance Program Baseline Samples", Combustion Engineering, TR-ESS-001, January 31, 1975.

4. Letter from P. Kruse (CE) to L. E. Titland (BG&E), CE Chattanooga Metallurgical Records Search, BG&E-10577-437, January, 1982.

5. Chexal, B., et al., "Calvert Cliffs Unit #1 Reactor Vessel; Pressurized Thermal Shock Analysis for a Small Steam Line Break, EPRI Special Report NP-3752-Sr, November, 1984.

6. Strosnider, J., et al., "Computerized Reactor Pressure Vessel Materials Information System", NUREG-0688, U.S. NRC, October, 1980.

7. "Baltimore Gas & Electric Unit #1 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Materials Test Reports, and Base Materials Test Reports", Combustion Engineering Contract No. 72167.

8. "Baltimore Gas & Electric Unit #2 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Materials Test Reports, and Base Materials Test Reports", Combustion Engineering Contract No. 73167.

9. Oldfield, W. et al., Nuclear Plant Irradiated Steel Handbook, EPRI Research Projects NP-1757-36, 1757-37, and 2455-5, September, 1985.

10. Davidson, J.A. and Yanicko, S.E., "Duke Power Company William B. McGuire Unit #1 Reactor Vessel Radiation Surveillance Program", WCAP-91995, November 1977.

APPENDIX A

Chemical Composition of Weldments in the Beltline Region
of Calvert Cliffs Reactor Vessel Unit #1 and Unit #2

W"ELD SEAM 2-203-A,B,C CCNPP UNIT #1

WIRE(S)	FLUX	LOT NO.	Cu (w/o)	Ni (w/o)	SOURCE / ANALYSIS NO.
12008	--	--	--	1.00	(1) / R-1990
20291	--	--	--	0.73	(1) / R-2248
20291	--	--	--	0.74	(1) / R-2293
12008	1092	3692	NA	1.01	(1) / D-4907
20291	1092	3833	0.21	0.74	(2,3) / NA
20291	1092	3833	0.22	0.73	(4)* / NA
12008 & 20291	1092	3854	0.21	0.88	(5,6) / 24117

CHEMISTRY CALCULATION

Ni: $([(1.00 + 1.01)/2 + (0.73 + 0.74 + 0.74 + 0.73)/4]/2 + 0.88)/2 = 0.88$ w/o Ni

ESTIMATED CHEMISTRY

0.21 w/o Cu based on the tandem wire deposit analysis

0.88 w/o Ni

* Average of five analysis

NA Not Available

-- Not applicable because Flux, Lot No. and Cu are not relevant for wire analyses, only for deposit analyses

(1) Letter from P. Kruse (CE) to L.E. Titland (BG&E), C-E Chattanooga Metallurgical Records Search, BG&E-10577-437, January 11, 1982.

(2) Letter from T.U. Maston (EPRI) to L.E. Titland, Attachment II: Cooper Station Surveillance Weld Chemistry, March 16, 1982.

(3) Strosnider, J., et al., "Computerized Reactor Pressure Vessel Materials Information System", NUREG-0688, U.S. NRC, October 1980.

(4) Cooper Surveillance Weld Evaluation, General Electric, EPRI Contract RP2180-6, August 1983.

(5) Oldfield, W., et al., Nuclear Plant Irradiated Steel H ndbook, EPRI Research Projects NP-1757-36, 1757-37, and 2455-5, September 198'

(6) Davidson, J.A. and Yanicko, S.E., "Duke Power [illegible] ..liam B. McGuire Unit #1 Reactor Vessel Radiation Surveillance Program", WCAP-91995, November 1977.

WELD SEAM 3-203-A,B,C CCNPP UNIT #1

WIRE(S)	FLUX	LOT NO.	Cu (w/o)	Ni (w/o)	SOURCE / ANALYSIS NO.
21935	--	--	--	0.70	(1) / R-2546
21935	--	--	--	0.68	(1) / R-2503
21935	--	--	--	0.71	(1) / R-2495
21935	1092	3869	0.20	NA	(1) / D-7279
21935	1092	3889	0.13	0.68	(1) / D-7569
21935	1092	3889	0.21	NA	(1) / D-7524

CHEMISTRY CALCULATION

Cu: (0.20 + 0.21)/2 = 0.21 w/o Cu*

Ni: (0.70 + 0.68 + 0.71 + 0.68)/4 = 0.69 w/o Ni

ESTIMATED CHEMISTRY

0.21 w/o Cu

0.69 w/o Ni

* Note that one deposit analysis reported a copper content of 0.13 w/o. This was omitted from the chemistry calculation due to the non-conservative effects on estimating the average weld metal copper content with a sample size of three.

NA Not Available

-- Not applicable because Flux, Lot No. and Cu are not relevant for wire analyses, only for deposit analyses

(1) Letter from P. Kruse (CE) to L.E. Titland (BG&E), C-E Chattanooga Metallurgical Records Search, BG&E-10577-437, January 11, 1982.

WELD SEAM 9-203 CCNPP UNIT #1

WIRE(S)	FLUX	LOT NO.	Cu (w/o)	Ni (w/o)	SOURCE / ANALYSIS NO.
33A277	0091	3922	0.30	NA	(1) / D-7947
33A277	0091	3922	0.23	NA	(1) / D-7948
33A277	0091	3977	0.23	NA	(1) / D-9217
33A277	0091	3922	0.24	0.18	(2) / NA
33A277	0091	3922	0.14	0.27	(3) / NA

CHEMISTRY CALCULATION

Cu: (0.30 + 0.23 + 0.23 + 0.24 + 0.14)/5 = 0.23 w/o Cu

Ni: (0.18 + 0.27)/2 = 0.23 w/o Ni

ESTIMATED CHEMISTRY

0.23 w/o Cu

0.23 w/o Ni

(1) "Baltimore Gas & Electric Unit #2 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Material Test Reports, and Base Material Test Reports", Combustion Engineering Contract No. 73167.

(2) Byrne, S.T., Biemiller, E.L., and Ragl, A., "Testing and Evaluation of Calvert Cliffs, Unit #1 and Unit #2 Reactor Vessel Materials Irradiation Surveillance Program Baseline Samples", Combustion Engineering, TR-ESS-001, January 31, 1975.

(3) Perrin, J.S., et al., "Calvert Cliffs Unit #1 Nuclear Plant Reactor Pressure Vessel Surveillance Program; Capsule 263", Final Report, Battelle Columbus Laboratories, December 15, 1980.

WELD SEAM 2-203-A,B,C CCNPP UNIT #2

WIRE(S)	FLUX	LOT NO.	Cu (w/o)	Ni (w/o)	SOURCE / ANALYSIS NO.
8746	124	3878	0.12	NA	(1) / D-7314

ESTIMATED CHEMISTRY

0.12 w/o Cu

1.01 w/o Ni*

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* Ni is an upperbound estimate since no data could be found for this wire.

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(1) "Baltimore Gas & Electric Unit #2 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Material Test Reports, and Base Material Test Reports", Combustion Engineering Contract No. 73167.

WELD SEAM 3-203-A,B,C CCNPP UNIT #2

WIRE(S)	FLUX	LOT NO.	Cu (w/o)	Ni (w/o)	SOURCE / ANALYSIS NO.
33A277	0091	3922	0.30	NA	(1) / D-7947
33A277	0091	3922	0.23	NA	(1) / D-7948
33A277	0091	3977	0.23	NA	(1) / D-9217
33A277	0091	3922	0.24	0.18	(2) / NA
33A277	0091	3922	0.14	0.27	(3) / NA

CHEMISTRY CALCULATION

Cu: (0.30 + 0.23 + 0.23 + 0.24 + 0.14)/5 = 0.23 w/o Cu

Ni: (0.18 + 0.27)/2 = 0.23 w/o Ni

ESTIMATED CHEMISTRY

0.23 w/o Cu

0.23 w/o Ni

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(1) "Baltimore Gas & Electric Unit #2 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Material Test Reports, and Base Material Test Reports", Combustion Engineering Contract No. 73167.

(2) Byrne, S.T., Biemiller, E.I., a. ᵈ Ragl, A., "Testing and Evaluation of Calvert Cliffs, Unit #1 and Unit #2 Reactor Vessel Materials Irradiation Surveillance Program Baseline Samples", Combustion Engineering, TR-ESS-001, January 31, 1975.

(3) Perrin, J.S., et al., "Calvert Cliffs Unit #1 Nuclear Plant Reactor Pressure Vessel Surveillance Program; Capsule 263", Final Report, Battelle Columbus Laboratories, December 15, 1980.

WELD SEAM 9-203 CCNPP UNIT #2

WIRE(S)	FLUX	LOT NO.	Cu (w/o)	Ni (w/o)	SOURCE / ANALYSIS NO.
10137	0091	3999	0.23	NA	(1) / D-10600
10137	0091	3999	0.20	0.04	(2) / NA
10137	0091	3999	0.24	0.06	(3) / NA

CHEMISTRY CALCULATION

Cu: (0.23 + 0.20 + 0.24)/3 = 0.22 w/o Cu

Ni: (0.04 + 0.06)/2 = 0.05 w/o Ni

ESTIMATED CHEMISTRY

0.22 w/o Cu

0.05 w/o Ni

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(1) "Baltimore Gas & Electric Unit #2 Reactor Vessel Master Index with Welding Procedures, PQR's, Weld Material Test Reports, and Base Material Test Reports", Combustion Engineering Contract No. 73167.

(2) Byrne, S.T., Biemiller, E.L., and Ragl, A., "Testing and Evaluation of Calvert Cliffs, Unit #1 and Unit #2 Reactor Vessel Materials Irradiation Surveillance Program Baseline Samples", Combustion Engineering, TR-ESS-001, January 31, 1975.

(3) Norris, E.B..., "Reactor Vessel Material Surveillance Program for Calvert Cliffs Unit #2 Analysis of 263° Capsule, Final Report, SwRI Project 06-7524, Southwest Research Institute, September 1985.

ATTACHMENT B

Unit 1 Fluence Calculations

(SwRI Report Without Appendices D through G)

Baltimore Gas and Electric Company

Docket Nos. 50-317 & 50-318

December 13, 1991

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PRESSURE-TEMPERATURE LIMITS FOR CALVERT CLIFFS NUCLEAR POWER PLANT UNIT 1

By
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M. L. Williams (Consultant)

FINAL REPORT
SwRI Project No. 06-1278-001

Prepared For
Baltimore Gas & Electric Co.
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1. SUMMARY OF RESULTS AND CONCLUSIONS

A detailed analysis was performed for developing new pressure-temperature limit curves for the Calvert Cliffs Unit 1 reactor pressure vessel. The analysis included new neutron transport calculations for 12, 18 and 24 month cycles, development of irradiated material properties based on NRC Regulatory Guide 1.99, Draft Rev. 2, and the generation of heat-up and cool-down limit curves for every 4 EFPY from 12 EFPY to end-of-life conditions.

The SwRI evaluation led to the following conclusions:

1. Based on a calculated neutron spectral distribution, the peak fluxes incident on the Reactor Pressure Vessel (RPV) are 5.31×10^{10} n/cm^2-sec, 5.69×10^{10} n/cm^2-sec and 4.17×10^{10} n/cm^2-sec for 12 month, 18 month and 24 month cycles respectively.
2. Adjusting the calculated flux with respect to the first capsule dosimeter analysis the 12 month cycle peak flux on the RPV was determined to be 4.88×10^{10} n/cm^2-sec. The value is within 4% of what was reported in the Unit 1 Capsule report[1].
3. The calculated lead factors for the vessel ID based on surveillance capsule locations are given below:

Cycle Type	Θ=7° Lead Factor	Θ=14° Lead Factor
12 month	1.26	0.93
18 month	1.23	0.90
24 month	1.17	0.77

4. The accumulated peak fluence on RPV ID was calculated to be 1.62×10^{19} n/cm^2 for the first 9 cycles and 4.56×10^{19} n/cm^2 to 32 EFPY.

5. Displacement per Atom (dpa) for 32 EFPY were calculated to be 7.62 x 10^{-2}, 4.85 x 10^{-2} and 1.4 x 10^{-2} for RPV ID, 1/4T and 3/4T respectively.

6. The 12 EFPY fluence on the RPV was calculated to be 1.96 x 10^{19} n/cm^2. Fluence rate of 1.3138 x 10^{18} per year was used to develop fluence value for 16, 20, 24, 28, 32, 36 and 40 EFPYs.

7. The controlling material for RPV operations was determined to be weld 2-203 with Cu=0.21% and Ni=0.87%. P-T limit data was developed for 12, 16, 20,24, 28, 32, 36 and 40 EFPYs. The data also reflects different heat-up and cool-down rates.

8. Based on the Regulatory Guide 1.99, Draft Rev. 2 approach, the 32 EFPY adjusted reference temperature for the controlling material will be 294°F at the RPV ID and 256°F at the 1/4T location.

9. Based on this study the Calvert Cliff Unit 1 reactor vessel has adequate material toughness for continued safe operation beyond 32 EFPY irradiation conditions.

DPA Values (Displacements Per Atom Per Second) in RPV of Calvert Cliffs-1 Due to Neutrons with Energies Above 15 KeV

Radial Location	12M	18M	24M
220.895	8.1138E-11	8.8356E-11	6.2720E-11
222.102	7.5060E-11	8.1737E-11	5.8022E-11
223.727	6.5401E-11	7.1219E-11	5.0556E-11
225.351	5.5903E-11	6.0876E-11	4.3213E-11
226.976	4.7506E-11	5.1732E-11	3.6722E-11
228.601	4.0243E-11	4.3822E-11	3.1108E-11
230.225	3.4009E-11	3.7034E-11	2.6289E-11
231.850	2.8626E-11	3.1172E-11	2.2128E-11
233.475	2.3950E-11	2.6080E-11	1.8513E-11
235.099	1.9844E-11	2.1609E-11	1.5339E-11
236.724	1.6185E-11	1.7625E-11	1.2511E-11
238.348	1.2868E-11	1.4012E-11	9.9467E-12
239.973	9.7644E-12	1.0633E-11	7.5479E-12
241.598	6.5633E-12	7.2118E-12	5.1194E-12

2. INTRODUCTION

The long-term degradation of reactor vessel structural material properties due to irradiation is measured by the evaluation of material surveillance capsules removed periodically from the reactor vessel. Combustion Engineering, Inc. has provided the material surveillance program for the Calvert Cliffs Nuclear Power Plant Unit 1. To date, one surveillance capsule has been removed and tested. Typically, the capsules contain Charpy V-notch and tensile specimens in various combinations representing the parent material, weld metal and heat-affected zone (HAZ) material of the vessel beltline region. In addition, the capsules contain iron, nickel, titanium, sulfur, uranium and copper neutron flux monitors and temperature monitors.

The objective of the surveillance program is to correlate changes in vessel material fracture toughness properties with neutron fluence so that the reactor vessel pressure temperature limits can be determined. Recently, the concern about pressurized thermal shock has placed additional requirements to determine the irradiated condition of vessel inner surface. The applicable regulations and documents that address the continued licensibility of reactor vessels include 10 CFR Part 50, Appendices B, G and H, 10 CFR Part 50.61, NRC Standard Review Plan 5.3.2, Regulatory Guide 1.99, Draft Rev 2 and ASME Boiler and Pressure Vessel Code Section III, Appendix G.

In this report a new neutron flux analysis for the reactor vessel is presented. Based on the analysis, projected vessel fluence conditions were developed for assessing the long-term integrity of the vessel. Pressure-temperature limit conditions are presented for 12, 16, 20, 24, 28, 32, 36 and 40 effective full power years of operation.

3. MATERIAL PROPERTY ASSESSMENT

In developing the pressure-temperature limit conditions for reactor vessels, the important material property required is the Reference Temperature - Nil Ductibility Transition (RT_{NDT}) of various vessel pressure boundary materials. The locations within the pressure boundary that are of interest include nozzle area, closure head region and the beltline region. The nozzle and closure head regions are locations of high stress concentrations while the beltline region is subject to neutron embrittlement with time.

Early in the life of the reactor vessel, nozzle and closure head regions tend to control the pressure-temperature limit curves. However, with time the beltline irradiated materials become controlling. In the case of Calvert Cliffs Unit 1, the controlling material for 12 EFPYs and beyond is the beltline region material. Between the nozzle and the closure head region, the closure head region poses greater restrictions on the PT limit curves.

10 CFR 50 "Fracture Toughness Requirements for Light-Water Nuclear Power Reactor" requires the closure head region materials to have, as a minimum, RT_{NDT} + 120° for normal operations and RT_{NDT} + 90° for hydrostatic pressure and leak tests. In the case of non-availability of RT_{NDT} data or where the data is not reliable, the RT_{NDT} for the closure region is determined using the method in NRC Standard Review Plan 5.3.2 Branch Technical Position 5-2, MTEB. Based on this method, the RT_{NDT} of the closure head material was assessed to be 60°F.

To provide the submittal to NRC on the Pressurized Thermal Shock issue,[2,5] extensive materials data information was developed by BG & E for all the beltline materials. Key information needed for these materials is the material chemistry, especially Cu and Ni. From the data supplied by BG & E to SwRI, the Cu and Ni values for the beltline materials are presented in Table

3.1. These chemistry values are used in Section 5 of this report to develop the irradiated Adjusted Reference Temperature for the critical beltline materials. Figure 3.1 is a Calvert Cliffs Unit-1, Reactor Pressure Vessel Map with all the key welds identified.

Table 3.1 Calvert Cliffs Unit No. 1 Reactor Vessel Beltline Material Properties

ID	Cu (w/o)	Ni (w/o)	Initial RT^{NDT} (°F)
2-203 A,B,C	0.21	0.87	-50.0
3-203 A,B,C	0.21	0.69	-56.0
9-203	0.23	0.23	-80.0
D-7206-1	0.11	0.55	20.0
D-7206-2	0.12	0.64	-30.0
D-7206-3	0.12	0.64	10.0
D-7206-1	0.13	0.54	10.0
D-7207-2	0.11	0.56	-10.0
D-7207-3	0.11	0.53	-20.0

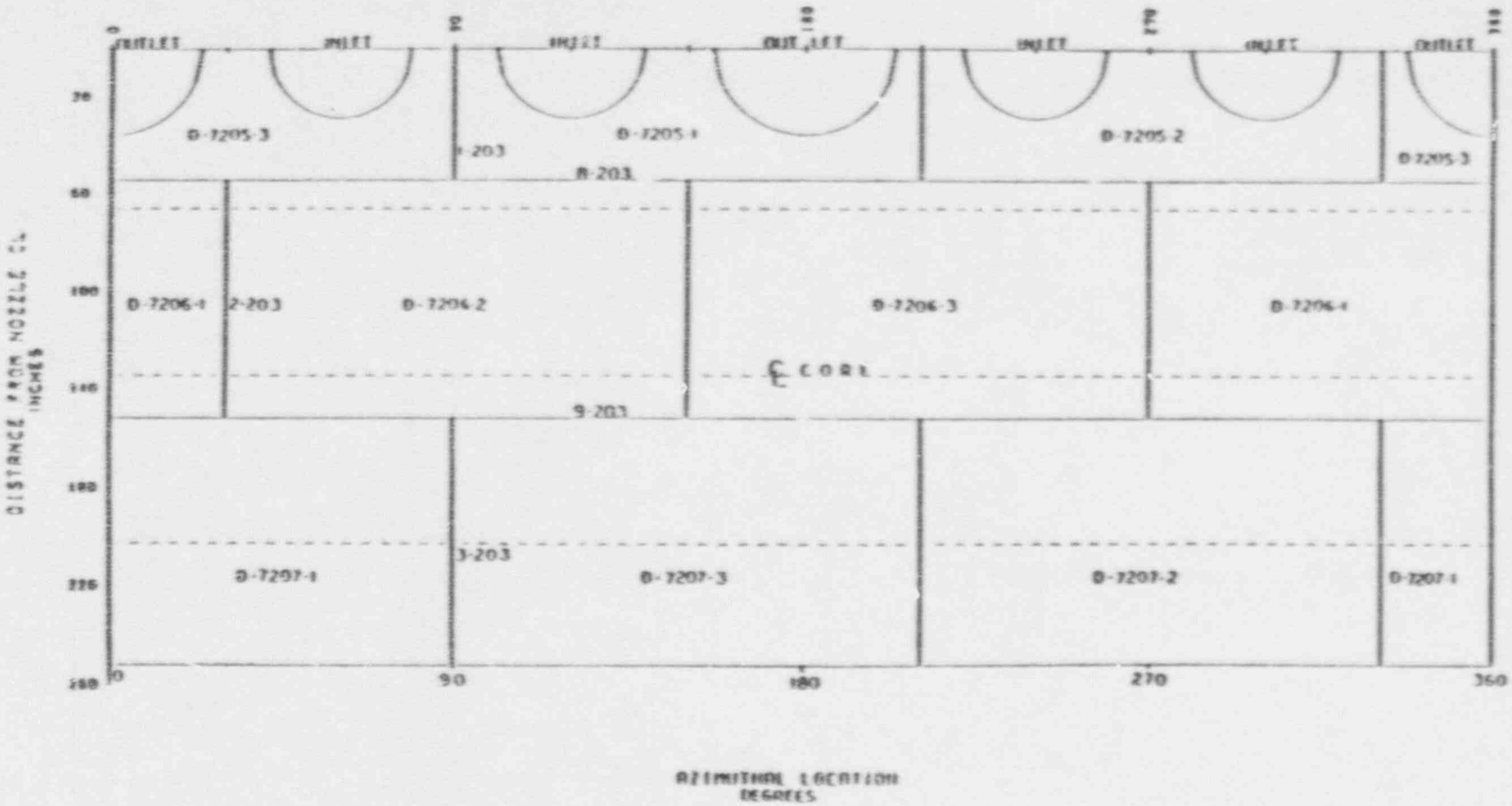

FIGURE 3.1 CALVERT CLIFFS UNIT 1, REACTOR PRESSURE VESSEL MAP

4. NEUTRON FLUENCE CALCULATIONS

The first surveillance capsule (263°) was removed from Unit 1 following Cycle 3, after 2.94 EFPYs of operation. A detailed capsule testing and analysis was conducted and reported in Reference [1]. The dosimetry and vessel fluence evaluation provided information on the vessel fracture toughness conditions for 3 cycles of 12 months cycle each. Beginning with cycle 5, the operating cycle period changed to 18 months. A low leakage core and a 24-month cycle is planned for future operations beginning with cycle 10. Full power conditions correspond to 2560 Mwth for cycle 1, and 2700 Mwth for all other cycles.

In this section a detailed neutron transport analysis for the reactor cross section is presented. A discrete ordinates calculation using the DOT-4 [3] code was performed to obtain the radial (R) and azimuthal (θ) fluence-rate distribution for the geometry is shown in Figure 4.1. As part of the reactor cross section model the details of the surveillance capsule geometry and location has to be modeled. The inclusion of the surveillance capsules in the R-θ model is mandatory to account for the significant perturbation effects from the physical presence of the capsule. Figure 4.2 represents the actual capsule geometry versus the DOT model used in the analysis. The DOT model incorporates a homogeneous mixture of inconel and water to simplify the overall model while maintaining the required accuracies for the calculation.

The spatial distribution of the core source was obtained by combining plant-specific assembly-wise power values and relative pin-wise powers for the appropriate cycles. The energy distribution was represented by a ^{235}U watt fission spectrum as specified in ENDF/BV. The axial variation of the flux is treated with a well known synthesis method.

The DOT-4 calculations were performed with the 47- group energy structure

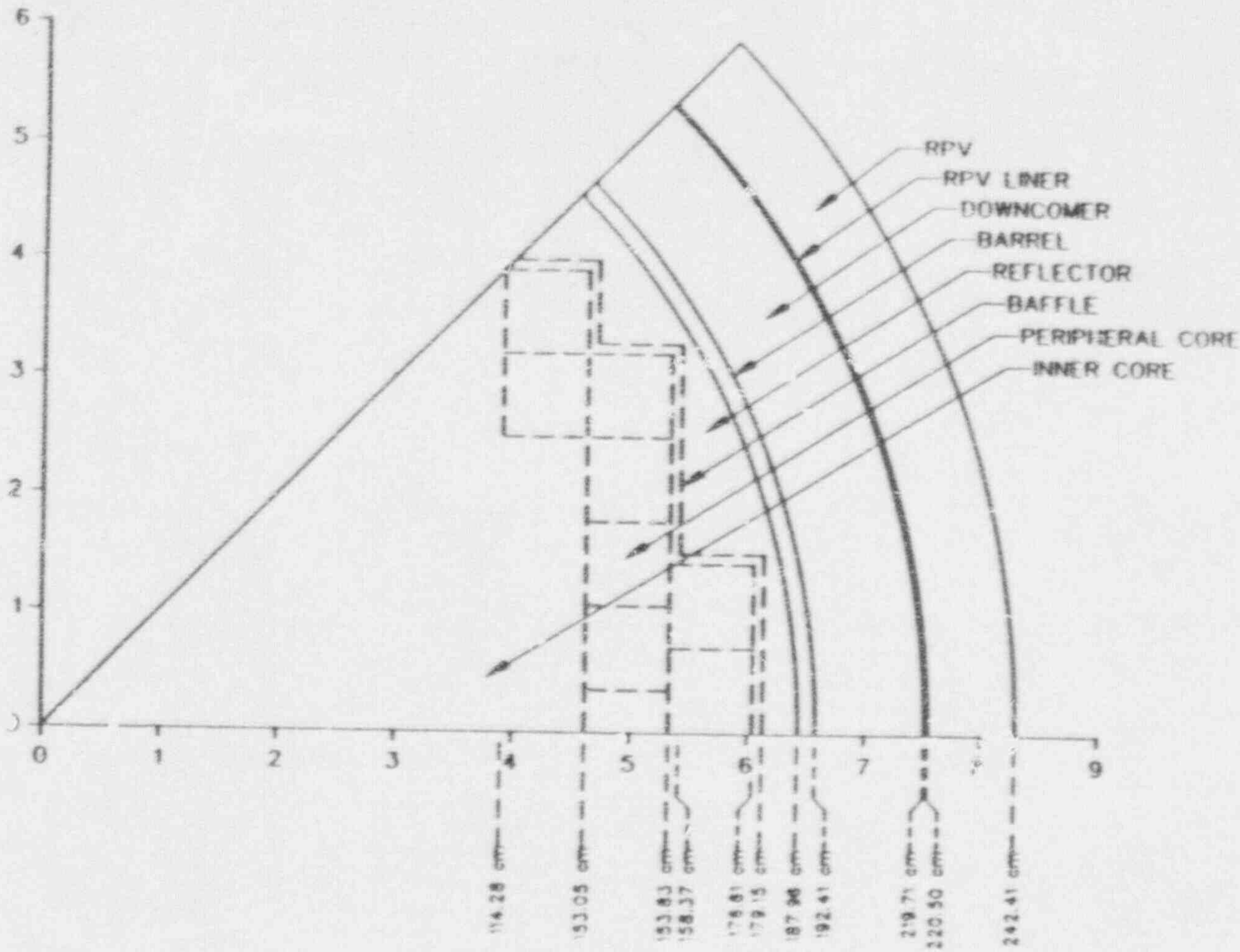

FIGURE 4.1 CALVERT CLIFFS UNIT-1 DOT-# Rθ MODEL*

*(Surveillance Capsules at 7° and 14° are not shown)

(Scale: 1 Large Division = 11.5 inches)

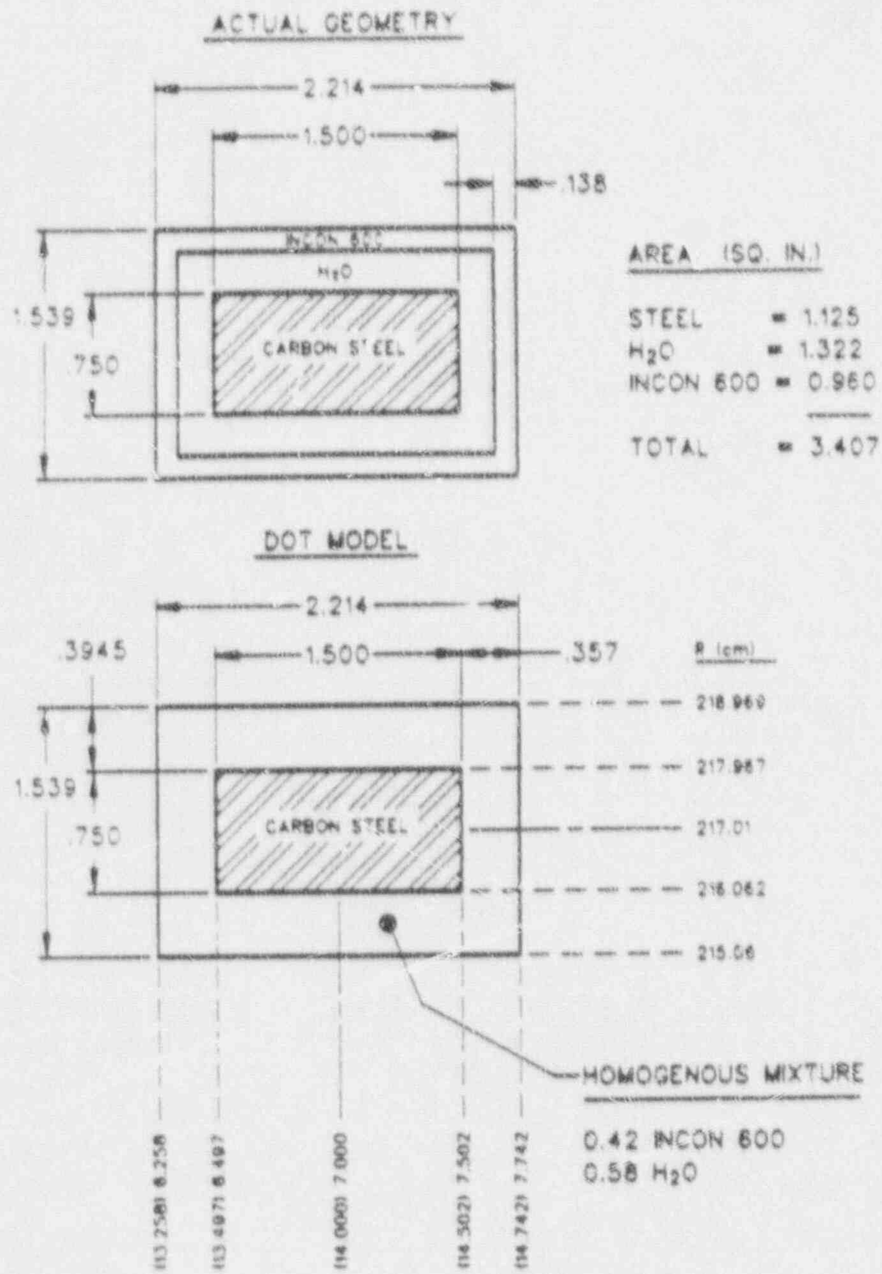

FIGURE 4.2 CAPSULE GEOMETRY MODELING

for the SAILOR [4] cross section library. An S_8 angular structure and a P_3 Lengendre cross-section expansion were used. The fine-group dosimeter cross-sections for the $^{63}Cu\ (n,\alpha)^{60}Co$ reaction were obtained from ENDF/B-V file and were collapsed to 47 groups using a fission plus 1/E weighting spectrum. The other reaction cross sections were taken from the SAILOR cross section library, which is based on ENDF/B-IV data. The DPA cross sections were obtained from MACLIB.

The results of the transport calculations for the RPV fluence analysis are presented in Tables 4.1 through 4.13. Table 4.1 presents the calculated saturated activities at the center of a 7 degree surveillance capsule for 12 months, 18 months and 24 months cycles of operation. In Table 4.2 the nonsaturated activities are calculated for end of cycles 3 and 8. The nonsaturation factors developed for the various dosimeters are described in Table 4.3. The measured A_{SAT} for the capsule is presented in Table 4.4. The comparison of measured and calculated parameters for the capsule 263° is presented in Table 4.5. Table 4.6 contains the relative azimuthal flux (> 1 MeV) variation incident on the vessel. Adjusted flux for the 12-month cycle with respect to the 263° capsule is presented in Table 4.7.

The adjusted flux is obtained by combining the measured dosimeter activities with the calculated spectrum-averaged cross sections using the expressions given in Appendix F. Since no measured activities are available fo the 18 and 24 month cycles, only computed activities are given for these areas. Peak flux for the various operation cycle periods in the vessel are described in Table 4.8. Table 4.9 presents the neutron spectra at the peak at the vessel I.D.. The spectrum averaged cross sections at the center of the surveillance capsule are presented in Table 4.10. Table 4.11 presents the calculated flux in the surveillance capsules and their lead factors with respect to the vessel I.D.. The accumulated RPV peak fluence levels for various cycles is summarized in Table 4.12. Table 4.13 presents the vessel fluence conditions after 12 EFPY.

Appendix A discusses the determination of space-dependent source distribution for the transport analysis performed for Calvert Cliffs Unit 1. Appendix B is a description of the 3D Flux synthesis method used in this analysis. The power-time history data is presented in Appendix C.

Table [illegible] Calculated Values for Midplane Saturated Activities at Center of 7° S. C. (Calvert Cliffs-1)

(Units = Bq/gm)

Dosimeter	A_{SAT} 12M Cycle	A_{SAT} 18M Cycle	A_{SAT} 24M Cycle
$^{54}Fe(n,p)^{54}Mn$	5.65E6	5.89E6	4.17E6
$^{58}Ni(n,p)^{58}Co$	8.03E7	8.40E7	5.93E7
$^{63}Cu(n,\alpha)^{60}Co$	7.00E5	7.30E5	5.27E5
$^{238}U(n,f)^{137}Cs$	4.59E6	4.81E6	3.36E6
$^{46}Ti(n,p)^{46}Sc$	1.57E6	1.64E6	1.17E6
ϕ > 1 MeV	6.69E10	7.00E10	4.88E10
ϕ >.111 MeV	1.23E11	1.29E11	8.95E10

Table -.2 Calculated Values for Non-Saturated Activities ("A_{TOR}")[1] at Center of "° S.C. (Calvert Cliffs-1)

Units = Bq/gm

Dosimeter	$(A_{TOR})_3$ [a]	$(A_{TOR})_8$ [b]
$^{54}Fe(n,p)^{54}Mn$	3.85E6	4.66E6
$^{58}Ni(n,p)^{58}Co$	5.95E6	7.42E7
$^{63}Cu(n,\alpha)^{60}Co$	2.08E5	4.15E5
$^{238}U(n,f)^{137}Cs$	2.96E5	8.02E5
$^{46}Ti(n,p)^{46}Sc$	1.16E6	1.45E6

(a) $(A_{TOR})_3 \equiv$ dosimeter activity (Bq/gm) at time of removal (EOC-3)

$= (A_{SAT})_{12M}\ h_{1-3}$

(b) $(A_{TOR})_8 \equiv$ dosimeter activity at EOC-8

$= (A_{TOR})_3\ e^{-\lambda\tau} + (A_{SAT})_{18M}\ h_{4-8}$

where $(A_{SAT})_{12}$, $(A_{SAT})_{18}$ = saturated activities for 12 and 18 month cycles

h_{1-3}, h_{4-8} = non-saturation factors from Table 4.3

τ = time (d) from EOC3 to EOC8 = 2739 days

Table -.3 Non-Saturation Factors(h) Used in Dosimeters Activities

Dosimeter	h_{1-3} (Cycles 1-3)	h_{4-8} (Cycles 4-8)
Fe54	0.683	.789
Ni58	0.741	.884
Cu63	0.297	.463
Ti46	0.738	.882
U238	0.0643	.115

(a) h ≡ non-saturation factor

$$= \sum_j P_j \, (1-e^{-\lambda T_j}) \, e^{-\lambda (T-t_j)},$$

where factors P_j, T_j and $T-t_j$ are given in Appendix C.

Table 4.4 "Measured" Saturated Activities (A_{SAT}) for Cycles 1-3 of Calvert Cliffs-1

Location

R = 217.01 cm
θ = 7°

Dosimeter	Center of S. C. (middle of compartment) A_{TOR} (1)	A_{SAT} (2)	Maximum of S. C. (compartment bottom) A_{TOR} (1)	A_{SAT} (2)
$^{54}Fe(n,p)^{54}Mn$	3.45E6	5.05E6	3.57E6	5.23E6
$^{58}Ni(n,p)^{58}Co$	5.46E7	7.37E7	6.09E7	8.22E7
$^{63}Cu(n,\alpha)^{60}Co$	1.96E5	6.60E5	2.13E5	7.17E5
$^{238}U(n,f)^{137}Cs$	3.17E5	4.93E6	3.56E5	5.54E6
$^{46}Ti(n,p)^{46}Sc$	1.29E6	1.75E6	1.36E6	1.84E6

(1) A_{TOR} values taken from Table 4A of Battelle report

(2) $A_{SAT} = \frac{A_{TOR}}{h_{1-3}}$

Table 4.5 Comparison of Unadjusted Calculated and Measured Parameters for Cycles 1-3 (12 month cycles) of Calvert Cliffs-1

Parameter	A_{TOR} Measured[1]	A_{TOR} Calculated[6]	C/E[5]
Fe54 dosimeter activity (dps/gm)[2]	3.45E6	3.85E6	1.12
Ni58 dosimeter activity (dps/gm)[2]	5.46E7	5.95E6	1.09
Cu63 dosimeter activity (dps/gm)[2]	1.96E5	2.08E5	1.06
U238 dosimeter activity (dps/gm)[2]	3.17E5	2.96E5	0.93
Ti46 dosimeter activity (dps/gm)[2]	1.29E6	1.16E6	0.90
Peak ϕ (>1 MeV) at center capsule[3]	6.7E10	7.08E10[4]	1.06

(1) A_{TOR} values taken from Batelle Report

(2) At center of capsule; time of removal from reactor

(3) At location of peak axial value

(4) This is a purely calculated value---no modifications are made to incorporate the experimental dosimeter results. The "adjusted flux" given in Table 4-7 reflects the incorporated measured values, and hence is believed to be more accurate.

(5) $C/E = \dfrac{\text{calculated activity}}{\text{experimental activity}}$

(6) Calculated values obtained from Table 4.2

Table 4.6 Relative Azimuthal Variation[a] In φ (> 1 MeV) Incident on Vessel

J	θ	12 Month Cycle	18 Month Cycle	24 Month Cycle
1	1.25000E+00	1.000	1.000	1.000
2	3.75000E+00	.995	.991	.966
3	5.62900E+00	.973	.965	.906
4	6.37750E+00	.924	.915	.848
5	6.64000E+00	.896	.886	.814
6	7.00000E+00	.879	.868	.787
7	7.35950E+00	.874	.863	.772
8	7.62200E+00	.887	.873	.776
9	8.37099E+00	.910	.895	.781
10	9.62500E+00	.879	.862	.734
11	1.08750E+01	.833	.815	.680
12	1.21250E+01	.781	.763	.630
13	1.30040E+01	.742	.726	.599
14	1.33775E+01	.709	.695	.572
15	1.36400E+01	.680	.667	.549
16	1.40000E+01	.654	.643	.528
17	1.43605E+01	.640	.630	.517
18	1.46220E+01	.639	.630	.517
19	1.49300E+01	.646	.637	.522
20	1.55590E+01	.631	.623	.512
21	1.65000E+01	.598	.595	.492
22	1.75000E+01	.570	.570	.475
23	1.85000E+01	.548	.553	.462
24	1.95000E+01	.534	.543	.454
25	2.05000E+01	.527	.541	.449
26	2.15000E+01	.524	.544	.446
27	2.25000E+01	.526	.551	.444
28	2.35000E+01	.530	.561	.444
29	2.45000E+01	.535	.572	.443
30	2.55000E+01	.541	.582	.443
31	2.65000E+01	.545	.590	.441
32	2.75000E+01	.546	.594	.436
33	2.84000E+01	.545	.597	.429
34	2.98118E+01	.535	.588	.418
35	3.09600E+01	.526	.579	.413
36	3.12330E+01	.525	.578	.411
37	3.15847E+01	.524	.577	.409
38	3.20500E+01	.521	.575	.406
39	3.25500E+01	.518	.572	.402
40	3.30500E+01	.515	.569	.399

Table 4.6 Continued

J	Z	12 Month Cycle	18 Month Cycle	24 Month Cycle
41	3.30500E+01	.571	.565	.395
42	3.41962E+01	.506	.559	.392
43	3.47000E+01	.501	.554	.388
44	3.49150E+01	.498	.551	.387
45	3.53723E+01	.492	.544	.384
46	3.60720E+01	.483	.534	.379
47	3.71220E+01	.468	.518	.372
48	3.81720E+01	.454	.502	.365
49	3.88720E+01	.446	.492	.360
50	3.95720E+01	.438	.484	.356
51	4.02360E+01	.433	.478	.352
52	4.07750E+01	.430	.474	.350
53	4.12500E+01	.429	.472	.349
54	4.17500E+01	.427	.471	.347
55	4.22500E+01	.427	.470	.346
56	4.27500E+01	.427	.470	.345
57	4.32500E+01	.427	.471	.345
58	4.37500E+01	.428	.471	.345
59	4.42500E+01	.428	.472	.345
60	4.47500E+01	.428	.472	.345

(a) Peak value normalized to unity

Table 4.7 Determination of "Adjusted" ϕ (>1) in S.C. for 12 Month Cycles 1-3 (Location R = 217.01 cm, θ = 7°)

PEAK FLUX: (bottom compartment of S. C.)

Dosimeter	Measured A_{SAT} (1)	Calculated σ_{eff} (2)	Adjusted ϕ(>1) (3)
$^{54}Fe(n,p)^{54}Mn$	5.23E6	.135	6.19E10
$^{58}Ni(n,p)^{58}Co$	8.22E7	.171	6.86E10
$^{63}Cu(n,\alpha)^{60}Co$	7.17E5	.00159	6.88E10
		Average	6.65E10

CENTER FLUX: (middle compartment of S. C.)

Dosimeter	Measured A_{SAT}	Calculated σ_{eff}	Adjusted ϕ(>1)
$^{54}Fe(n,p)^{54}Mn$	5.05E6	.135	5.98E10
$^{58}Ni(n,p)^{58}Co$	7.37E7	.171	6.15E10
$^{63}Cu(n,\alpha)^{60}Co$	6.60E5	.00159	6.33E10
		Average	6.15E10

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(1) Measured values from Table 4.4

(2) Calculated values from Table 4.10

(3) Adjust $\phi(>1) \equiv \frac{[A_{SAT}]\ \text{measured}}{N_o\ [\sigma_{eff}]\ \text{calc.}}$

Table 4.8 Peak ϕ (>1) in RPV of Calvert Cliffs-1

Radial Location[a]	12M Cycle, adjusted[b]	12M Cycle, calculated[c]	18M Cycle, calculated[c]	24M Cycle, calculated[c]
IR RPV(R=221.29)	4.88E10	5.31E10	5.69E10	4.17E10
1/4T(R=225.98)	2.91E10	3.17E10	3.40E10	2.49E10
3/4T(R=236.[illegible])	5.94E9	6.46E9	6.93E9	5.08E9

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[a] RPV liner begins at 220.5
RPV begins at 221.29
RPV ends at 242.41

[b] Obtained by dividing adjusted S.C. flux (see Table 4.7) by lead factor in Table 4.11

[c] Obtained by dividing calculated S.C. flux in Table 4.1 by lead factor in Table 4.11 (Note: no experimental data is available for 18 and 24 month cycles.)

Table 4.9 Neutron Spectra at Peak OT Location
(R = 219.71, θ = 2.50, Z = 97.2)

	12 Month Cycle	18 Month Cycle	24 Month Cycle
GROUP	FLUX	FLUX	FLUX
1	1.63988E+07	1.73866E+07	1.31134E+07
2	7.10135E+07	7.53926E+07	5.67293E+07
3	2.99141E+08	3.07735E+08	2.30241E+08
4	5.81799E+08	[illegible]	4.62564E+08
5	1.03873E+09	1.10750E+09	8.23571E+08
6	2.29010E+09	2.77234E+09	2.05537E+09
7	3.70197E+09	3.95742E+09	2.92251E+09
8	6.40955E+09	6.86845E+09	5.03438E+09
9	4.40453E+09	4.72431E+09	3.45306E+09
10	3.20180E+09	3.43594E+09	2.50827E+09
11	3.60783E+09	3.87247E+09	2.82407E+09
12	1.79107E+09	1.92257E+09	1.40193E+09
13	[illegible]	4.96226E+08	3.63585E+08
14	2.21936E+09	2.78704E+09	1.73658E+09
15	5.43502E+09	5.83351E+09	4.25138E+09
16	[illegible]	5.98065E+09	4.35409E+09
17	7.41847E+09	7.96247E+09	5.79295E+09
18	1.09533E+10	1.17505E+10	8.53567E+09
19	7.02557E+09	7.53394E+09	5.45967E+09
20	3.41084E+09	3.65900E+09	2.65397E+09
21	9.19686E+09	9.85802E+09	7.11397E+09
22	[illegible]	8.30455E+09	5.98543E+09
23	8.33296E+09	8.93075E+09	6.43968E+09
24	9.82576E+09	9.12917E+09	6.54771E+09
25	1.11019E+10	1.18926E+10	8.55208E+09
26	1.00745E+10	1.07977E+10	7.73826E+09
27	[illegible]	7.56220E+09	5.42580E+09
28	[illegible]	6.45933E+09	4.63553E+09
29	2.21013E+09	2.36901E+09	1.70444E+09
30	1.22376E+09	1.31191E+09	9.45816E+08
31	[illegible]	2.77684E+09	1.97048E+09
32	[illegible]	1.79995E+09	1.27232E+09
33	3.35531E+09	3.59256E+09	2.56025E+09

Table 4.10 Spectrum Averaged Cross Sections at Center of 7' S. C.

Reaction	σ_{eff}(b) 12 Month Cycle	σ_{eff}(b) 18 Month Cycle	σ_{eff}(b) 24 Month Cycle
$^{54}Fe(n,p)$	0.135	0.135	0.137
$^{58}Ni(n,p)$	0.171	0.171	0.173
$^{63}Cu(n,\alpha)$	0.00159	0.00159	0.00164
$^{238}U(n,f)$	0.452	0.452	0.453
$^{46}Ti(n,p)$	0.0230	0.0230	0.0236

$$\sigma_{eff} = \frac{\int_{0}^{\infty} \sigma(E)\, \phi(E)\, dE}{\int_{1}^{\infty} \phi(E)\, dE}$$

Table 4.11 Calculated ϕ (E>1) in Surveillance Capsules and Lead Factors (LF)[2] for Calvert Cliffs-1

AZIMUTHAL LOCATION: θ = 7°

Cycle Type	ϕ (>1)[1]	RPV Lead Factor	1/4T Lead Factor	3/4T Lead Factor
12M	6.69E10(6.15E10)	1.26	2.11	10.35
18M	7.00E10	1.23	2.06	10.08
24M	4.88E10	1.17	1.96	9.61

AZIMUTHAL LOCATION: θ = 14°

Cycle Type	ϕ (>1)[1]	RPV Lead Factor	1/4T Lead Factor	3/4T Lead Factor
12M	4.92E10	0.93	1.56	7.62
18M	5.12E10	0.90	1.51	7.39
24M	3.21E10	0.77	1.29	6.32

(1) Results from transport calculations are shown (results for θ = 7° are shown in Table 4.1). For 12 month 7° case the "adjusted" flux obtained from dosimeter measurements is shown in parenthesis (Table 4.7).

(2) $LF = \frac{\phi_{sc}\ (>1)}{\phi_{pv}\ (>1)}$, where ϕ_{sc} is the calculated flux at the center of the surveillance capsule, and ϕ_{pv} is the maximum calculated flux incident at the indicated RPV location (Table 4.9).

Table 4.12 Determination of RPV Peak Fluence for Calvert Cliffs-1

Cycles	Full Power Days	Accumulated Fluence[3] (neutrons/cm^2)
1-4 (12 month)	1441.3	6.08E18
5-8 (18 month)	1618.1	7.95E18
9 (18 month)	404.5 [1]	1.99E18
10-EOL (24 month)	8216.1 [2]	2.96E19
TOTALS	11,680 (32 EFPY)	4.56E19

[1] Projected value based on number EFPD/cycle for cycles 5-8

[2] Projected, based on 32 EFPY lifetime

[3] 12 month fluence rate based on adjusted flux values in Table 4.8, 18 and 24 month values based on calculated fluxes from Table 4.8.

Table -.13 Fluence in RPV after 12 EFPY for Calvert Cliffs-1

Location	Fluence $\frac{neutrons}{cm^2}$
RPV IR (R=221.29)	1.93E19
1/4T (R=225.98)	1.15E19
3/4T (R=236.93)	1.35E18

5. ADJUSTED REFERENCE TEMPERATURE DETERMINATION

NRC Regulatory Guide 1.99, Draft Revision 2, provides the approach for computing the adjusted reference nil-ductility temperatures for beltline materials. The adjusted reference temperature (ART) is given by

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin} \quad (1)$$

where

$$\Delta RT_{NDT} \text{ (surface)} = [CF] f^{(0.28 - 0.1 \log f)} \quad (2)$$

and CF = chemistry factor specified in Reg. Guide 1.99, Rev. 2.

$$f = \text{fluence factor} = \frac{\text{fluence}}{10^{19}}$$

$$\text{Margin} = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2}$$

where σ_I = initial standard deviations of data = 0°F

σ_Δ = 28°F for welds and 17°F for plate materials.

Table 5-1, presents an evaluation of the ART of beltline materials for 12 EFPY. The large margin of 56°F was used for the weld metal 2-203, since this material is not in the Unit 1 Surveillance Program. From this table it is clear that the weld 2-203 is the controlling material for the pressure vessel. The ART of weld 2-203 at various irradiation conditions are used in developing the various P-T limit curves.

The through thickness attenuation of ΔRT_{NDT} is given by Regulatory Guide 1.99, Draft Revision 2, as

$$\Delta RT_{NDT} = [\Delta RT_{NDT} \text{ surface}] e^{-0.067X} \quad (3)$$

The ΔRT_{NDT} values for the various depths for the controlling weld 2-203 for 12, 16, 20, 24, 28, 32, 36 and 40 EFPYs are presented in table 5-2. Table 5-3 presents ART at 1/4T and 3/4T locations for the various EFPY.

Table 5-1. ART Evaluation for Beltline Materials for 12 EFPY

Material	Chemistry Cu	Ni	C.F.	Initial RT_{NDT} °F	ΔRT_{NDT} Surface °F	Margin °F	ART
2-203 A, B, C	0.21	0.87	208.2	-50	246	56	252
3-203 A, B, C	0.21	0.69	178.9	-56	213	56	213
9-203	0.23	0.23	120.[illegible]	-80	142	56	118
D-7206-1	0.11	0.55	122.8	20	145	56	221
D-7206-2	0.12	0.64	83.6	-30	99	56	125
D-7206-3	0.12	0.64	83.6	10	99	56	165
D-7207-1	0.13	0.59	89.2	10	105	56	171
D-7207-2	0.11	0.56	124.2	-10	147	56	193
D-7207-3	0.11	0.53	119.9	-20	1[illegible]2	56	178
HAZ	0.18	0.19	94.2	0	1[illegible]1	56	167

Table 5-2. ΔRT_{NDT} vs EFPY

EFPY	ΔRT_{NDT} Surface °F	ΔRT_{NDT} (1/4 T) °F	ΔRT_{NDT} (3/4 T) °F
12	246	213	160
16	259	225	168
20	269	233	175
24	277	240	180
28	283	245	184
32	288	250	187
36	293	254	190
40	296	256	192

Table 5-3. Adjusted Reference Temperatures at 1/4 T and 3/4 T

EFPY	ART (1/4 T) °F	ART (3/4 T) °F
12	219	166
16	231	174
20	239	181
24	246	186
28	251	190
32	256	193
36	260	196
40	262	198

6. HEAT-UP AND COOL-DOWN LIMITS

The adjusted reference temperature (ART) for 12, 16, 20, 24, 28 and 32 EFPYs were presented in Section 5. These ART values were used to develop the pressure-temperature limit conditions for the EFPYs described above. A SwRI computer program PTLIMT was used. The generic procedures for PTLIMT are described in Appendix D.

The following pressure vessel constants were employed as input data in the Calvert Cliffs Unit 1 analysis:

Vessel Inner Radius, r_i	=	86.81 in.
Vessel Outer Radius, r_o	=	95.43 in.
Operating Pressure, P_o	=	2235 psig
Initial Temperature, T_f	=	550°F
Effective Coolant Flow Rate, Q	=	128.8×10^6 lbm/hr
Effective FLow Area, A	=	39.83 ft^2
Effective Hydraulic Diameter, D	=	22.44 in.

Heat-up limits were computed for heat-up rates of 40°F/hr, 50°F/hr, 60°F/hr and 70°F/hr. Cool-down curves were computed for cool-down rates of 0°F/hr, 20°F/hr, 50°F/hr, and 100°F/hr.

Figures 6-1 and 6-2 present the heat-up and cool-down limit curves, respectively, for 12 EFPY. These figures were developed based on the NRC Standard Review Plan (5.3.2). In Figure 6-1, the lowest service temperatures, minimum bolt-up temperature (70°F) and inservice leak test curves are incorporated. In developing the heat-up and cool-down curves, instrument error margins of -60 psig for pressure measurements and +10°F for temperature monitoring have been included. These margins have been used industry wide to allow for possible errors in measuring instruments and to account for variations between bulk temperatures and local (near beltline) temperatures.

Appendix E presents the tables containing heat-up and cool-down data for 16, 20, 24, 28, 32, 36 and 40 EFPYs.

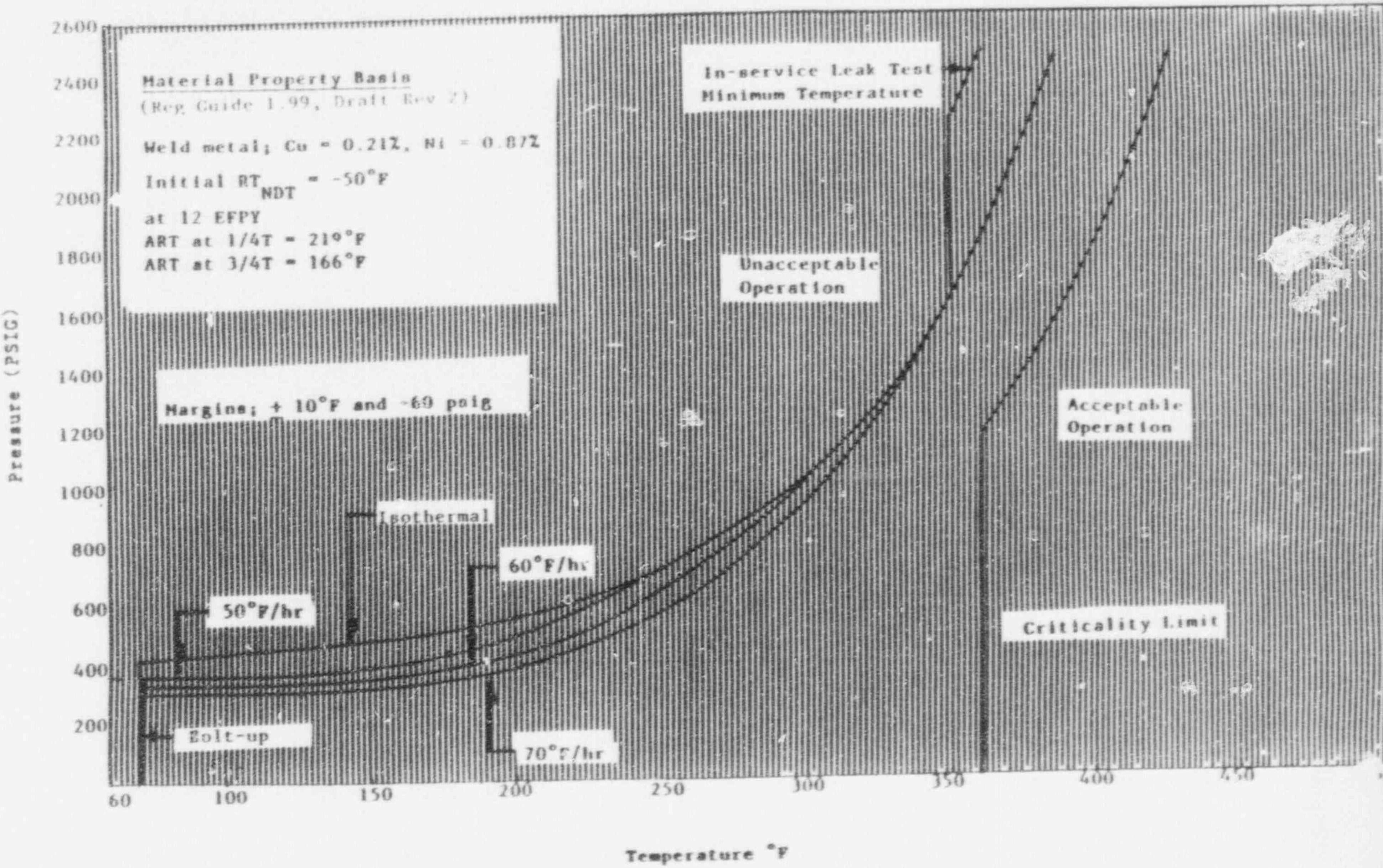

FIGURE 6.1 - Heat-Up Pressure-Temperature Limitation Curves for Calvert Cliff Unit 1 Reactor Vessel (12 EFPY)

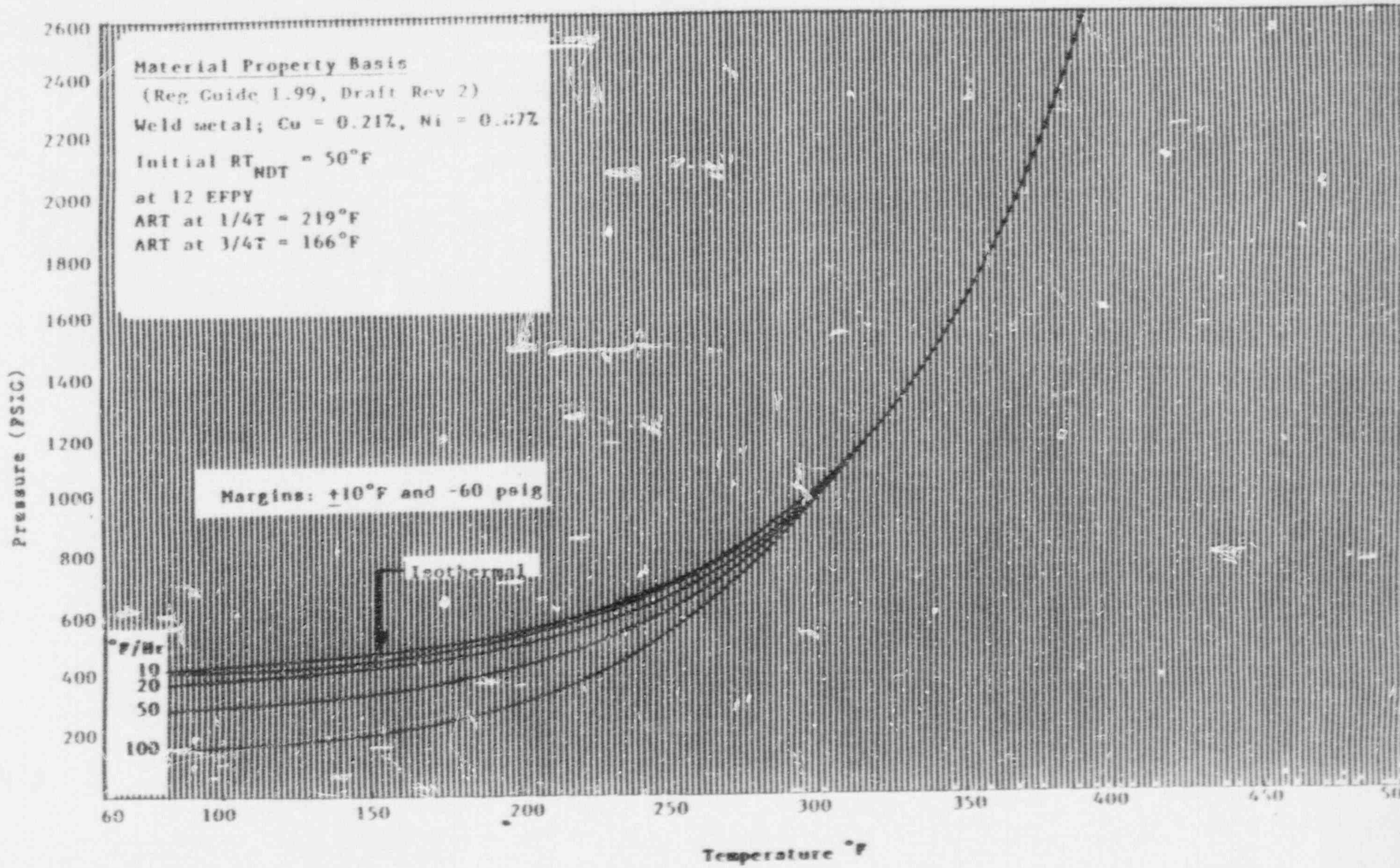

Figure 6.2 Cool-down Pressure-Temperature Limitation Curve for Calvert Cliff Unit 1 Reactor Vessel (12 EFPY)

REFERENCES

1. Perrin, J. S., Fromm, E. O., Farmelo, D. R., Denning, R. S., and Jung, R. G. "Calvert Cliffs Unit No. 1 Nuclear Plant Reactor Pressure Vessel Surveillance Program: Capsule 263", Final Report, December 15, 1980.

2. JAT (BG & E) letter to NRC, January 23, 1986.

3. Rhoades, W. A., Childs, R. L., "An Updated Version of the DOT-4 One- and Two-Dimensional Neutron/Photon Transport Code", ORNL-5851, Oak Ridge National Laboratory, Oak Ridge, TN, July, 1982.

4. Simons, G. L. and Roussin, R., "SAILOR-A Coupled Cross Section Library for Light Water Reactors", DLC-76, RSIC.

5. Don Wright's (BG & E) Calculations, January 15, 1986.

APPENDIX A

DETERMINATION OF SPACE-DEPENDENT SOURCE DISTRIBUTION FOR TRANSPORT ANALYSIS OF CALVERT CLIFFS-1

Appendix A.

Determination of Space-Dependent Source Distribution for Transport Analysis of Calvert Cliffs-1

The space-dependent source distribution used in the transport calculations was obtained by combining the assembly-wise power distribution with relative pinwise power values for the peripheral assemblies (i.e., XY Zones 9, 18, 26, 34, 42, 49 in Figure A.1). The relative assembly-wise power distributions for the 12, 18, and 24 month cycles are shown in Figure A.1. These values were obtained by averaging BOC, MOC, and EOC distributions provided by Baltimore Gas and Electric in References A-1 and A-2 as representative for the appropriate cycles. (The 24 month cycle distribution corresponds to a projected MOC core.) The absolute power produced for each assembly is obtained by multiplying the relative assembly power by a value of

$$\frac{2700 \text{ MWth}}{217 \text{ assemblies}} = 12.44 \frac{\text{MW}}{\text{assembly}} .$$

The absolute assembly power distribution for each type of cycle is given by Table A.1.

The power density is assumed flat within the interior assemblies, but is represented with a pinwise variation for the boundary assemblies, which account for virtually all of the RPV fluence. Examination of the BOC, MOC, and EOC relative pin powers provided by BG&E shows that the MOC distribution is a good approximation for the average over the cycle, and hence was used as the representative pinwise variation. The relative pin powers in the peripheral assemblies are very similar for the 12 and 18 month cycles, and therefore the 18 month pinwise distribution is used for both (the assemblywise distributions are different, however). Tables A.2-A.3 give the relative pinwise variations for configuration in Figure A.1.

The combination of the assembly and pinwise powers results in an absolute space-dependent power density defined for the quarter core. The power density values are converted to a source density by multiplying by the factor,

$$7.84 \times 10^{16} \ \frac{\text{neutron/s}}{\text{MW}}$$

The 1/4 core XY source distribution is then mapped onto the 1/8 core $R\theta$ mesh used in DOT by utilizing an interpolating program previously developed for this purpose.

References

A-1. Letter from Stanley to P. K. Nair, dated September 10, 1986.

A-2. Letter from Runion to P. K. Nair, dated October 10, 1986.

Figure A.1 Relative Power Distributions (Assembly-wise) for 12, 18, and 24 Month Cycles

Zone: Z
A — 12M
B — 18M
C — 24M

45° (diagonal line at assembly 48)

43 1.27 .98 1.02	44 1.14 1.24 1.34	45 1.12 .88 1.05	46 1.22 1.21 1.34	47 .78 1.05 1.10	48 1.03 1.10 1.03	49 .74 .86 .40		
35 1.07 1.20 1.37	36 1.21 1.01 1.07	37 1.03 1.17 1.32	38 .86 .91 .99	39 1.20 1.14 1.32	40 .78 1.05 1.10	41 .96 1.13 1.02	42 .65 .78 .32	
27 1.23 .81 1.03	28 1.02 1.27 1.33	29 1.10 .89 .99	30 1.22 1.24 .79	31 .84 .91 .99	32 1.22 1.21 1.34	33 .81 .96 .97	34 .89 1.00 .79	
19 1.07 1.10 .98	20 1.28 .95 1.02	21 .88 1.10 1.30	22 1.10 .89 .99	23 1.03 1.17 1.32	24 1.12 .88 1.05	25 1.20 .95 1.29	26 1.11 1.11 .84	
10 1.11 .80 1.02	11 .86 1.22 1.29	12 1.28 .95 1.02	13 1.02 1.27 1.33	14 1.21 1.10 1.07	15 1.14 1.25 1.35	16 .83 .81 1.01	17 1.09 .86 1.16	18 .73 .74 .34
1 .79 .56 .80	2 1.11 .80 1.08	3 1.07 1.10 .98	4 1.23 .81 1.03	5 1.07 1.20 1.37	6 1.27 .98 1.08	7 .93 .86 1.05	8 .92 1.04 .96	9 .87 .95 .79

Table A.1. Absolute Assembly Powers (MW_{th}) for Calvert Cliffs-1

ZONE	12 Month Cycle	18 Month Cycle	24 Month Cycle
1(**)	2.445(**)	1.739(**)	2.485(**)
2(*)	6.912(*)	4.946(*)	6.693(*)
3(*)	6.663(*)	6.812(*)	6.108(*)
4(*)	7.658(*)	5.027(*)	6.383(*)
5(*)	6.644(*)	7.459(*)	8.523(*)
6(*)	7.926(*)	6.103(*)	6.433(*)
7(*)	5.767(*)	5.238(*)	6.538(*)
8(*)	5.699(*)	6.451(*)	6.003(*)
9	10.825	11.833	9.879
10(*)	6.906(*)	4.946(*)	6.371(*)
11	10.651	15.167	16.076
12	15.964	11.82	12.778
13	12.641	15.814	16.499
14	15.043	13.687	13.301
15	14.135	15.491	16.785
16	10.315	10.128	12.554
17	13.575	10.688	14.371
18	9.108	9.257	4.279
19(*)	6.663(*)	6.812(*)	6.115(*)
20	15.964	11.820	12.753
21	10.924	13.736	16.225
22	13.724	11.012	12.368
23	12.828	14.582	16.474
24	13.985	10.937	13.114
25	14.869	11.833	16.013
26	13.861	13.786	10.414
27(*)	7.658(*)	5.027(*)	6.371(*)
28	12.651	15.814	16.474
29	13.724	11.012	12.355
30	15.130	15.453	9.792
31	10.738	11.310	12.306
32	15.167	15.105	16.71
33	10.041	12.007	12.044
34	11.012	12.467	9.892
35(*)	6.644(*)	7.459(*)	8.492(*)
36	15.043	12.567	13.276
37	12.828	14.595	16.449
38	10.738	11.31	12.293
39	14.981	14.371	16.424
40	9.705	13.051	13.749

Table A.1. Continued

Zone	12 Month Cycle	18 Month Cycle	24 Month Cycle
41	11.957	14.010	12.629
42	8.068	9.668	4.006
43(*)	7.926(*)	6.105(*)	6.371(*)
44	14.135	15.491	16.685
45	13.985	10.937	13.089
46	15.167	15.105	16.698
47	9.705	13.015	13.736
48	12.778	13.687	[illegible].853
49	9.162	10.676	5.027
50	0.0	0.0	0.0

Average Assembly Power = $\frac{217\ MW}{17\ assemblies}$ = 12.44 $\frac{MW}{ass.}$

(*)½ assembly per zone

(**)½ assembly per zone

Table A.2. Relative Pin Powers for 18 Month Cycle

```
105R1. 1.22 1.19 1.19 1.17 1.11 1.05 .99 .97 .93 .88 .84 .76 .67 .58
105R1. 1.2 1.30 1.41 1.38 1.21 1.03 .97 .95 .91 .96 .99 .91 .74 .58
105R1. 1.23 1.43 0.0 0.00 1.33 1.04 .97 .95 .92 1.05 0.00 0.00 .82 .59
105R1. 1.23 1.42 0.00 0.00 1.32 1.04 .98 .95 .92 1.05 0.00 0.00 .82 .58
105R1. 1.21 1.28 1.38 1.35 1.20 1.04 1.00 .99 .92 .96 .98 .89 .72 .57
105R1. 1.17 1.12 1.11 1.09 1.06 1.15 1.22 1.20 1.03 .86 .79 .72 .63 .55
105R1. 1.15 1.08 1.08 1.06 1.06 1.26 0.00 0.00 1.13 .86 .77 .69 .61 .58
105R1. 1.12 1.06 1.05 1.05 1.05 1.25 0.00 0.00 1.10 .84 .76 .68 .60 .54
105R1. 1.14 1.08 1.08 1.06 1.04 1.12 1.19 1.152 .99 .83 .76 .69 .61 .54
105R1. 1.16 1.22 1.32 1.29 1.15 .99 .96 .93 .87 .91 .93 .85 .69 .54
105R1. 1.17 1.34 0.00 0.00 1.26 .99 .92 .89 .86 .99 0.00 0.00 .77 .55
105R1. 1.16 1.34 0.00 0.00 1.25 .98 .90 .88 .85 .98 0.00 0.00 .77 .55
105R1. 1.13 1.21 1.31 1.29 1.13 .96 .89 .87 .84 .89 .93 .85 .69 .54
105R1. 1.13 1.11 1.12 1.10 1.04 .98 .92 .89 .86 .83 .79 .72 .64 .56
105R1. 1.12 1.10 1.102 1.083 1.028 .97 .912 .881 .847 .814 .777 .711 .62
0.54
105R1. 1.1 1.17 1.27 1.24 1.09 .92 .86 .83 .8 .85 .875 .802 .647 .501
105R1. 1.11 1.27 0. 0. 1.17 .91 .84 .814 .786 .90 0. 0. .692 .488
105R1. 1.1 1.25 0. 0. 1.15 .896 .83 .8 .77 .878 0. 0. .668 .469
105R1. 1.065 1.11 1.19 1.16 1.02 .87 .83 .8 .75 .778 .79 .72 .57 .439
105R1. 1.03 .965 .95 .927 .89 .956 1. .969 .82 .677 .62 .554 .477 .401
105R1. .997 .93 .908 .893 .885 1.044 0. 0. .885 .659 .585 .516 .447 .387
   91R1. 1.228 1.198 1.210 1.201 1.163 1.127 1.097
         1.115 1.118 1.129 1.143 1.130 1.095 1.086
 .981 .91 .874 .85 .835 .98 0. 0. .855 .635 .563 .497 .432 .376
   91R1. 1.211 1.298 1.416 1.406 1.258 1.099 1.064
         1.073 1.078 1.205 1.319 1.302 1.165 1.048
 .972 .9 .87 .837 .8 .848 .884 .87 .733 .6 .542 .482 .415 .359
   91R1. 1.239 1.431 0.000 0.000 1.389 1.120 1.074
         1.071 1.086 1.312 0.000 0.000 1.262 1.047
 .968 .99 1.03 .989 .855 .722 .679 .66 .61 .626 .625 .56 .447 .344
   91R1. 1.246 1.437 0.000 0.000 1.398 1.133 1.092
         1.078 1.086 1.305 0.000 0.000 1.241 1.029
 .96 1.06 0. 0. .91 .688 .626 .607 .57 .64 0. 0. .47 .33
   91R1. 1.224 1.305 1.421 1.414 1.277 1.135 1.124
         1.100 1.079 1.179 1.271 1.238 1.092 0.976
 .925 1.02 0. 0. .855 .642 .579 .561 .527 .596 0. 0. .439 .306
   91R1. 1.205 1.159 1.166 1.164 1.151 1.242 1.335
         1.296 1.173 1.052 1.027 0.986 0.934 0.919
```

Table A.2. Continued

```
.867 .873 .9 .85 .71 .58 .53 .52 .48 .495 .504 .454 .357 .274
  91R1. 1.195 1.144 1.139 1.143 1.158 1.352 0.000
        0.000 1.273 1.052 0.998 0.941 0.886 0.863
.805 .72 .674 .63 .58 .532 .494 .48 .438 .404 .372 .333 .286 .248
 91R1.0 1.193 1.142 1.138 1.142 1.157 1.348 0.000
        0.000 1.246 1.022 0.965 0.917 0.868 0.832  14Z
 91R1.0 1.220 1.171 1.176 1.172 1.155 1.240 1.325
        1.279 1.143 1.011 0.973 0.920 0.850 0.794  14Z
 91R1.0 1.256 1.333 1.448 1.436 1.290 1.138 1.118
        1.081 1.041 1.115 1.174 1.113 0.939 0.771  14Z
 91R1.0 1.295 1.484 0.000 0.000 1.423 1.143 1.092
        1.055 1.037 1.213 0.000 0.000 1.026 0.757  14Z
 91R1.0 1.300 1.429 0.000 0.000 1.425 1.139 1.081
        1.042 1.027 1.204 0.000 0.000 1.012 0.743  14Z
 91R1.0 1.280 1.364 1.481 1.464 1.301 1.125 1.078
        1.036 1.010 1.094 1.156 1.090 0.905 0.724  14Z
 91R1.0 1.292 1.262 1.274 1.261 1.209 1.156 1.111
        1.062 1.031 1.008 0.984 0.923 0.833 0.747  14Z
 91R1. 1.294 1.261 1.271 1.256 1.201 1.145 1.084 1.05 1.027 1.004 .977
     .915 .825  .741   14Z
 91R1. 1.265 1.351 1.465 1.444 1.280 1.099 1.039 1.002 .981 1.058 1.109
   1.037 .858 .689  14Z
 91R1. 1.273 1.466 0.0 0.0 1.39 1.1 1.028 .992 .976 1.136 0.0 0.0 .923
 .675  14Z
 91R1. 1.259 1.45 0.0 0.0 1.377 1.094 1.028 .992 .969 1.121 0. 0. .9
 .654  14Z
 91R1. 1.217 1.297 1.408 1.391 1.24 1.082 1.047 1.012 6 1.01 1.042
   .963 .785 .622  14Z
 91R1. 1.179 1.134 1.137 1.128 1.104 1.197 1.277 1.234 1.065 .897 .837
   .674 .598  14Z
91R1.  1.147 1.098 1.093 1.092 1.1 1.312 0.0 0.0 1.16 .887 .805 .73 .654
   .59  14Z
91R1. 1.147 1.095 1.088 1.086 1.093 1.302 0. 0. 1.152 .882 .8 .725 .649
   .584  14Z
91R1. 1.172 1.121 1.119 1.107 1.081 1.17 1.242 1.202 1.037 .87 .808 .735
   .647 .573  14Z
91R1. 1.204 1.272 1.371 1.348 1.197 1.04 .999 .969 .915 .956 .979 .9 .73
   .575   14Z
91R1. 1.239 1.41 0. 0. 1.314 1.035 .963 .933 .904 1.036 0. 0. .812 .583
 14Z
```

Table A.2. Continued

```
91R1. 1.243 1.414 0. 0. 1.308 1.024 .945 .914 .89 1.027 0. 0. .902 .570
 14Z
91R1. 1.222 1.29 1.387 1.355 1.186 1.005 .937 .904 .874 .932 .967 .891
    .722 .564  14Z
91R1. 1.232 1.188 1.185 1.158 1.094 1.029 .965 .928 .894 .861 .823 .754
    .662 .577  14Z
 91R1.
 1.206 1.169 1.167 1.14 1.077 1.013 0.951 0.915 0.879 0.843 0.805 0.737
 0.649 0.567
 14Z   91R1.0
 1.179 1.248 1.338 1.304 1.139 0.964 0.899 0.865 0.83 0.88 0.906 0.833
 0.675 0.529
 14Z   91R1.
 1.184 1.348 0.0 0.0 1.228 0.955 0.882 0.847 0.815 0.933 0.0 0.0 0.723
0.516
 14Z   91R1.
 1.166 1.324 0.0 0.0 1.204 0.938 0.87 0.834 0.797 0.907 0.0 0.0 0.696
.495
 14Z   .    0
 1.117 1.173 1.254 1.218 1.065 0.911 0.869 0.833 0.774 0.802 0.817 0.74
 0.594 0.461
 14Z   91R1.0
 1.069 1.011 0.994 0.967 0.928 0.991 1.041 0.996 0.842 0.694 0.636 0.57
 0.493 0.429
 14Z   91R1.0
 1.024 0.96. 0.94 0.921 0.909 1.069 0.0 0.0 0.899 0.669 0.594 0.525 .457
 0.399
14Z   91R1.0
 1.002 0.94 0.913 0.89 0.876 1.028 0.0 0.0 0.877 0.752 0.577 0.51 0.444
 0.39
 14Z   91R1.0
 0.993 0.929 0.902 0.87 0.83 0.883 0.921 0.893 0.752 0.613 0.557 0.496
0.431 0.376
 14Z   91R1.0
```

Table A.2. Continued

```
 0.987 1.016 1.064 1.019 0.883 0.747 0.703 0.678 0.626 0.641 0.642 0.58
 0.464 0.363
  14Z  91R1.0
 0.98 1.082 0. 6. 0.926 0.706 0.643 0.617 0.582 0.655 0. 0. 0.47 .348
   14Z  91R1.0
 0.943 1.034 0.0 0.0 0.868 0.753 0.59 0.564 0.534 0.605 0.0 0.0 0.455
.322
   14Z  91R1.0
 0.879 0.878 0.907 0.853 0.716 0.585 0.535 0.513 0.478 0.499 0.511 0.46
 0.368 0.286
   14Z  91R1.0
 .813 .713 .669 .629 .575 .529 .491 .472 .434 .403 .374 .337
 0.293 0.258   14Z
77R1. 1.29 1.25 1.25 1.22 1.17 1.12 1.08 1.05 1.03 1.01 1.00 .96 .90 .83
28Z
77R1. 1.25 1.32 1.43 1.40 1.24 1.07 1.03 .99 .97 1.05 1.12 1.07 .90 .73
28Z
77R1. 1.25 1.43 0.00 0.00 1.35 1.06 1.01 .97 .95 1.12 0.00 0.00 .94 .69
28Z
77R1. 1.22 1.40 0.00 0.00 1.31 1.04 .99 .95 .92 1.07 0.00 0.00 .89 .65
28Z
77R1. 1.17 1.24 1.33 1.31 1.16 1.01 .98 .94 .89 .94 .98 .92 .75 .60
28Z
77R1. 1.12 1.07 1.06 1.04 1.01 1.06 1.13 1.07 .93 .80 .76 .70 .62 .56
28Z
77R1. 1.07 1.02 1.00 .99 .98 1.13 0.00 0.00 .97 .77 .70 .64 .58 .52
28Z
77R1. 1.05 .99 .97 .96 .94 1.08 0.00 0.00 .95 .74 .68 .62 .55 .51
28Z
77R1. 1.03 .97 .95 .92 .89 .94 .98 .95 .82 .69 .64 .59 .52 .47
28Z
77R1. 1.02 1.05 1.11 1.07 .94 .81 .77 .74 .69 .72 .73 .67 .55 .44
28Z
77R1. 1.01 1.12 0.00 0.00 .98 .76 .70 .68 .64 .53 0.00 0.00 .57 .42
28Z
77R1. .97 1.07 0.00 0.00 .92 .70 .64 .62 .59 .67 0.00 0.00 .53 .38
28Z
77R1. .90  .90 .94 .89 .76 .62 .58 .55 .52 .55 .57 .53 .42 .34
28Z
77R1. .83 .74 .69 .66 .61 .56 .52 .51 .47 .44 .42 .38 .39 .30
   28Z
```

Table A.3. Relative Pin Powers for 24 Month Cycle

```
105R1.0    1.063 1.047 1.039 1.007 0.956 0.899 0.849
  0.805 0.766 0.731 0.691 [illegible] 0.551 0.458
105R1.0    1.071 1.076 1.177 1.166 0.982 0.908 0.843
  0.798 0.764 0.748 0.786 0.722 0.569 0.465
105R1.0    1.087 1.200 0.000 0.000 1.076 0.906 0.839
  0.793 0.766 0.832 0.000 0.000 0.640 0.474
105R1.0    1.090 1.196 0.000 0.000 1.089 0.982 0.838
  0.793 0.763 0.826 0.000 0.000 0.634 0.471
105R1.0    1.075 1.057 1.149 1.116 0.960 0.891 0.846
  0.802 0.757 0.729 0.759 0.694 0.549 0.456
105R1.0    1.053 1.006 0.984 0.955 0.919 0.899 0.954
  0.907 0.768 0.700 0.646 0.584 0.512 0.439
105R1.0    1.035 0.900 0.947 0.921 0.903 0.987 0.000
  0.000 0.848 0.689 0.620 0.557 0.492 0.426
105R1.0    1.016 0.967 0.935 0.908 0.890 0.972 0.000
  0.000 0.833 0.675 0.606 0.544 0.480 0.416
105R1.0    1.009 0.972 0.950 0.919 0.882 0.862 0.913
  0.866 0.729 0.661 0.607 0.547 0.479 0.411
105R1.0    1.017 1.005 1.088 1.051 0.899 0.830 0.784
  0.739 0.693 0.663 0.686 0.625 0.493 0.410
105R1.0    1.025 1.121 0.000 0.000 0.995 0.816 0.751
  0.705 0.673 0.723 0.000 0.000 0.548 0.407
105R1.0    1.013 1.110 0.000 0.000 0.977 0.796 0.727
  0.680 0.651 0.703 0.000 0.000 0.534 0.396
105R1.0    0.989 0.982 1.060 1.015 0.853 0.768 0.707
  0.660 0.626 0.609 0.637 0.582 0.458 0.376
105R1.0    0.976 0.951 0.925 0.878 0.812 0.747 0.692
  0.645 0.607 0.575 0.541 0.494 0.430 0.361
105R1.0    .711 .685 .646 .603 .562 .521 .482
  .444 .407 .372 .338 .304 .267 .224
105R1.0    .697 .000 .661 .615 .547 .506 .465
  .427 .391 .356 .336 .304 .000 .217
105R1.0    .670 .672 .000 .000 .550 .486 .444
  .406 .371 .351 .000 .000 .254 .205
105R1.0    .640 .637 .000 .000 .530 .465 .423
  .386 .353 .335 .000 .000 .238 .192
105R1.0    .612 .581 .573 .541 .000 .442 .399
  .365 .336 .000 .288 .256 .214 .180
```

Table A.3. Continued

```
105R1.0    .586 .553 .520 .488 .453 .412 .389
  .357 .316 .289 .260 .230 .200 .167
105R1.0    .563 .526 .491 .457 .421 .400 .000
  .000 .308 .270 .242 .213 .185 .156
91R1.0    1.14 1.11 1.09 1.06 1.02 .97 .93
  .90 .86 .84 .80 .76 .72 .67
  .539 .500 .463 .429 .395 .376 .000
  .000 .288 .250 .223 .196 .170 .143
91R1.0    1.13 1.12 1.17 1.14 1.02 .96 .91
  .87 .84 .83 .85 .80 .71 .66
  .516 .477 .441 .409 .378 .344 .325
  .296 .259 .233 .207 .182 .158 .132
91R1.0    1.14 1.20 0.00 0.00 1.08 .95 .89
  .85 .83 .86 0.00 0.00 .74 .64
  .492 .454 .437 .406 .000 .328 .296
  .267 .241 .000 .198 .175 .146 .122
91R1.0    1.13 1.18 0.00 0.00 1.07 .93 .88
  .84 .81 .84 0.00 0.00 .72 .63
  .467 .449 .000 .000 .353 .308 .276
  .247 .221 .205 .000 .000 .140 .113
91R1.0    1.10 1.08 1.13 1.09 .97 .92 .87
  .83 .80 .77 .78 .74 .65 .60
  .442 .427 .000 .000 .327 .284 .254
  .226 .202 .187 .000 .000 .129 .103
91R1.0    1.08 1.04 1.01 .98 .94 .91 .92
  .88 .79 .74 .70 .65 .61 .57
  .414 .000 .363 .329 .286 .257 .230
  .205 .182 .162 .150 .133 .000 .093
91R1.0    1.06 1.02 .98 .95 .92 .95 0.00
  0.00 .82 .72 .67 .62 .57 .53
  .366 .331 .300 .273 .247 .223 .200
  .178 .158 .140 .124 .109 .095 .079
91R1.0 1.06 1.01 .97 .94 .91 .94 0.00
  0.00 .81 .71 .65 .60 .55 .49
14Z  91R1.0    1.06 1.01 .98 .94 .90 .87 .88
  .84 .74 .69 .64 .59 .53 .46
14Z  91R1.0    1.07 1.03 1.07 1.03 .91 .86 .81
  .77 .72 .69 .68 .63 .53 .45
14Z  91R1.0    1.07 1.11 0.00 0.00 .98 .85 .79
  .75 .71 .72 0.00 0.00 .56 .44
```

Table A.3. Continued

```
14Z  91R1.0   1.06 1.10 0.00 0.00 .97 .84 .78
  .74 .70 .71 0.00 0.00 .55 .44
14Z  91R1.0   1.05 1.02 1.05 1.01 .90 .83 .78
  .73 .69 .66 .66 .60 .50 .42
14Z  91R1.0   1.04 1.00 .97 .93 .87 .82 .77
  .73 .68 .64 .60 .55 .49 .41
      14Z  91R1.0 1.137 1.102 1.083 1.048 0.990 0.93 0.878
        0.833 0.794 0.761 0.723 0.666 0.589 0.506
      14Z 91R1.0  1.128 1.113 1.209 1.171 1.002 0.918 0.859
        0.814 0.781 0.766 0.808 0.745 0.594 0.497
      14Z 91R1.0  1.127 1.230 0.000 0.000 1.113 0.920 0.852
        0.807 0.780 0.849 0.000 0.000 0.661 0.495
      14Z 91R1.0  1.106 1.211 0.000 0.000 1.102 0.914 0.851
        0.806 0.776 0.840 0.000 0.000 0.648 0.482
      14Z 91R1.0  1.086 1.058 1.155 1.124 0.969 0.903 0.861
        0.817 0.770 0.741 0.771 0.705 0.556 0.457
      14Z 91R1.0  1.027 0.996 0.980 0.956 0.925 0.914 0.981
        0.935 0.786 0.711 0.653 0.590 0.514 0.433
      14Z 91R1.0  1.001 0.962 0.938 0.917 0.907 1.008 0.000
        0.000 0.871 0.699 0.625 0.560 0.491 0.417
      14Z 91R1.0  0.986 0.947 0.922 0.901 0.891 0.990 0.000
        0.000 0.854 0.684 0.610 0.546 0.479 0.408
      14Z 91R1.0  0.983 0.950 0.931 0.906 0.876 0.866 0.930
        0.884 0.739 0.664 0.607 0.547 0.477 0.404
      14Z 91R1.0  0.991 0.979 1.063 1.030 0.885 0.823 0.783
        0.740 0.693 0.661 0.633 0.621 0.489 0.404
      14Z 91R1.0  1.000 1.089 0.000 0.000 0.973 0.801 0.741
        0.697 0.666 0.716 0.[illegible] 0.000 0.542 0.401
      14Z 91R1.0  0.990 1.075 0.000 0.000 0.949 0.775 0.711
        0.667 0.640 0.692 0.000 0.000 0.525 0.389
      14Z 91R1.0  0.964 0.943 1.016 0.974 0.822 0.742 0.686
        0.642 0.610 0.594 0.622 0.568 0.446 0.367
      14Z 91R1.0  0.945 0.906 0.880 0.840 0.782 0.723 0.672
        0.629 0.592 0.561 0.527 0.479 0.417 0.351
 14Z  91R1.0  .676 .640 .605 .570 .534 .497 .461
.425 .390 .356 .322 .288 .253 .212
 14Z  91R1.0  .652 .618 .608 .572 .514 .476 .439
.403 .369 .335 .315 .283 .239 .201
 14Z  91R1.0  .632 .622 0.0 0.0 .513 .455 .417
.382 .348 .328 0.0 0.0 .235 .190
 14Z  91R1.0  .612 .600 0.0 0.0 .490 .432 .395
```

Table A.3. Continued

```
.361 .329 .310 0.0 0.0 .221 .178
 14Z  91R1.0  .590 .553 .539 .502 .446 .408 .373
.341 .311 .283 .265 .237 .199 .167
 14Z  91R1.0  .565 .527 .491 .455 .419 .384 .366
.335 .294 .267 .240 .213 .185 .155
 14Z  91R1.0  .541 .501 .464 .429 .394 .376 0.0
0.0 .288 .251 .224 .198 .171 .144
 14Z  91R1.0  .517 .477 .440 .405 .372 .355 0.0
0.0 .270 .234 .208 .183 .158 .133
 14Z  91R1.0  .493 .453 .417 .383 .351 .322 .306
.278 .242 .216 .191 .169 .146 .123
 14Z  91R1.0  .468 .429 .410 .376 .331 .302 .274
.248 .222 .197 .182 .161 .135 .113
 14Z  91R1.0  .441 .420 0.0 0.0 .323 .281 .253
.227 .203 .187 0.0 0.0 .129 .104
 14Z  91R1.0  .412 .392 0.0 0.0 .299 .259 .231
.207 .184 .170 0.0 0.0 .118 .094
 14Z  91R1.0  .378 .344 .326 .298 .259 .232 .208
.185 .165 .147 .136 .121 .101 .084
 14Z  91R1.0  .338 .301 .272 .249 .225 .203 .182
.162 .145 .129 .114 .100 .087 .072
14Z  77R1.0 .841 .791 .752 .714 .673 .631 .592
  .554 .517 .482 .446 .408 .367 .322
28Z 77R1.0 .815 .772 .767 .725 .650 .604 .562
  .524 .488 .454 .436 .400 .345 .296
28Z 77R1.0 .793 .784 .000 .000 .653 .577 .532
  .494 .459 .443 .000 .000 .336 .275
28Z 77R1.0 .767 .754 .000 .000 .621 .546 .502
  .465 .431 .415 .000 .000 .313 .256
28Z 77R1.0 .734 .685 .673 .630 .558 .512 .472
  .436 .404 .373 .357 .325 .278 .237
28Z 77R1.0 .697 .643 .600 .560 .518 .478 .460
  .426 .378 .348 .318 .287 .254 .218
28Z 77R1.0 .658 .604 .550 .521 .483 .466 .000
  .000 .368 .323 .293 .263 .232 .199
28Z 77R1.0 .618 .568 .526 .488 .452 .436 .000
  .000 .342 .298 .269 .240 .211 .182
28Z 77R1.0 .582 .537 .497 .460 .425 .392 .376
  .346 .303 .273 .245 .219 .193 .165
```

Table A.3. Continued

```
28Z 77R1.0 .549 .508 .491 .453 .399 .365 .334
  .305 .276 .248 .231 .207 .176 .150
28Z 77R1.0 .516 .490 .000 .000 .309 .338 .306
  .277 .250 .233 .000 .000 .166 .135
28Z 77R1.0 .479 .462 .000 .000 .357 .309 .277
  .250 .225 .210 .000 .000 .150 .121
28Z 77R1.0 .437 .401 .385 .353 .306 .275 .247
  .222 .200 .180 .169 .151 .127 .107
28Z 77R1.0 .389 .347 .317 .289 .263 .230 .214
  .193 .173 .155 .139 .124 .108 .091
  28Z
```

APPENDIX B

DESCRIPTION OF THE 3D FLUX SYNTHESIS METHOD

Appendix B. Description of the 3D Flux Synthesis Method

A 3D (RθZ) flux distribution is synthesized using the following well established approximation:

$$\phi(R, \theta, Z) = \phi_{R\theta}(R,\theta) \frac{\phi_{RZ}(R,Z)}{\phi_R(R)} = \phi_{R\theta} A(R,Z) \qquad B.1$$

where $\phi_{R\theta}$ is the flux obtained from the Rθ DOT calculation; and

$A(R,Z) \equiv \frac{\phi_{RZ}}{\phi_R}$ = axial distribution function obtained by representing the RZ flux = (ϕ_{RZ}) distribution and dividing it by the integral over Z of the RZ flux, i.e.,

$$\phi_R \equiv \int_Z \phi_{RZ}\, dZ.$$

In previous studies the RZ flux distribution was represented by the results obtained from a DOT RZ calculation, while the radial flux ϕ_R was obtained from a one-dimension calculation. However, it has been discovered that a simplier approximation gives similar results (within a few percent) as the results of these transport calculations for locations not outside of the RPV and near the reactor midplane. In this approach we represent

$$A(R,Z) \equiv \frac{\phi_{RZ}\ (R,Z)}{\phi_R} = \frac{P_{(Z)}}{\int_Z P(Z)dZ} \qquad B.2$$

where P(Z) is the average axial distribution of power in the core. The function P(Z) has been represented by discrete nodal values obtained by averaging BOC, MOC and EOC relative axial powers provided by Baltimore Gas and Electric for the peripheral assemblies. The relative axial power values were provided at 51 points for the 12 and 18 month cycles, and at 24 points for the 24 month cycle. Therefore employing the expression eq. B.2 for axial point k, we find

$$A(R,Z) \cong A(Z) \rightarrow A_k = \frac{P_k}{\int P(Z)dZ} \; ; \; k=1, \text{ \# of axial points}$$

There are 51 points used for the 12 and 18 month cycles, in the axial dimension. The 51 points define 50 nodes (i.e., intervals). The active core height was assumed to be 136.7 inches, so that the height of each axial interval will be:

$$\Delta Z_1 = \frac{(136.7)(2.54)}{50} = 6.94 \text{ cm}$$

To calculate the integrated axial power we use the expression

$$\int_0^H P(Z)dZ \sim \sum_{k=1}^{50} \overline{P}_k \, \Delta Z_1 \qquad \text{B.3}$$

where $\overline{P}_k$ is the average power (relative) in the kth axial node. This value is approximated by $\overline{P}_k = \frac{P_k + P_{k+1}}{2}$, where P_k and P_{k+1} are the point powers taken from the axial power data provided by BG&E. Substituting this expression for $\overline{P}_k$ into eq. (B.3) gives

$$\int_0^H P(Z)dZ \sim \left[\sum_{k=1}^{51} P_k - \left(\frac{P_1 + P_{51}}{2} \right) \right] \Delta Z_1 \qquad \text{B.4}$$

Eq. B.4 was used to approximate the denominator of eq. B.2, for the 12 and 18 month cycles.

The axial distribution provided by BG&E for the 24 month cycle only has 24 intervals instead of 51 as for the 12 and 18 month cycles. A similar development for this gives

$$\int_0^H P(Z)\,dZ \approx \left[\sum_{k=2}^{23} P_k + \left(\frac{P_1 + P_{24}}{2}\right)\right] \Delta Z_J \qquad \text{B.5}$$

where $\Delta Z_J = \frac{(136.7)(2.54)}{23} = 15.1$ cm

Eq. B-3 was used to approximate the denominator of eq. B.2 for the 12 & 18 month cycle.

The final axial synthesis factors for the 12 and 18 month cycles are given in Table B.1, and for the 24 month cycle in Table B.2.

In order to compute the 3D flux or activity at some axial location (corresponding to a height Z in Table B.1 and B.2), for some Rθ location one must

(a) find the flux or activity at the appropriate (R_I, θ_J) location in the DOT Rθ run

(b) find the axial flux factor at the appropriate node K

(c) compute the 3D value using expression

$$\phi(R_I, \theta_J, Z_K) = \phi_{R\theta}(R_I, \theta_J) * A_K$$

(*) For example, in the 12 month cycle the peak power corresponds approximately to Z = 97.2. From Table B.1 it can be seen that the axial flux factor for this location is equal to 3.26×10^{-3}. Therefore all activties and fluxes in the DOT Rθ output should bc multiplied by this factor in order to obtain the corresponding peak values.

References

B-1. R. E. Marker, B. L. Broodhead, M. L. Williams, "Recent Progress and Developments in LWR-PV Calculational Methodology," Reactor Dosimetry, D. Reidel Publishing, Dordrecht, Holland, 1985.

B-2. M. L. Williams, P. Chowdhary, "DOTSYN: A Module for Synthesizing Three-Dimensional Fluxes in the LEPRICON Computer Code System," Electric Power Research Institute.

B-3. N. Tsoulfanidis, "Calculation of Neutron Energy Spectra in the Core and Cavity of a PWR (ANO-1)," EPRI NP-3776, Electric Power Research Institute, 1984.

B-4. Ltr. from Stanley to Nair, dated September 10, 1986.

Table B.1. Axial Distribution Factors for Flux Synthesis: 12 and 18 Month Cycles

	z (cm)	A_k, 12 Month	A_k, 18 Month
(TOP)	347.2	1.61E-3	1.55E-3
	340.3	1.82E-3	1.77E-3
	333.3	2.08E-3	1.98E-3
	326.4	2.21E-3	2.16E-3
	319.4	2.51E-3	2.33E-3
	312.5	2.52E-3	2.49E-3
	305.6	2.65E-3	2.62E-3
	298.6	2.77E-3	2.47E-3
	291.7	2.87E-3	2.84E-3
	204.7	2.96E-3	2.92E-3
	277.8	3.02E-3	2.98E-3
	270.8	3.06E-3	3.04E-3
	263.9	3.09E-3	3.08E-3
	256.9	3.12E-3	3.11E-3
	250.0	3.14E-3	3.12E-3
	243.1	3.24E-3	3.13E-3
	236.1	3.24E-3	3.13E-3
	229.2	3.14E-3	3.12E-3
	222.2	3.13E-3	3.11E-3
	215.3	3.12E-3	3.10E-3
	208.3	3.10E-3	3.10E-3
	201.4	3.09E-3	3.09E-3
	194.4	3.09E-3	3.08E-3
	187.5	3.08E-3	3.08E-3
	180.6	3.08E-3	3.08E-3
(MIDDLE)	173.6	3.08E-3	3.09E-3
	166.7	3.07E-3	3.07E-3
	159.7	3.08E-3	3.09E-3
	152.8	3.10E-3	3.11E-3
	145.8	3.12E-3	3.14E-3
	138.9	3.15E-3	3.17E-3
	131.9	3.17E-3	3.20E-3
	125.0	3.19E-3	3.23E-3
	118.1	3.21E-3	3.26E-3
	111.1	3.23E-3	3.28E-3
	104.2	3.25E-3	3.30E-3
(PEAK)	97.2	3.26E-3	3.31E-3
	90.3	3.25E-3	3.31E-3
	83.3	3.24E-3	3.30E-3
	76.4	3.21E-3	3.27E-3
	69.4	3.17E-3	3.23E-3
	62.5	3.18E-3	3.18E-3
	55.6	3.30E-3	3.09E-3

Table B.1. Continued

z		12 Month	18 Month
	48.6	2.94E-3	2.99E-3
	41.7	2.82E-3	2.87E-3
	34.7	2.74E-3	2.73E-3
	27.8	2.57E-3	2.57E-3
	20.8	2.42E-3	2.38E-3
	13.9	2.16E-3	2.18E-3
	6.9	1.95E-3	1.96E-3
(BOTTOM)	0.0	1.74E-3	1.77E-3

Table 5.2. Axial Distribution Factors for Flux Synthesis: 24 Month Cycle

	Z (cm)	A_k, 24 Month
(TOP)	347.2	1.35E-3
	332.1	1.92E-3
	317.2	2.40E-3
	301.9	2.70E-3
	286.8	2.93E-3
	271.7	3.09E-3
	256.6	3.16E-3
	241.5	3.18E-3
	226.4	3.18E-3
	211.4	3.17E-3
	196.3	3.17E-3
(MIDDLE: 173.6)	181.2	3.18E-3
	166.1	3.18E-3
	151.0	3.19E-3
	135.9	3.21E-3
	120.8	3.22E-3
	105.7	3.23E-3
(PEAK)	90.6	3.23E-3
	75.5	3.18E-3
	60.4	3.03E-3
	45.3	2.82E-3
	30.3	2.53E-3
	15.1	2.06E-3
(BOTTOM)	0.0	1.51E-3

APPENDIX C

POWER-TIME HISTORY FOR CALVERT CLIFFS, UNIT 1

Appendix C. Power-Time History for Calvert Cliffs, Unit 1

Table C.1 gives the power time history for Cycles 1-3, which correspond to the 12 month cycles that the first surveillance capsule was in the reactor.

Table C.2 gives the power time history for Cycles 4-8. Cycle 4 is a 12 month cycle, while the remainder are 18 month cycles.

Table C.1. Power Time History for Calvert Cliffs Unit-1; Cycles 1-3 (12 month cycles)

Time Step	Operating Period	Fraction of Reference Power (P_j)	Irradiation Time (T_j)	Decay Time ($T-t_j$)
1	1-75	0.169	31	1549
2	2-75	0.305	28	1521
3	3-75	0.429	31	1490
4	4-75	0.413	30	1460
5	5-75	0.553	31	1429
6	6-75	0.679	30	1399
7	7-75	0.801	31	1368
8	8-75	0.402	31	1337
9	9-75	0.636	30	1307
10	10-75	0.929	31	1276
11	11-75	0.861	30	1246
12	12-75	0.906	31	1215
13	1-76	0.878	31	1184
14	2-76	0.902	28	1156
15	3-76	0.921	31	1125
16	4-76	0.500	30	1095
17	5-76	0.931	31	1064
18	6-76	0.893	30	1034
19	7-76	0.920	31	1003
20	8-76	0.932	31	972
21	9-76	0.836	30	942
22	10-76	0.907	31	911
23	11-76	0.785	30	881
24	12-76	0.614	31	850
25	1-77	0.0	31	819
26	2-77	0.0	28	791
27	3-77	0.0	31	760
28	4-77	0.687	30	730
29	5-77	0.745	31	699
30	6-77	0.871	30	669
31	7-77	0.915	31	638
32	8-77	0.928	31	607
33	9-77	0.954	30	577
34	10-77	0.848	31	546
35	11-77	0.961	30	516
36	12-77	0.872	31	485
37	1-78	0.563	31	454
38	2-78	0.0	28	426
39	3-78	0.0	31	395
40	4-78	0.387	30	365

Table C.1. Continued

Time Step	Operating Period	Fraction of Reference Power (P_j)	Irradiation Time (T_j)	Decay Time ($T-t_j$)
41	5-78	0.627	31	334
42	6-78	0.905	30	304
43	7-78	0.876	31	273
44	8-78	0.901	31	242
45	9-78	0.912	30	212
46	10-78	0.916	31	181
47	11-78	0.897	30	151
38	12-78	0.482	31	120
49	1-79	0.344	31	89
50	2-79	0.943	28	61
51	3-79	0.943	31	30
52	4-79	0.652	30	0

Effective Full Power Days = 1073.2

Table C.2. Power Time History for Calvert Cliffs Unit 1: Cycles 4-8 (1)

Time Step	Operating Period	Fraction of Reference Power (Pj) (2)	Irradiation Time (T_j)	Decay Time ($T-t_j$)
1	5-79	0.00	31	2708
2	6-79	0.00	30	2678
3	7-79	0.373	31	2647
4	8-79	0.881	31	2616
5	9-79	0.953	30	2586
6	10-79	0.904	31	2555
7	11-79	0.612	30	2525
8	12-79	0.561	31	2494
9	1-70	0.463	31	2463
10	2-80	0.431	28	2435
11	3-80	0.949	31	2404
12	4-80	0.[illegible]6	30	2374
13	5-80	0.821	31	2343
14	6-80	0.943	30	2313
15	7-80	0.955	31	2282
16	8-80	0.946	31	2251
17	9-80	0.956	30	2221
18	10-80	0.460	31	2190
19	11-80	0.00	30	3160
20	12-80	0.00	31	2129
21	1-81	0.539	31	2098
22	2-81	0.979	28	2070
23	3-81	0.960	31	2039
24	4-81	0.782	30	2009
25	5-81	0.895	31	1978
26	6-81	0.811	30	1948
27	7-81	0.430	31	1917
28	8-81	0.909	31	1886
29	9-81	0.944	30	1856
30	10-81	0.728	31	1825
31	11-81	0.878	30	1795
32	12-81	0.983	31	1764
33	1-82	0.982	31	1733
34	2-82	0.982	28	1705
35	3-82	0.980	31	1674
36	4-82	0.526	30	1644
37	5-82	0.00	31	1613
38	6-82	0.00	30	1583
39	8-82	0.725	31	1552
40	8-82	0.747	31	1521
41	9-82	0.672	30	1491
42	10-82	0.995	31	1460
43	11-82	0.960	30	1430

Table C.2. Continued

44	12-82	0.940	31	1399
45	1-83	0.942	31	1368
46	2-83	0.891	28	1340
47	3-83	0.980	31	1309
48	4-83	0.809	30	1279
49	5-83	0.989	31	1248
50	6-83	0.910	30	1218
51	7-83	.988	31	1187
52	8-83	.932	31	1156
53	9-83	.896	30	1126
54	10-83	0.0	31	1095
55	11-83	0.0	30	1065
56	12-83	.531	31	1034
57	1-84	.932	31	1003
58	2-84	.976	28	975
59	3-84	.807	31	944
60	4-84	.994	30	914
61	5-84	.176	31	883
62	6-84	.981	30	853
63	7-84	.996	31	822
64	8-84	.882	31	791
65	9-84	.992	30	761
66	10-84	.965	31	730
67	11-84	.785	30	700
68	12-84	.501	31	669
69	1-85	.885	31	638
70	2-85	.967	28	610
71	3-85	.979	31	579
72	4-85	.151	30	549
73	5-85	0.0	31	518
74	6-85	0.0	30	488
75	7-85	0.0	31	457
76	8-85	.226	31	426
77	9-85	.928	30	396
78	10-85	.776	31	365
79	11-85	.995	30	335
80	12-85	.994	31	304
81	1-86	.932	31	273
82	2-86	.997	28	245
83	3-86	.772	31	214
84	4-86	.991	30	184
85	5-86	.986	31	153
86	6-86	.919	30	123
87	7-86	.94	31	92
88	8-86	.977	31	61
89	9-86	.995	31	31
90	10-86	.717	31	0

Effective Full Power Days = 1986.2
(1) Cycle 4 is a 12-month cycle; all others, 18 month.
(2) Reference Power = 2700 Mwth.

ATTACHMENT C

Unit 2 Fluence Calculations

(SwRI Report Without Appendices E through G)

Baltimore Gas and Electric Company

Docket Nos. 50-317 & 50-318

December 13, 1991

SOUTHWEST RESEARCH INSTITUTE
Post Office Drawer 28510, 6220 Culebra Road
San Antonio, Texas 78284

PRESSURE-TEMPERATURE LIMITS FOR CALVERT CLIFFS NUCLEAR POWER PLANT UNIT 2

By
P. K. Nair
M. L. Williams
M. Asgari

FINAL REPORT
SwRI Project No. 06-1278-002

Prepared For
Baltimore Gas & Electric Co.
P. O. Box 1472
Baltimore, MD 21203

December 1988

Approved:

Edward M. Briggs, Director
Department of Structural
and Mechnical Systems

8911060070 78p.

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1. SUMMARY OF RESULTS AND CONCLUSIONS

A detailed analysis was performed for developing new pressure-temperature limit curves for the Calvert Cliffs Unit 2 reactor pressure vessel. The analysis included new neutron transport calculations for 12, 18 and 24 month cycles, development of irradiated material properties based on NRC Regulatory Guide 1.99, Rev. 2, and the generation of heat up and cool down limit curves for every 4 EFPY from 12 EFPY to 40 EFPY conditions.

The SwRI evaluation led to the following conclusions:

1. Based on a calculated neutron spectral distribution, the peak fluxes incident on the Reactor Pressure Vessel (RPV) are 5.04×10^{10} n/cm^2-sec, 4.89×10^{10} n/cm^2-sec and 4.10×10^{10} n/cm^2-sec for 12 month, 18 month and 24 month cycles respectively.
2. Adjusting the calculated flux with respect to the first capsule dosimeter analysis the 12 month and 18 month cycle peak fluxes on the RPV was determined to be 4.72×10^{10} n/cm^2-sec and 4.59×10^{10} n/cm^2-sec respectively.
3. The calculated lead factors for the vessel ID based on surveillance capsule capsule locations are given below:

Cycle Type	θ=7° Lead Factor	θ=14° Lead Factor
12 month	1.26	0.94
18 month	1.24	0.91
24 month	1.18	0.79

4. The accumulated peak fluence on RPV ID was calculated to be 1.17×10^{19} n/cm^2 for the first 7 cycles and 4.28×10^{19} n/cm^2 to end-of-life conditions.

5. Displacement per Atom (dpa) for 12 EFPY were calculated to be 2.632×10^{-2}, 1.747×10^{-2} and 0.5206×10^{-2} for RPV ID, 1/4T and 3/4T respectively. For 32 EFPY dpa are 6.498×10^{-2}, 4.302×10^{-2}, 1.275×10^{-2} for RPVID, 1/4T and 3/4T respectively.

6. The 12 EFPY fluence on the RPV was calculated to be 1.69×10^{19} n/cm^2. Fluence rate of 1.2933×10^{18} (n/cm^2) per year was used to develop fluence value for 16, 20, 24, 28, 32, 36 and 40 EFPYs.

7. The controlling material for RPV operations was determined to be weld 2-203 with Cu = 0.12% and Ni = 1.01%. P-T limit data was developed for 12, 16, 20, 24, 28, 32, 36 and 40 EFPYs. The data also reflects different heat-up and cool down rates.

8. Based on the Reg Guide 1.99, Rev. 2 approach, the end of the life adjusted reference temperature for the controlling material will be 222°F at the RPV ID and 201°F at the 1/4T location.

9. Based on this study the Calvert Cliff Unit 2 reactor vessel has adequate material toughness for continued safe operated to end-of-life irradiation conditions.

2. INTRODUCTION

The long-term degradation of reactor vessel structural material properties due to irradiation is measured by the evaluation of material surveillance capsules removed periodically from the reactor vessel. Combustion Engineering, Inc. has provided the material surveillance program for the Calvert Cliffs Nuclear Power Plant Unit 2. To date, one surveillance capsule has been removed and tested (Reference 1). Typically, the capsules contain Charpy V-notch and tensile specimens in various combinations representing the present materials, weld metal and heat-affected zone (HAZ) material of the vessel beltline region. In addition, the capsules contain iron, nickel, titanium, sulfur, uranium and copper neutron flux monitors and temperature monitors.

The objective of the surveillance program is to correlate changes in vessel material fracture toughness properties with neutron fluence so that the reactor vessel pressure temperature limits can be determined. Recently, the concern about pressurized thermal shock has placed additional requirements to determine the irradiated condition of vessel inner surface. The applicable regulations and documents that address the continued licensibility of reactor vessels include 10 CFR Part 50, Appendices, B, G and H, 10 CFR Part 50.61, NRC Standard Review Plan 5.3.2, Regulatory Guide 1.99, Rev 2 and ASME Boiler and Pressure Vessel Code Section III, Appendix G.

In this report a new neutron flux analysis for the reactor vessel is presented. Based on the analysis, projected vessel fluence conditions were developed for assessing the long term integrity of the vessel. Pressure-temperature limit conditions are presented for 12, 16, 20, 24, 28, 32, 36 and 40 effective full power years of operation.

3. MATERIAL PROPERTY ASSESSMENT

In developing the pressure-temperature limit conditions for reactor vessels, the important material property required is the Reference Temperature - Nil Ductibility Transition (RT_{NDT}) of various vessel pressure boundary materials. The locations within the pressure boundary that are of interest include nozzle area, closure head region and the beltline region. The nozzle and closure head regions are locations of high stress concentrations while the beltline region is subject to neutron embrittlement with time.

Early in the life of the reactor vessel, nozzle and closure head regions tend to control the pressure-temperature limit curves. However, with time the beltline irradiated materials become controlling. In the case of Calvert Cliffs Unit 2, the controlling material for 12 EFPYs and beyond is the beltline region material. Between the nozzle and the closure head region, the closure head region poses greater restrictions on the PT limit curves.

10 CFR 50 "Fracture Toughness Requirements for Light-Water Nuclear Power Reactor" requires the closure head region materials to have, as a minimum, RT_{NDT} + 120° for normal operations and RT_{NDT} + 90° for hydrostatic pressure and leak tests. In the case of non-availability of RT_{NDT} data or where the data is not reliable, the RT_{NDT} for closure region is determined using the method in NRC Standard Review Plan 5.3.2, Branch Technical Position 5-2, MTEB. Based on this method, the RT_{NDT} of the closure head material was assessed to be 60°F.

To provide the submittal to NRC on the Pressurized Thermal Shock issue, Reference 2 extensive materials data information was developed for all the beltline materials (Reference 2). A key information needed is the material chemistry, especially Cu and Ni. The Cu and Ni values for the beltline materials are presented in Table 3.1. These chemistry values are used in Section 5 of this report to develop the irradiated Adjusted Reference Temperature for the critical beltline materials. Figure 3.1 presents the Calvert Cliffs Unit-2 Reactor Pressure Vessel map with all the key beltine welds identified.

Table 3.1. Calvert Cliffs Unit No. 2 Reactor Vessel Beltline Material Properties

ID	Cu (w/o)	Ni (w/o)	Initial RT^{NDT} (°F)
2-203(1) A,B,C	0.12	1.01	-56.0
3-203 A,B,C	0.23	0.23	-80.0
9-203	0.22	0.05	-60.0
D-8906-1	0.15	0.56	10.0
D-8906-2	0.11	0.56	10.0
D-8906-3	0.14	0.55	5.0
D-8907-1	0.15	0.60	-8.0
D-8907-2	0.14	0.66	20.0
D-8907-3	0.11	0.74	-16.0

(1) The value used for Ni is an upper bound due to the lack of available data. The generic initial RT_{NDT} = -56°F, is used for this weld.

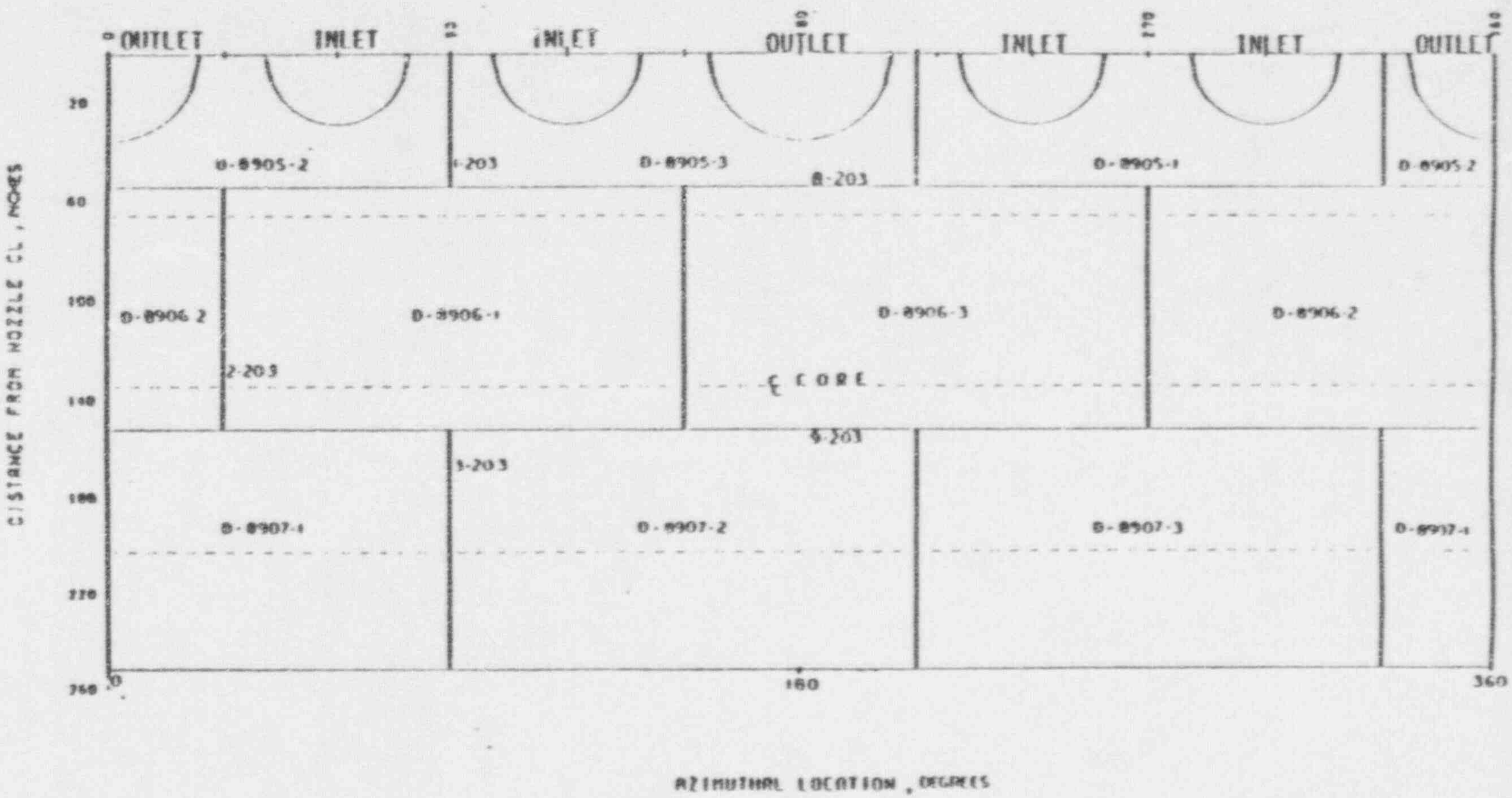


Figure 3.1 Calvert Cliffs Unit-2, Reactor Pressure Vessel Map

4. NEUTRON FLUENCE CALCULATIONS

In this section a detailed neutron transport analysis for the Calvert Cliffs-2 is discussed. A discrete ordinates calculation using the DOT-4 [3] code was performed to obtain the radial (R) and azimuthal (Θ) fluence-rate distribution for the geometry is shown in Figure 4.1. As part of the reactor cross section model the details of the surveillance capsule geometry and location has to be modeled. The inclusion of the surveillance capsules in the R-Θ model is mandatory to account for the significant perturbation effects from the physical presence of the capsule. Figure 4.2 represents the actual capsule geometry versus the DOT model used in the analysis. The DOT model incorporates a homogenized mixture of inconel and water to simplify the overall model while maintaining the required accuracies for the calculation.

The DOT-4 calculations were performed with the first 33 groups of the 47 group energy structure for the SAILOR [4] cross section library. The 47 group structure is given in Table C.1 of Appendix C. An S8 angular structure and a P_3 Legendre cross-section expansion were used. The fine-group dosimeter cross-sections for the $^{63}Cu\ (n, \alpha)^{60}Co$ reaction were obtained from ENDF/B-V file and were collapsed to 47 groups using a fission plus 1/E weighting spectrum. The other reaction cross sections were taken from the SAILOR cross section library. The dosimeter activation cross sections are given in Table C.2 of Appendix C. The DPA cross sections were obtained from MACLIB.

The results of the transport calculations for the RPV fluence analysis are presented in Tables 4.1 through 4.15. Appendix A discusses the determination of space-dependent source distribution for the transport analysis performed for Calvert Cliffs Unit 2. Appendix B is a description of the 3D Flux synthesis method used in this analysis. Appendix C gives the

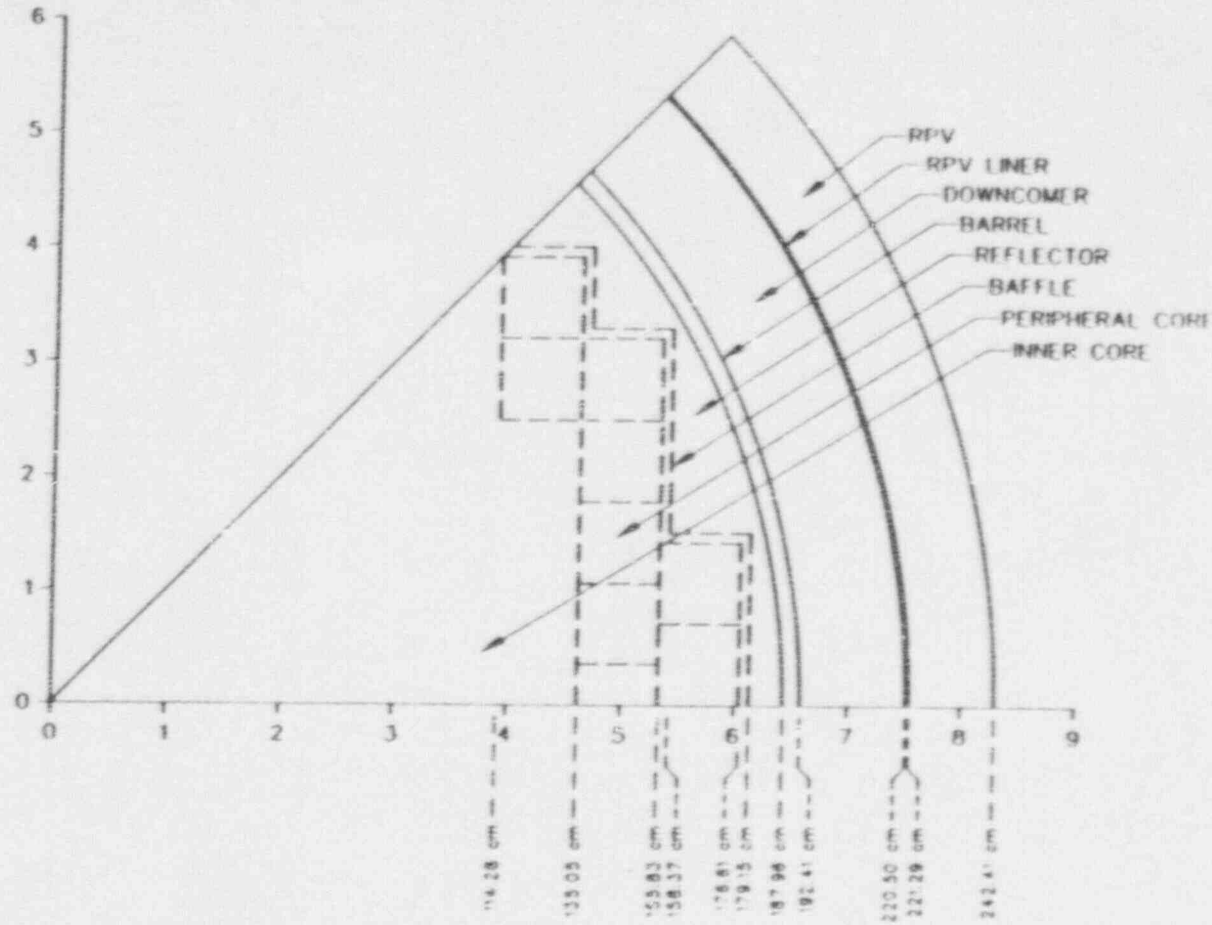
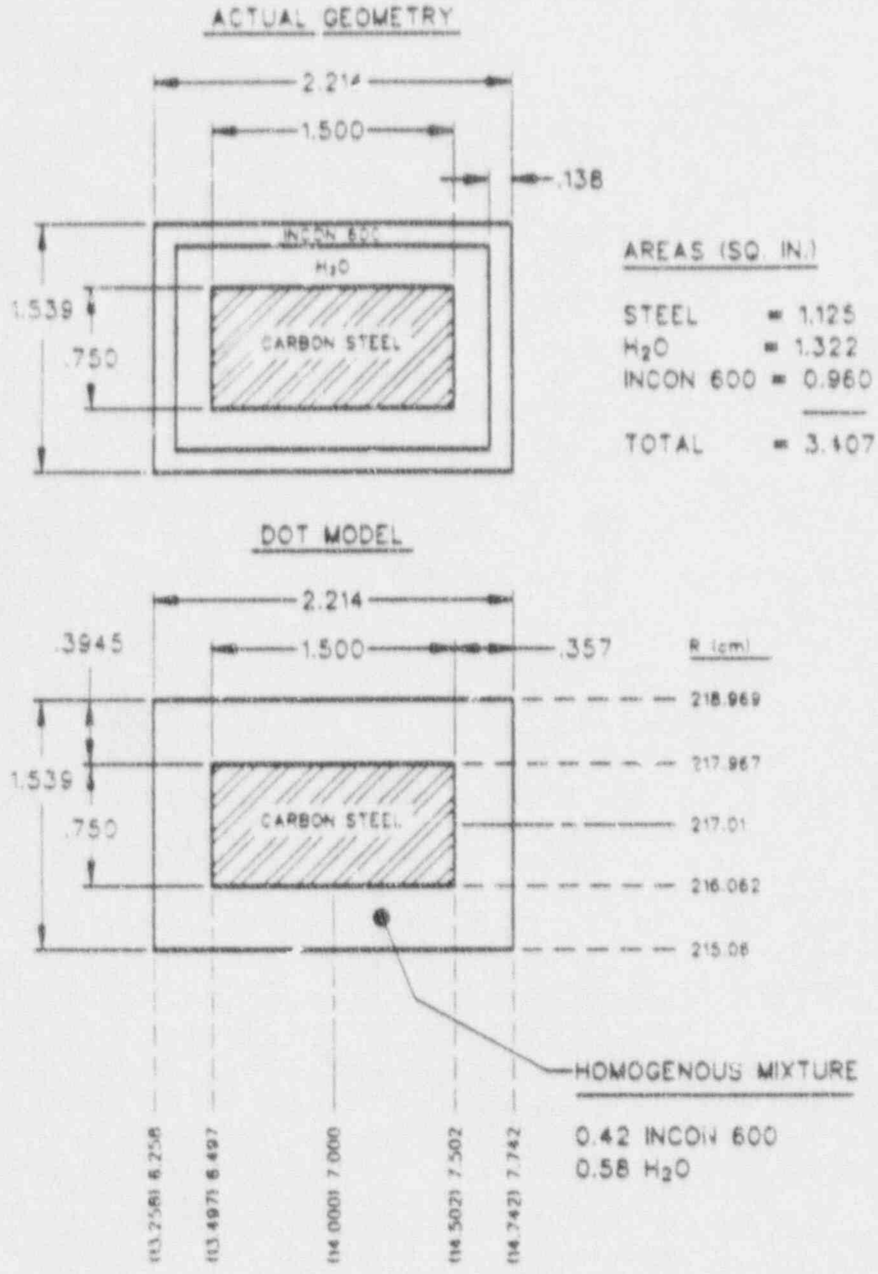


Figure 4.1 Calvert Cliffs Unit-2 DOT-4 RO MODEL*

*(Surveillance Capsules at 7° and 14° are not shown)
(Scale: 1 Large Division = 11.5 inches)


ACTUAL GEOMETRY
2.214
1.500
.138
INCON 600
H2O
1.539
.750
CARBON STEEL
AREAS (SQ. IN.)
STEEL = 1.125
H2O = 1.322
INCON 600 = 0.960
TOTAL = 3.407
DOT MODEL
2.214
.3945
1.500
.357
R (cm)
218.969
217.967
217.01
216.062
215.06
1.539
.750
CARBON STEEL
HOMOGENOUS MIXTURE
0.42 INCON 600
0.58 H2O
(13.258) 6.258
(13.497) 6.497
(14.000) 7.000
(14.502) 7.502
(14.742) 7.742

group structure and the dosimeter cross sections used in the calculations. Appendix D discusses the expressions used in obtaining the measured saturated activities; and Appendix E gives the power time history for cycles 1-8.

The first surveillance capsule (263°) was removed from Unit 2 following cycle 4 after 4.58 EFPYs of operation. A detailed capsule testing and analysis was conducted and reported in Reference (2). The dosimetry and vessel fluence evaluation provided information on the vessel fracture toughness conditions for 3 cycles of 12 months each and one 18 month cycle. Since the removal of the 263° capsule, 18 month cycles have been used for cycles 5-7; and beginning with cycle 8, a 24 month is being employed. A 24 month cycle is planned for future operations.

In order to verify the accuracy of the present calculations, computed results have been compared on an absolute basis with experimental results from the earlier capsule analysis. The average C/E value obtained for the Fe56, Ni58, Cu63, U238, Ti46 and Np237 activities was 1.07. The worst C/E obtained was 1.12 for U238. This good agreement indicates that the transport calculation methodology is accurate and that projected fluences should be reliable. In addition the experimental results can be used to adjust the calculated values to obtain even better agreement for the 12 and 18 month cycles (no experimental data is presently available for 24 month cycles). The adjusted fluence rates, which differs from the original calculated values by only about 10%, were used to obtain the projected RPV fluence.

The transport calculations indicate the maximum fast fluence (E>1 MeV) at the 0-T location of the Calvert Cliffs Unit-2 RPV will be (a) 1.38×10^{19} n/cm^2 at the end of the present cycle (cycle 8), and (b) 4.28×10^{19} n/cm^2 at the end of 32 EFPY, assuming all future cycles to be the 24 month loading configuration.

Table 4.1 Spectrum Averaged Cross Sections at Center of S.C.

Reaction	σeff(b) 12 Month Cycle	σeff(b) 18 Month Cycle	σeff(b) 24 Month Cycle
$^{54}Fe(n,p)$	0.135	0.135	0.137
$^{58}Ni(n,p)$	0.171	0.172	0.174
$^{63}Cu(n,\alpha)$	0.00160	0.00160	0.00165
$^{238}U(n,f)$	0.452	0.452	0.454
$^{46}Ti(n,p)$	0.0231	0.0231	0.0236

$$\sigma eff = \frac{\int_0^\infty \sigma(E)\,\phi(E)\,dE}{\int_1^\infty \phi(E)\,dE}$$

Table 4.2-a Absolute Calculated Neutron Fluence Rate Spectra (i.e., group flux) at the Center of 7° Surveillance Capsules (SC) for Calvert Cliffs Unit-2

Group	Upper Energy (MeV)	ϕ $n\text{-}cm^{-2} \cdot s^{-1}$ 12 M	18 M	24 M
1	1.733E+01	1.59292E+07	1.52822E+07	1.27832E+07
2	1.419E+01	6.93740E+07	6.65497E+07	5.56482E+07
3	1.221E+01	2.88874E+08	2.76866E+08	2.29367E+08
4	1.000E+01	5.90160E+08	5.65460E+08	4.66652E+08
5	8.607E+00	1.06918E+09	1.02397E+09	8.40528E+08
6	7.408E+00	2.68699E+09	2.57274E+09	2.10562E+09
7	6.065E+00	3.87362E+09	3.70630E+09	3.01119E+09
8	4.966E+00	6.86589E+09	6.56254E+09	5.26914E+09
9	3.679E+00	4.85415E+09	4.63744E+09	3.70105E+09
10	3.012E+00	3.56590E+09	3.40593E+09	2.71246E+09
11	2.725E+00	4.02853E+09	3.84738E+09	3.06022E+09
12	2.466E+00	1.98716E+09	1.89776E+09	1.50951E+09
13	2.365E+00	5.24276E+08	5.00711E+08	3.98751E+08
14	2.346E+00	2.48412E+09	2.37234E+09	1.88732E+09
15	2.231E+00	5.92853E+09	5.66162E+09	4.50071E+09
16	1.920E+00	6.01068E+09	5.73971E+09	4.55897E+09
17	1.653E+00	7.83818E+09	7.48456E+09	5.94153E+09
18	1.353E+00	1.07824E+10	1.02965E+10	8.17687E+09
19	1.003E+00	6.61976E+09	6.32146E+09	5.02059E+09
20	8.208E-01	3.41830E+09	3.26402E+09	2.58966E+09
21	7.427E-01	7.39563E+09	7.06203E+09	5.60636E+09
22	6.081E-01	6.29429E+09	6.01018E+09	4.77007E+09
23	4.979E-01	6.70364E+09	6.40121E+09	5.08137E+09
24	3.688E-01	6.70364E+09	5.40516E+09	4.29365E+09
25	2.972E-01	9.26295E+09	8.84492E+09	7.02081E+09
26	1.832E-01	7.82055E+09	7.46754E+09	5.92668E+09
27	1.111E-01	5.97356E+09	5.70375E+09	4.52540E+09
28	6.738E-02	5.51274E+09	5.26369E+09	4.17532E+09
29	4.097E-02	2.16627E+09	2.06833E+09	1.64014E+09
30	3.183E-02	9.61249E+09	9.17733E+08	7.27404E+08
31	2.606E-02	1.65836E+09	1.58337E+09	1.25580E+09
32	2.418E-02	1.03785E+09	9.90926E+09	7.86043E+08
33	2.188E-02	2.77008E+09	2.64510E+09	2.09854E+09

Table 4.2-b Absolute Calculated Neutron Fluence Rate Spectra (i.e., group flux) at the Center of 14° Surveillance Capsules (SC) for Calvert Cliffs Unit-2

Group	Upper Energy (MeV)	ϕ $n\text{-}cm^{-2}\cdot s^{-1}$ 12 W	18 W	24 W
1	1.733E+01	1.36555E+07	1.28002E+07	1.03138E+07
2	1.419E+01	5.90405E+07	5.53381E+07	4.44927E+07
3	1.221E+01	2.39561E+08	2.24094E+08	1.77171E+08
4	1.000E+01	4.82710E+08	4.51223E+08	3.54086E+08
5	8.607E+00	8.59415E+08	8.02627E+08	6.23235E+08
6	7.408E+00	2.13034E+09	1.98863E+09	1.53439E+09
7	6.065E+00	3.00697E+09	2.80412E+09	2.13254E+09
8	4.966E+00	5.19617E+09	4.83870E+09	3.59520E+09
9	3.679E+00	3.62438E+09	3.37305E+09	2.47393E+09
10	3.012E+00	2.64975E+09	2.46516E+09	1.79860E+09
11	2.725E+00	2.98304E+09	2.77488E+09	2.01863E+09
12	2.466E+00	1.46982E+09	1.36719E+09	9.94068E+08
13	2.365E+00	3.88458E+08	3.61376E+08	2.63181E+08
14	2.346E+00	1.83812E+09	1.70987E+09	1.24329E+09
15	2.231E+00	4.38728E+09	4.08118E+09	2.96463E+09
16	1.920E+00	4.44645E+09	4.13607E+09	2.99903E+09
17	1.653E+00	5.79570E+09	5.39088E+09	3.90357E+09
18	1.353E+00	7.99680E+09	7.43919E+09	5.39179E+09
19	1.003E+00	4.91889E+09	4.57636E+09	3.31787E+09
20	8.208E-01	2.53234E+09	2.35556E+09	1.70335E+09
21	7.427E-01	5.50761E+09	5.12462E+09	3.71182E+09
22	6.081E-01	4.68683E+09	4.36098E+09	3.15694E+09
23	4.979E-01	4.98422E+09	4.63761E+09	3.35877E+09
24	3.688E-01	4.23105E+09	3.93799E+09	2.85763E+09
25	2.972E-01	6.89253E+09	6.41386E+09	4.64476E+09
26	1.832E-01	5.82004E+09	5.41600E+09	3.92080E+09
27	1.111E-01	4.44033E+09	4.13191E+09	2.98901E+09
28	6.738E-02	4.09527E+09	3.81070E+09	2.75518E+09
29	4.097E-02	1.60846E+09	1.49660E+09	1.08127E+09
30	3.183E-02	7.13850E+08	6.64133E+08	4.79399E+08
31	2.606E-02	1.23418E+09	1.14840E+09	8.30116E+08
32	2.418E-02	7.72632E+08	7.19027E+08	5.20131E+08
33	2.188E-02	2.06304E+09	1.91978E+09	1.38761E+09

Table 4.3-a Calculated Saturated Midplane Activities in Calvert Cliffs Unit-1 Surveillance Capsules (12 M Cycle)

Dosimeter or Flux	Saturated Activities for 7° Surveillance Capsule, Bq/g			Saturated Activities for 14° Surveillance Capsule, Bq/g		
	R = 216.379cm	R = 217.014cm	R = 217.649cm	R = 216.379cm	R = 217.014cm	R = 217.649cm
$^{54}Fe(n,p)^{54}Mn$	5.95E6	5.36E6	4.76E6	4.58E6	4.13E6	3.70E6
$^{58}Ni(n,p)^{58}Co$	8.45E7	7.62E7	6.81E7	6.48E7	5.86E7	5.25E7
$^{63}Cu(n,\alpha)^{60}Co$	7.40E5	6.66E5	5.98E5	5.95E5	5.36E5	4.82E5
$^{237}Np(n,f)^{137}Cs$	2.25E7	2.11E7	1.92E7	1.68E7	1.58E7	1.44E7
$^{238}U(n,f)^{137}Cs$	4.75E6	4.35E6	3.91E6	3.58E6	3.29E6	2.96E6
$^{46}Ti(n,p)^{46}Sc$	1.66E6	1.49E6	1.33E6	1.31E6	1.18E6	1.05E6
ϕ(E>1.0 MeV)	6.84E10	6.35E10	5.73E10	5.11E10	4.76E10	4.31E10
ϕ(E>0.1 MeV)	1.22E11	1.17E11	1.08E11	9.11E10	8.71E10	8.10E10

Table 4.3-b Calculated Saturated Midplane Activities in Calvert Cliffs Unit-2 Surveillance Capsules (18 M Cycle)

Dosimeter or Flux	Saturated Activities for 7° Surveillance Capsule, Bq/g			Saturated Activities for 14° Surveillance Capsule, Bq/g		
	R = 216.379cm	R = 217.014cm	R = 217.649cm	R = 216.379cm	R = 217.014cm	R = 217.649cm
$^{54}Fe(n,p)^{54}Mn$	5.69E6	5.12E6	4.57E6	4.27E6	3.84E6	3.44E6
$^{58}Ni(n,p)^{58}Co$	8.08E7	7.29E7	6.51E7	6.03E7	5.46E7	4.88E7
$^{63}Cu(n,\alpha)^{60}Co$	7.08E5	6.38E5	5.73E5	5.55E5	5.00E5	4.50E5
$^{237}Np(n,f)^{137}Cs$	2.15E7	2.01E7	1.84E7	1.56E7	1.47E7	1.34E7
$^{238}U(n,f)^{137}Cs$	4.54E6	4.16E6	3.74E6	3.33E6	3.06E6	2.76E6
$^{46}Ti(n,p)^{46}Sc$	1.59E6	1.43E6	1.28E6	1.22E6	1.10E6	9.84E5
ϕ(E>1.0 MeV)	6.53E10	6.06E10	5.48E10	4.76E10	4.43E10	4.01E10
ϕ(E>0.1 MeV)	1.17E11	1.11E11	1.03E11	8.48E10	8.11E10	7.54E10

Table 4.3-c Calculated Saturated Midplane Activities in Calvert Cliffs Unit-2 Surveillance Capsules (24 M Cycle)

Dosimeter or Flux	Saturated Activities for 7° Surveillance Capsule, Bq/g			Saturated Activities for 14° Surveillance Capsule, Bq/g		
	R = 216.379cm	R = 217.014cm	R = 217.649cm	R = 216.379cm	R = 217.014cm	R = 217.649cm
$^{54}Fe(n,p)^{54}Mn$	4.60E6	4.14E6	3.70E6	3.22E6	2.91E6	2.61E6
$^{58}Ni(n,p)^{58}Co$	6.52E7	5.80E7	5.26E7	4.54E7	4.11E7	3.68E7
$^{63}Cu(n,\alpha)^{60}Co$	5.82E5	5.24E5	4.71E5	4.32E5	3.89E5	3.51E5
$^{237}Np(n,f)^{137}Cs$	1.71E7	1.61E7	1.47E7	1.14E7	1.08E7	9.87E6
$^{238}U(n,f)^{137}Cs$	3.64E6	3.34E6	3.00E6	2.47E6	2.27E6	2.04E6
$^{46}Ti(n,p)^{46}Sc$	1.30E6	1.16E6	1.04E6	9.36E5	8.42E5	7.56E5
ϕ(E>1.0 MeV)	5.22E10	4.84E10	4.38E10	3.49E10	3.25E10	2.95E10
ϕ(E>0.1 MeV)	9.31E10	8.87E10	8.24E10	6.18E10	5.92E10	5.51E10

Table 4.4 Non-Saturation Factors(h) Used in Dosimeters Activities

Dosimeter	h_{1-3} (Cycles 1-3)	h_4 (Cycle 4)
Fe54	0.7007	0.6110
Ni58	0.5159	0.7394
Cu63	0.3211	0.1642
Ti46	0.5560	0.7542
U238	0.0699	0.0313

(a) h = non-saturation factor

$$= \sum_j P_j(1-e^{-\lambda T_j})\, e^{-\lambda(T-t_j)},$$

where factors P_j, T_j and $T-t_j$ are given in Appendix C.

Table 4.5 Comparison of Unadjusted Calculated and Measured Parameters of Calvert Cliffs-2 Dosimeters Removed Following Cycle 4

Parameter	Measured[1]	Calculated[3]	C/E
Fe54 dosimeter activity (dps/gm)[2]	3.761E6	4.17E6	1.11
Ni58 dosimeter activity (dps/gm)[2]	5.079E7	5.40E7	1.06
Cu63 dosimeter activity (dps/gm)[2]	2.680E5	2.79E5	1.04
U238 dosimeter activity (dps/gm)[2]	3.78E5	4.23E5	1.12
Ti46 dosimeter activity (dps/gm)[2]	1.07E6	1.09E6	1.01

(1) A_{TOR} values taken from Reference 1.

(2) At center of capsule; time of removal from reactor.

(3) $(A_{TOR})_4$ = dosimeter activity at EOC-4

$$= (A_{TOR})_3 \, e^{-\lambda\tau} + (A_{SAT})_{18M} \, h_4$$

where $(A_{TOR})_3 = (A_{SAT})_{12M} h_{1\to3}$

and $(A_{SAT})_{12M}$, $(A_{SAT})_{18M}$ = saturated activites for 12 and 18 month cycle respectively, and $h_{1\to3}$, h_4 = non-saturation factors from Table 3;

τ = time (d) from EOC3 to EOC4 = 579 days.

Table 4.6 "Measured" Saturated Activities (A_{SAT}) for 12 and 18 Month Cycles, Based on Cycles 1-4 Dosimetry[(2)]

Dosimeter	Center of S.C. (12 M Cycle)		Center of S.C. (18 M Cycle)	
	$A_{TOR}^{(1)}$	$A_{SAT}^{(2)}$	$A_{TOR}^{(1)}$	$A_{SAT}^{(2)}$
$^{54}Fe(n,p)^{54}Mn$	3.76E6	4.84E6	3.76E6	4.62E6
$^{58}Ni(n,p)^{58}Co$	5.10E7	7.19E7	5.10E7	6.88E7
$^{63}Cu(n,\alpha)^{60}Co$	2.68E5	5.41E5	2.68E5	6.14E5
$^{238}U(n,f)^{137}Cs$	3.78E5	3.88E6	3.78E5	3.71E6
$^{46}Ti(n,p)^{46}Sc$	1.07E6	1.47E6	1.07E6	1.41E6

[(1)] A_{TOR} values taken from Reference 1.

[(2)] See Appendix D for definition of measured saturated activities

Table 4.7-a Determination of "Adjusted" ϕ (>1) in S.C. for 12 Month Cycles

CENTER FLUX:

Dosimeter	Measured A_{SAT}	Calculated σ_{eff}	Adjusted ϕ (>1)[(1)]
$^{54}Fe(n,p)^{54}Mn$	4.84E6	0.135	5.73E10
$^{58}Ni(n,p)^{58}Co$	7.19E7	0.171	6.00E10
$^{63}Cu(n,\alpha)^{60}Co$	6.41E5	0.0016	6.11E10
$^{238}U(n,f)^{137}Cs$	3.88E6	0.452	5.65E10
$^{46}Ti(n,p)^{46}Sc$	1.47E6	0.0231	6.25E10
		Average	5.95E10

(1) $\text{Adjust } \phi\ (>1) \equiv \dfrac{[A_{SAT}]\ \text{measured}}{\text{No } [\sigma_{eff}]\ \text{calc.}}$

Table 4.7-b Determination of "Adjusted" ϕ (>1) in S.C. for 18 Month Cycles

CENTER FLUX:

Dosimeter	Measured A_{SAT}	Calculated σ_{eff}	Adjusted ϕ (>1)[1]
$^{54}Fe(n,p)^{54}Mn$	4.62E6	0.135	5.47E10
$^{58}Ni(n,p)^{58}Co$	6.88E7	0.172	5.71E10
$^{63}Cu(n,\alpha)^{60}Co$	6.14E5	0.00'6	5.85E10
$^{238}U(n,f)^{137}Cs$	3.71E6	0.432	5.41E10
$^{46}Ti(n,p)^{46}Sc$	1.41E6	0.0231	6.00E10
		Average	5.69E10

[1] Adjust ϕ (>1) = $\dfrac{[A_{SAT}]\ \text{measured}}{\text{No}\ [\sigma_{eff}]\ \text{calc}}$

Table 4.8 Relative Azimuthal Variation[a] In ϕ (> 1 MeV) Incident on Vessel

J	$\bar{\theta}$	12 M Cycle	18 M Cycle	24 M Cycle
1	1.25000E+00	1.000	1.000	1.000
2	3.75000E+00	0.992	0.987	0.965
3	5.62900E+00	0.963	0.953	0.901
4	6.37750E+00	0.918	0.906	0.847
5	6.64000E+00	0.891	0.879	0.814
6	7.00000E+00	0.870	0.856	0.785
7	7.35950E+00	0.870	0.854	0.774
8	7.62200E+00	0.882	0.864	0.777
9	8.37099E+00	0.901	0.880	0.780
10	9.62500E+00	0.877	0.853	0.740
11	1.08750E+01	0.834	0.808	0.690
12	1.21250E+01	0.784	0.756	0.640
13	1.30040E+01	0.745	0.717	0.608
14	1.33775E+01	0.717	0.690	0.585
15	1.36400E+01	0.690	0.663	0.563
16	1.40000E+01	0.664	0.637	0.541
17	1.43605E+01	0.653	0.626	0.533
18	1.46220E+01	0.654	0.626	0.533
19	1.49300E+01	0.658	0.629	0.536
20	1.55590E+01	0.649	0.620	0.529
21	1.65000E+01	0.624	0.595	0.514
22	1.75000E+01	0.602	0.573	0.501
23	1.85000E+01	0.586	0.557	0.491
24	1.95000E+01	0.577	0.549	0.485
25	2.05000E+01	0.575	0.546	0.483
26	2.15000E+01	0.579	0.549	0.483
27	2.25000E+01	0.586	0.556	0.485
28	2.35000E+01	0.596	0.565	0.488
29	2.45000E+01	0.607	0.576	0.490
30	2.55000E+01	0.617	0.585	0.492
31	2.65000E+01	0.624	0.592	0.491
32	2.75000E+01	0.628	0.596	0.487
33	2.84000E+01	0.629	0.597	0.481
34	2.98118E+01	0.620	0.588	0.468
35	3.09600E+01	0.612	0.581	0.461
36	3.12330E+01	0.611	0.580	0.459
37	3.15647E+01	0.609	0.578	0.456
38	3.20500E+01	0.607	0.576	0.451
39	3.25500E+01	0.604	0.573	0.447
40	3.30500E+01	0.600	0.570	0.442
41	3.35500E+01	0.595	0.566	0.437
42	3.41962E+01	0.589	0.560	0.431
43	3.47000E+01	0.584	0.556	0.428
44	3.49150E+01	0.581	0.553	0.426
45	3.53723E+01	0.573	0.545	0.420
46	3.60720E+01	0.561	0.534	0.413
47	3.71220E+01	0.544	0.518	0.402

48	3.81720E+01	0.527	0.503	0.392
49	3.88720E+01	0.517	0.494	0.385
[illegible]	3.95720E+01	0.508	0.486	0.380
[illegible]	4.02360E+01	0.501	0.480	0.375
52	4.07750E+01	0.498	0.477	0.373
53	4.12500E+01	0.495	0.475	0.370
54	4.17500E+01	0.493	0.474	0.368
55	4.22500E+01	0.492	0.473	0.366
56	4.27500E+01	0.492	0.473	0.364
57	4.32500E+01	0.492	0.473	0.363
58	4.37500E+01	0.493	0.474	0.363
59	4.42500E+01	0.494	0.475	0.363
60	4.47500E+01	0.494	0.475	0.363

(a) Peak value normalized to unity

Table 4.9 Calculated ϕ (E>1) in Surveillance Capsules and Lead Factors[1] for Calvert Cliffs Unit 2

AZIMUTHAL LOCATION: $\theta = 7°$

Cycle Type	RPV Lead Factor	1/4T Lead Factor	3/4T Lead Factor
12 M	1.26	2.11	10.35
18 M	1.24	2.09	10.23
24 M	1.18	1.97	9.74

AZIMUTHAL LOCATION: $\theta = 14°$

Cycle Type	RPV Lead Factor	1/4T Lead Factor	3/4T Lead Factor
12 M	0.94	1.58	7.76
18 M	0.91	1.53	7.48
24 M	0.79	1.32	6.54

(1) $LF = \frac{\phi_{sc}(>1)}{\phi_{pv}(>1)}$, where ϕ_{sc} is the calculated flux at the center of the surveillance capsule, and ϕ_{pv} is the maximum calculated flux incident a the indicated RPV location.

Table 4.10 Peak ϕ (>1) in RPV of Calvert Cliffs-2

Radial[a] Location	12M Cycle[b] adjusted	12M Cycle[c] calculated	18M Cycle[c] calculated	18 Month[b] adjusted	24M Cycle[c] calculated
IR RPV (R=221.29)	4.72E10	5.04E10	4.89E10	4.59E10	4.10E10
1/4 T (R=225.98)	2.82E10	3.01E10	2.90E10	2.72E10	2.46E10
3/4 T (R=236.93)	5.75E9	6.13E9	5.92E9	5.56E9	4.97E10

(a) RPV liner begins at 220.5
RPV begins at 221.29
RPV ends at 242.41

(b) Obtained by dividing adjusted S.C. flux (see Table 4.7) by lead factor for 7° capsule in Table 4.9.

(c) Obtained by dividing calculated S.C. flux in Table 4.3 by lead factor in Table 4.9. (Note: no experimental data is available for 24 month cycles.)

Table 4.1[illegible] DPA Values (Displacements Per Atom Per Second) in RPV of Calvert Cliffs-2 Due to Neutrons with Energies Above 15 KeV

Radial Location	12W	18M	24W
220.895	7.70120E-11	7.44755E-11	6.28325E-11
222.102	7.12429E-11	6.88783E-11	5.80282E-11
223.727	6.20802E-11	5.99981E-11	5.04510E-11
225.351	5.30644E-11	5.12647E-11	4.30195E-11
226.976	4.50996E-11	4.35527E-11	3.64720E-11
228.601	3.82092E-11	3.68842E-11	3.08251E-11
230.225	3.22920E-11	3.11603E-11	2.59904E-11
231.850	2.71842E-11	2.62221E-11	2.18313E-11
233.475	2.27459E-11	2.19337E-11	1.82302E-11
235.099	1.88462E-11	1.81679E-11	1.50774E-11
236.724	1.5372[illegible]E-11	1.48154E-11	1.22790E-11
238.348	1.22209E-11	1.17754E-11	9.74867E-12
239.973	9.27444E-12	8.93477E-12	7.39050E-12
241.598	6.21949E-12	5.99104E-12	4.95297E-12

Table 4.12-a Calculated Fluence Multigroup-Spectra in Reactor Pressure Vessel at Peak Axial and Azimuthal Location ($\theta = 0^{\circ}$) for Calvert Cliffs Unit-2 (12M Cycle)

Group	Upper Energy (MeV)	ϕ $n \cdot cm^{-2} \cdot s^{-1}$ 0-T R=221.29	1/4-T R=225.98	3/4-T R=236.93
1	1.733E+01	0.13903E+08	0.66299E+07	0.11341E+07
2	1.419E+01	0.60230E+08	0.29019E+08	0.49589E+07
3	1.221E+01	0.24316E+09	0.11322E+09	0.17639E+08
4	1.000E+01	0.48806E+09	0.22636E+09	0.33443E+08
5	8.607E+00	0.86725E+09	0.39420E+09	0.53867E+08
6	7.408E+00	0.21627E+10	0.95554E+09	0.11839E+09
7	6.065E+00	0.30616E+10	0.13013E+10	0.14864E+09
8	4.966E+00	0.52688E+10	0.22331E+10	0.25428E+09
9	3.679E+00	0.36265E+10	0.16645E+10	0.21901E+09
10	3.012E+00	0.26524E+10	0.13040E+10	0.18234E+09
11	2.725E+00	0.29983E+10	0.15343E+10	0.22442E+09
12	2.466E+00	0.14882E+10	0.76602E+09	0.11316E+09
13	2.365E+00	0.38856E+09	0.22000E+09	0.36853E+08
14	2.346E+00	0.18615E+10	0.10640E+10	0.18309E+09
15	2.231E+00	0.45795E+10	0.26909E+10	0.46962E+09
16	1.920E+00	0.47468E+10	0.31886E+10	0.68395E+09
17	1.633E+00	0.63481E+10	0.44750E+10	0.10201E+10
18	1.353E+00	0.95161E+10	0.78817E+10	0.23706E+10
19	1.003E+00	0.61356E+10	0.55743E+10	0.21153E+10
20	8.208E-01	0.29275E+10	0.23763E+10	0.81196E+09
21	7.427E-01	0.82006E+10	0.89881E+10	0.42637E+10
22	6.081E-01	0.68423E+10	0.73336E+10	0.36954E+10
23	4.979E-01	0.73867E+10	0.82570E+10	0.41833E+10
24	3.688E-01	0.76526E+10	0.97683E+10	0.58506E+10
25	2.972E-01	0.96759E+10	0.10321E+11	0.54995E+10
26	1.832E-01	0.88561E+10	0.10286E+11	0.59507E+10
27	1.111E-01	0.60800E+10	0.63931E+10	0.35515E+10
28	6.738E-02	0.51275E+10	0.49135E+10	0.25663E+10
29	4.097E-02	0.17987E+10	0.13050E+10	0.64403E+09
30	3.183E-02	0.90129E+09	0.40188E+09	0.19741E+09
31	2.606E-02	0.23025E+10	0.27542E+10	0.17347E+10
32	2.418E-02	0.14558E+10	0.16674E+10	0.11334E+10
33	2.188E-02	0.27861E+10	0.25650E+10	0.14953E+10

Table 4.12-b Calculated Neutron Fluence Multigroup Spectra in Reactor Pressure Vessel at Peak Axial and Azimuthal Location ($\theta = 0$) for Calvert Cliffs Unit-2 (18M Cycle)

		ϕ $n \cdot cm^{-2} \cdot s^{-1}$		
Group	Upper Energy (MeV)	0-T R=221.29	1/4-T R=225.98	3/4-T R=236.93
1	1.733E+01	0.13469E+08	0.64234E+07	0.10976E+07
2	1.419E+01	0.58343E+08	0.28108E+08	0.47986E+07
3	1.221E+01	0.23551E+09	0.10963E+09	0.17062E+08
4	1.000E+01	0.47268E+09	0.21917E+09	0.32348E+08
5	8.607E+00	[illegible]	0.38166E+09	0.52098E+08
6	7.408E+00	[illegible]	[illegible]	0.11452E+09
7	6.065E+00	[illegible]	[illegible]	0.14373E+09
8	4.966E+00	[illegible]	0.21604E+10	0.24572E+09
9	3.679E+00	[illegible]	0.16097E+10	0.21155E+09
10	3.012E+00	0.25655E+10	0.12610E+10	[illegible]
11	2.725E+00	0.29002E+10	0.14836E+10	0.21672E+09
12	2.466E+00	0.14395E+10	0.74066E+09	0.10927E+09
13	2.365E+00	0.37586E+09	0.21270E+09	0.35580E+08
14	2.346E+00	0.18005E+10	0.10287E+10	0.17675E+09
15	2.231E+00	0.44294E+10	0.26014E+10	0.45340E+09
16	1.920E+00	0.45904E+10	0.30817E+10	0.66008E+09
17	1.653E+00	0.61384E+10	0.43244E+10	0.98444E+09
18	1.353E+00	0.91989E+10	0.76132E+10	0.22864E+10
19	1.003E+00	0.59284E+10	0.53813E+10	0.20388E+10
20	8.208E-01	0.28293E+10	0.22945E+10	0.78276E+09
21	7.427E-01	0.79182E+10	0.86704E+10	0.41066E+10
22	6.081E-01	0.66054E+10	0.70723E+10	0.35582E+10
23	4.979E-01	0.71318E+10	0.79628E+10	0.40280E+10
24	3.688E-01	0.73814E+10	0.94122E+10	0.56296E+10
25	2.972E-01	0.93382E+10	0.99482E+10	0.52924E+10
26	1.822E-01	0.65427E+10	0.99081E+10	0.57241E+10
27	1.111E-01	0.58681E+10	0.61583E+10	0.34158E+10
28	6.738E-02	0.49478E+10	0.47333E+10	0.24680E+10
29	4.097E-02	0.17364E+10	0.12573E+10	0.61938E+09
30	3.183E-02	0.87043E+09	0.38722E+09	0.18986E+09
31	2.606E-02	0.22178E+10	0.26498E+10	0.16663E+10
32	2.418E-02	0.14009E+10	0.16024E+10	0.10876E+10
33	2.188E-02	0.26844E+10	0.24671E+10	0.14349E+10

Table 4.12-c Calculated Neutron Fluence Rate Multigroup Spectra in Reactor Pressure Vessel and Azimuthal Location (θ = 0°) for Calvert Cliffs Unit-2 (24M Cycle)

		ϕ $n \cdot cm^{-2} \cdot s^{-1}$		
Group	Upper Energy (MeV)	O-T R=221.29	1/4-T R=225.98	3/4-T R=236.93
1	1.733E+01	0.11591E+08	0.55590E+07	0.94675E+06
2	1.419E+01	0.50126E+08	0.24272E+08	0.41304E+07
3	1.221E+01	0.20170E+09	0.94309E+08	0.14620E+08
4	1.000E+01	0.40426E+09	0.18826E+09	0.27671E+08
5	8.607E+00	0.71675E+09	0.32716E+09	0.44461E+08
6	7.408E+00	0.17856E+10	0.79253E+09	0.97652E+08
7	6.065E+00	0.25196E+10	0.10759E+10	0.12216E+09
8	4.966E+00	0.43157E+10	0.18363E+10	0.20776E+09
9	3.679E+00	0.29651E+10	0.13650E+10	0.17838E+09
10	3.012E+00	0.21668E+10	0.10684E+10	0.14832E+09
11	2.725E+00	0.24476E+10	0.12500E+10	0.18237E+09
12	2.466E+00	0.12148E+10	0.62695E+09	0.91920E+08
13	2.365E+00	0.31728E+09	0.17998E+09	0.29906E+08
14	2.346E+00	0.15190E+10	0.87010E+09	0.14851E+09
15	2.231E+00	0.37360E+10	0.22003E+10	0.38106E+09
16	1.920E+00	0.38682E+10	0.26024E+10	0.55363E+09
17	1.653E+00	0.51700E+10	0.36495E+10	0.82514E+09
18	1.353E+00	0.77353E+10	0.64101E+10	0.19110E+10
19	1.003E+00	0.49740E+10	0.45179E+10	0.16982E+10
20	8.208E-01	0.23761E+10	0.19283E+10	0.65267E+09
21	7.427E-01	0.66195E+10	0.72511E+10	0.34081E+10
22	6.081E-01	0.55162E+10	0.59050E+10	0.29483E+10
23	4.979E-01	0.59595E+10	0.66488E+10	0.33378E+10
24	3.688E-01	0.61390E+10	0.78256E+10	0.46495E+10
25	2.972E-01	0.77868E+10	0.82842E+10	0.43738E+10
26	1.832E-01	0.71057E+10	0.82270E+10	0.47195E+10
27	1.111E-01	0.48838E+10	0.51122E+10	0.28142E+10
28	6.738E-02	0.41218E+10	0.39300E+10	0.20325E+10
29	4.097E-02	0.14498E+10	0.10448E+10	0.51013E+09
30	3.183E-02	0.72818E+09	0.32185E+09	0.15640E+09
31	2.606E-02	0.18316E+10	0.21863E+10	0.13643E+10
32	2.418E-02	0.11519E+10	0.13152E+10	0.88646E+09
33	2.188E-02	0.22205E+10	0.20290E+10	0.11692E+10

Table 4.13 Radial Gradient of Fast Fluence Rate [ϕ (E > 1)] Through RPV, at Peak Azimuthal and Axial Locations in Calvert Cliffs-2

$\bar{R}^{(1)}$ (cm)	ϕ (E > 1 MeV) $n \cdot cm^{-2} \cdot s^{-1}$ 12M	18M	24M
220.895	5.19E10	5.02E10	4.24E10
222.102	4.72E10	4.57E10	3.86E10
223.727	3.98E10	3.84E10	3.24E10
225.351	3.25E10	3.14E10	2.64E10
22[illegible]6	2.62E10	2.53E10	2.13E10
22[illegible].[illegible]01	2.10E10	2.03E10	1.70E10
230.225	1.67E10	1.61E10	1.35E10
231.850	1.32E10	1.28E10	1.07E10
233.475	1.04E10	1.01E10	8.42E9
235.099	8.16E9	7.87E9	6.58E9
236.724	6.33E9	6.10E9	5.10E9
238.348	4.83E9	4.66E9	3.89E9
239.973	3.58E9	3.45E9	2.88E9
241.598	2.43E9	2.34E9	1.95E9

Table 4.14 Fluence in RPV after 12 EFPY for Calvert Cliffs-2

Location	Fluence neutrons.cm^{-2}
RPV IR (R=221.29)	1.69E19
1/4T (R=225.98)	1.01E19
3/4T (R=236.93)	2.05E18

Table 4.15 Determination of RPV Peak Fluence for Calvert Cliffs-2

Cycles		Full Power Days	Accumulated Fluence[3] neutrons.cm^{-2}
1-3	(12 month)	1165.94	4.76E18
4	(18 month)	508.53	2.02E18
5-7	(18 month)	1242.92	4.93E18
8	(24 month)[1]	586.17	2.08E18
9-EOL	(24 month)[2]	8184.44	2.90E19
	Totals	11688.00	4.28E19

[1] Projected value based on estimated EFPD/cycle for cycle 8

[2] Projected, based on 32 EFPY lifetime

[3] 12 month and 18 month cycle fluence rate based on adjusted flux values in Table 6; 24 month values based on calculated fluxes from Table 4.10.

5. ADJUSTED REFERENCE TEMPERATURE DETERMINATION

NRC Regulatory Guide 1.99, Revision 2, provides the approach for computing the adjusted reference nil-ductility temperatures for beltline materials. The adjusted reference temperature (ART) is given by

$$ART = \text{Initial } RTNDT + \Delta RT_{NDT} + \text{Margin} \qquad (1)$$

where

$$\Delta RT_{NDT} = [CF] f^{(0.28 - 0.1 \log f)} \qquad (2)$$

and

CF = chemistry factor specified in Reg. Guide 1.99, Rev. 2.

f = fluence (10^{19} n/cm^2, E > 1 MeV)

$$\text{Margin} = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2}$$

where σ_I = initial standard deviation of data = 0°F

σ_Δ = 28°F for welds and 17°F for plate materials

Table 5.1a and b presents an evaluation of the ART of beltline materials for 12 EFPY and 32 EFPY respectively. From this table it is clear that the weld 2-203 is the controlling material for the pressure vessel. The ART of weld 2-203 at various irradiation conditions are used in developing the various P-T limit curves.

Fluence at various depths is given by,

$$f = f \text{ surface } (e^{-0.24X}) \qquad (3)$$

The through thickness attenuation of ΔRT_{NDT} is calculated by using equation (2).

The ΔRT_{NDT} values for the various depths for the controlling weld 2-203 for 12, 16, 20, 24, 28, 32, 36 and 40 EFPYs are presented in table 5.2. Table 5.3 presents ART at 1/4T and 3/4T locations for the various EFPY.

Table 5.1(a). ART Evaluation for Beltline Materials for 12 EFPY

Material	Chemistry Cu	Chemistry Ni	C.F.	Initial RT_{NDT} °F	ΔRT_{NDT} Surface °F	Margin °F	ART
Weld 2-203	0.12	1.01	161	-56	184	56	184
3-203	0.23	0.23	120	-80	137	56	113
9-203	0.22	0.05	101	-60	116	56	112
Plate D-8906-1	0.15	0.56	107	10	122	34	166
D-8906-3	0.14	0.55	98	5	112	34	141
D-8907-1	0.15	0.6	110	-8	126	34	152
D-8907-2	0.14	0.66	102	20	117	34	171

NOTE: D8906-2 and D8907-3 are not included because they are bounded by the chemistry and initial RT_{NDT} by D8906-1 and D8907-2, respectively.

Table 5.1(b). ART Evaluation for Beltline Materials for 32 EFPY

Material	Chemistry Cu	Chemistry Ni	C.F.	Initial RT_{NDT} °F	ΔRT_{NDT} Surface °F	Margin °F	ART
Weld 2-203	0.12	1.01	161	-56	222	56	222
3-203	0.23	0.23	120	-80	165	56	189
9-203	0.22	0.05	101	-60	139	56	135
Plate D-8906-1	0.15	0.56	107	10	147	34	191
D-8906-3	0.14	0.55	98	5	135	34	174
D-8907-1	0.15	0.6	110	-8	151	34	177
D-8907-2	0.14	0.66	102	20	140	34	194

Table 5.2. ΔRT_{NDT} vs EFPY for Controlling Weld 2-203

EFPY	ΔRT_{NDT} Surface °F	ΔRT_{NDT} (1/4 T) °F	ΔRT_{NDT} (3/4 T) °F
12	184	161	115
16	196	173	127
20	204	183	136
24	211	190	144
28	216	196	151
32	222	201	157
36	224	206	162
40	228	210	166

Table 5.3. Adjusted Reference Temperatures (ART) at 1/4 T and 3/4 T for Controlling Weld 2-203

EFPY	ART (1/4 T) °F	ART (3/4 T) °F
12	161	115
16	173	127
20	183	136
24	190	144
28	196	151
32	201	157
36	206	162
40	210	166

6. HEAT-UP AND COOL-DOWN LIMITS

The adjusted reference temperature (ART) for 12, 16, 20, 24, 28, 32, 36 and 40 EFPYs were presented in Section 5. These ART values were used to develop the pressure-temperature limit conditions for the EFPYs described above. An inhouse computer program PTLIMT was used. The generic procedures for PTLIMT are described in Appendix D.

The following pressure vessel constants were employed as input data in the Calvert Cliffs Unit 2 analysis:

Vessel Inner Radius, ri	= 86.81 in.
Vessel Outer Radius, r_o	= 95.43 in.
Operating Pressure, P_o	= 2235 psig
Initial Temperature, T_f	= 550°F
Effective Coolant Flow Rate, Q	= 128.8×10^6 lbm/hr
Effective Flow Area, A	= 39.83 ft^2
Effective Hydraulic Diameter, D	= 22.44 in.

Heat-up limits were computed for heat-up rates of 40°F/hr, 50°F/hr, 60°F/hr and 70°F/hr. Cool-down curves were computed for cool-down rates of 0°F/hr, 20°F/hr, 50°F/hr, and 100°F/hr.

Figures 6.1 and 6.2 presents the heat up and cool down limit curves respectively for 12 EFPY. These figures were developed based on the NRC Standard Review Plan (5.3.2). In Figure 6.1, the lowest service temperatures, minimum bolt-up temperature (70°F) and inservice leak test curves are incorporated. In developing the heat-up and cool down curves, instrument error margins of -60 psig for pressure measurements and +10°F for temperature monitoring have been included. These margins have been used industry-wide to

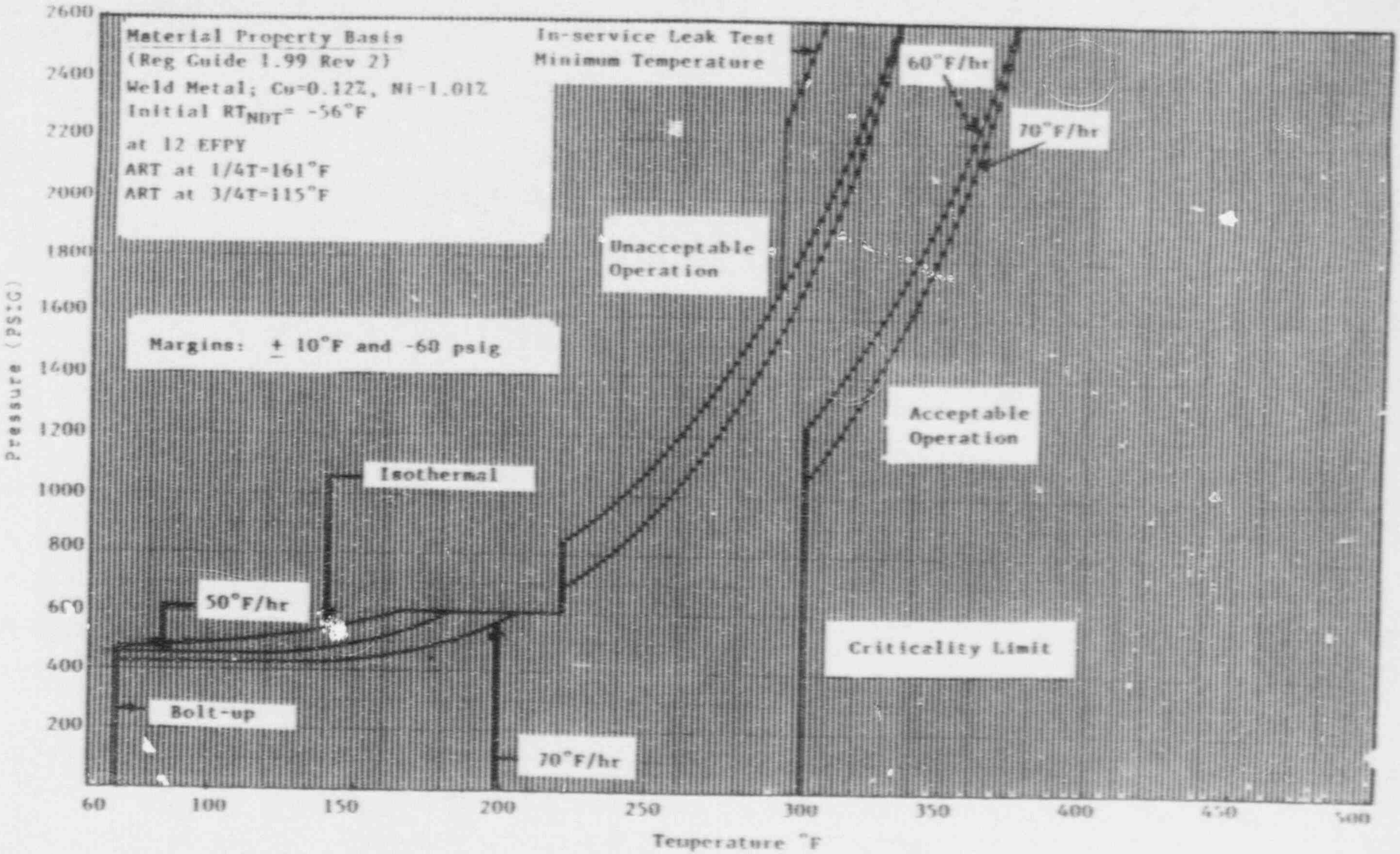


Figure 6.1 Heat-Up Pressure-Temperature Limitation Curves for Calvert Cliff Unit 2 Reactor Vessel (12 EFPY)

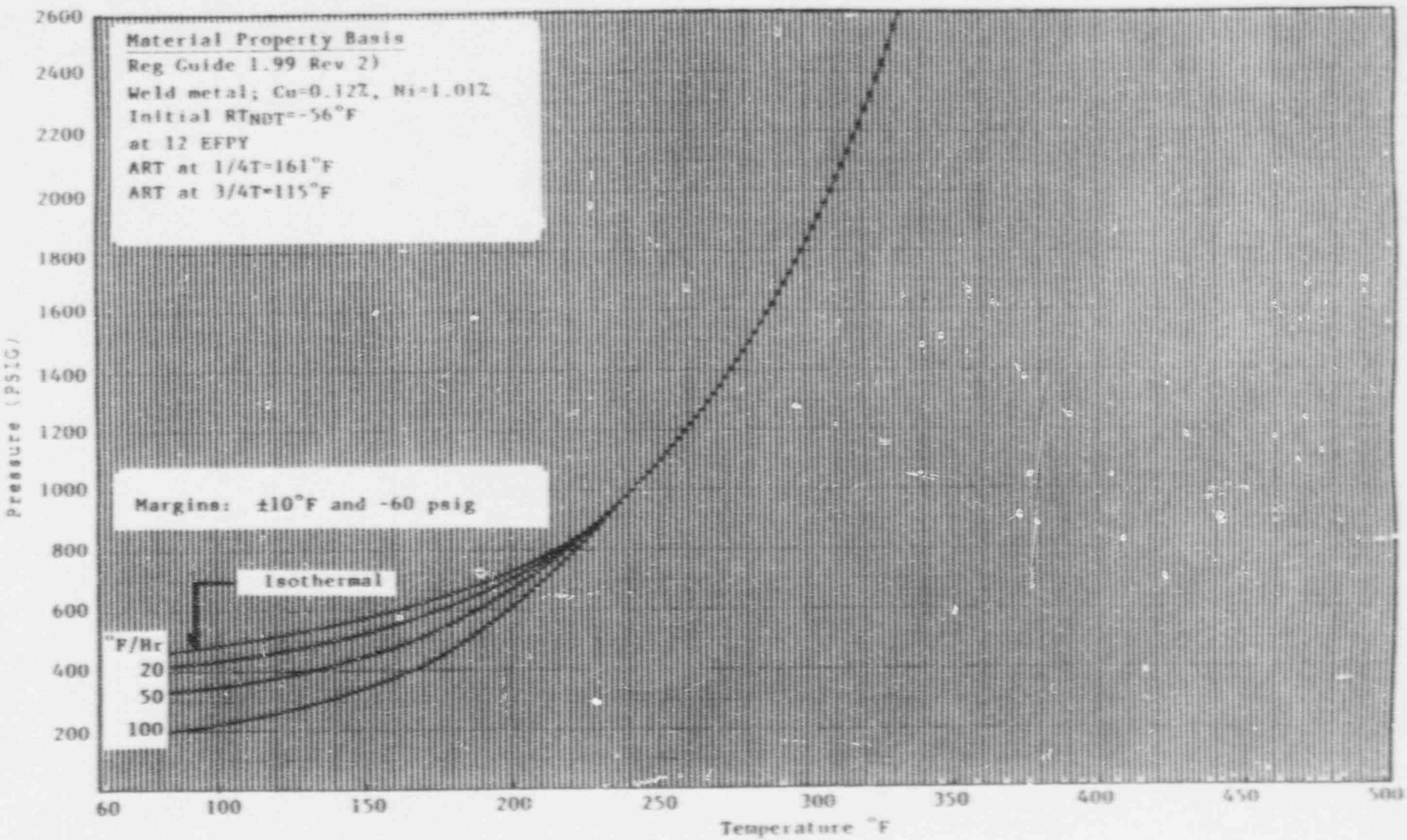


Figure 6.2 Cool-down Pressure-Temperature Limitation Curve for Calvert Cliff Unit 2 Reactor Vessel (12 EFPY)

allow for possible errors in measuring instruments and account for variations between bulk temperatures and local (near beltline) temperatures.

Appendix E presents the tables containing heat-up and cool-down data for 16, 20, 24, 28, 32, 36 and 40 EFPYs. Appendix F contains the P-T limit tables for varying cooldown rates for 12 EFPY. Appendix G presents the P-T limit tables for isothermal conditions.

References

1. Norris, E. B., "Reactor Vessel Materials Surveillance Program for Calvert Cliffs Unit 2 Analysis of 263° Capsule," Final Report, SwRI Project 06-7524, September 1985.

2. JAT (BG&E) letter to NRC, January 23, 1986 and Don Wright's (BG&E) Calculations, January 15, 1986.

3. Rhoades, W. A., Childs, R. L., "An Updated Version of the DOT-4 One- and Two-Dimensional Neutron/Photon Transport Code", ORNL-5851, Oak Ridge National Laboratory, Oak Ridge, TN, July, 1982.

4. Simons, G. L. and Roussin, R., "SAILOR-A Coupled Cross Section Library for Light Water Reactors", DLC-76, RSIC.

APPENDIX A

Determination of Space-Dependent Source Distribution
for Transport Analysis of Calvert Cliffs-2

Appendix A. Determination of Space-Dependent Source Distribution for Transport Analysis of Calvert Cliffs-2

The space-dependent source distribution used in the transport calculations was obtained by combining the assembly-wise power distribution with relative pinwise power values for the peripheral assemblies (i.e., XY Zones 9, 18, 26, 34, 4[illegible] [illegible] Figure 1). The relative assembly-wise power distributions for the 1[illegible], [illegible], and 24 month cycles are shown in Figure A.1. These values were obtained by averaging BOC, MOC, and EOC absolute assembly powers provided by Baltimore Gas and Electric as representative for the appropriate cycles and then dividing the average assembly power. (The 24 month cycle distribution corresponds to a projected MOC core.) Note that all interior assemblies are approximated as having a unity relative power (i.e., producing the average power). Since the interior elements contribute a negligible amount to the RPV fluence, this approximation is very adequate. The absolute assembly power distributions provided by BG&E for each type of cycle is given by Table A.1.[1]

The power density is assumed flat within the interior assemblies, but is represented with a pinwise variation for the boundary assemblies, which account for virtually all of the RPV fluence. Baltimore Gas and Electric has confirmed that the relative pin-power variation within the peripheral assemblies is similar for Calvert Cliffs Units 1 and 2;[2] therefore the same relative pin-power values obtained for the previous Unit 1 analysis[3] were also used in the present Unit 2 calculations. Examination of the BOC, MOC, and EOC relative pin powers provided by BG&E shows that the MOC distribution is a good approximation for the average over the cycle, and hence was used as the representative pinwise variation. The relative pin power in the peripheral assemblies are very similar for the 12 and 18 month cycles, and therefore the 18 month is used for both (the assembly-wise distributions are different, however). Tables A.3-A.4 give the relative pinwise variations for configuration in Figure A.1 (given in "FIDO FORMAT").

The combination of the assembly and pinwise powers results in an absolute space-dependent power density defined for the quarter core. The power density values are converted to a source density by multiplying by the factor,

$$7.84 \times 10^{16} \ \frac{\text{neutrons/s}}{\text{Mw}}$$

The 1/4 core XY source distribution is then mapped onto the 1/8 core Rθ mesh used in DOT by utilizing an interpolating program previously developed for this purpose.

REFERENCES

(1) J. B. Couch, letter to M. L. Williams from Baltimore Gas and Electric dated January 7, 1988.

(2) J. B. Couch, personal communication to M. L. Williams, January 6, 1988.

(3) P. Nair, M. L. Williams, "Pressure-Temperature Limits for Calvert Cliffs Nuclear Power Plant Unit 1", Southwest Research Institute, Final Report.

Figure A.1 Relative Power Distributions (Assembly-wise) for 12, 18, and 24 Month Cycles for Calvert Cliffs Unit 2

Zone

Z

A — 12M
B — 18M
C — 24M

45°

43 1.0	44 1.0	45 1.0	46 1.0	47 1.0	48 1.0	49 .82 .75 .42		
35 1.0	36 1.0	37 1.0	38 1.0	39 1.0	40 1.0	41 1.16 1.00 1.07	42 .75 .68 .40	
27 1.0	28 1.0	29 1.0	30 1.0	31 1.0	32 1.0	33 1.08 1.06 1.09	34 .98 .91 .87	
19 1.0	20 1.0	21 1.0	22 1.0	23 1.0	24 1.0	25 1.00 1.14 1.26	26 1.10 .91 .85	
10 1.0	11 1.0	12 1.0	13 1.0	14 1.0	15 1.0	16 .85 1.08 1.07	17 1.06 .98 [illegible]	.71 .65 .36
1 1.0	2 1.0	3 1.0	4 1.0	5 1.0	6 1.0	7 1.15 .96 1.29	8 .85 1.07 .90	9 .86 .84 .80

Table A.1. Absolute Assembly Powers (MW_{th}) for Calvert Cliffs-2

Zone	12 Month Cycle	18 Month Cycle	24 Month Cycle
** 1	3.11	3.11	3.11
* 2	6.22	6.22	6.22
* 3	6.22	6.22	6.22
* 4	6.22	6.22	6.22
* 5	6.22	6.22	6.22
* 6	6.22	6.22	6.22
* 7	7.16	5.96	8.02
* 8	5.26	6.68	5.58
9	10.60	10.41	10.00
* 10	6.22	6.22	6.22
11	12.44	12.44	12.44
12	12.44	12.44	12.44
13	12.44	12.44	12.44
14	12.44	12.44	12.44
15	12.44	12.44	12.44
16	10.60	13.43	13.27
17	13.16	12.17	14.10
18	8.82	8.02	4.45
* 19	6.22	6.22	6.22
20	12.44	12.44	12.44
21	12.44	12.44	12.44
22	12.44	12.44	12.44
23	12.44	12.44	12.44
24	12.44	12.44	12.44
25	12.44	14.12	15.62
26	13.72	11.36	10.53
* 27	6.22	6.22	6.22
28	12.44	12.44	12.44
29	12.44	12.44	12.44
30	12.44	12.44	12.44
31	12.44	12.44	12.44
32	12.44	12.44	12.44
33	13.41	13.15	13.53
34	12.16	11.36	10.76
* 35	6.22	6.22	6.22
36	12.44	12.44	12.44
37	12.44	12.44	12.44
38	12.44	12.44	12.44
39	12.44	12.44	12.44
40	12.44	12.44	12.44
41	14.45	12.48	13.26
42	9.35	8.48	5.02
* 43	6.22	6.22	6.22
44	12.44	12.44	12.44
45	12.44	12.44	12.44
46	12.44	12,44	12.44
47	12.44	12.44	12.44
48	12.44	12.44	12.44

49	10.15	9.36	5.21
50	0.0	0.0	0.0

(*) indicates 1/2-assembly zone
(**) indicates 1/4-assembly zone

Table A.2. Relative Pin Powers for 18 Month Cycle

```
105R1. 1.22 1.19 1.19 1.17 1.11 1.05 .99 .97 .93 .88 .84 .76 .67 .58
105R1. 1.2 1.30 1.41 1.38 1.21 1.03 .97 .95 .91 .96 .99 .91 .74 .58
105R1. 1.23 1.43 0.0 0.00 1.33 1.04 .97 .95 .92 1.05 0.00 0.00 .82 .59
105R1. 1.23 1.42 0.00 0.00 1.32 1.04 .98 .95 .92 1.05 0.00 0.00 .82 .58
105R1. 1.21 1.28 1.38 1.35 1.20 1.04 1.00 .99 .92 .96 .98 .89 .72 .57
105R1. 1.17 1.12 1.11 1.07 1.06 1.15 1.22 1.20 1.03 .86 .79 .72 .63 .55
105R1. 1.15 1.08 1.08 1.06 1.06 1.26 0.00 0.00 1.13 .86 .77 .69 .61 .58
105R1. 1.12 1.06 1.05 1.05 1.05 1.25 0.00 0.00 1.10 .84 .76 .68 .60 .54
105R1. 1.14 1.08 1.08 1.06 1.04 1.12 1.19 1.152 .99 .83 .76 .69 .61 .54
105R1. 1.16 1.22 1.32 1.29 1.15 .99 .96 .93 .87 .91 .93 .85 .69 .54
105R1. 1.17 1.34 0.00 0.00 1.26 .99 .92 .89 .86 .99 0.00 0.00 .77 .55
105R1. 1.16 1.34 0.00 0.00 1.25 .98 .90 .88 .85 .98 0.00 0.00 .77 .55
105R1. 1.13 1.21 1.31 1.29 1.13 .96 .89 .87 .84 .89 .93 .85 .69 .54
105R1. 1.13 1.11 1.12 1.10 1.04 .98 .92 .89 .86 .83 .79 .72 .64 .56
105R1. 1.12 1.10 1.102 1.083 1.028 .97 .912 .881 .847 .814 .777 .711 .62
0.54
105R1. 1.1 1.17 1.27 1.24 1.09 .92 .86 .83 .8 .85 .875 .802 .647 .501
105R1. 1.11 1.27 0. 0. 1.17 .91 .84 .814 .786 .90 0. 0. .692 .480
105R1. 1.1 1.25 0. 0. 1.15 .896 .83 .8 .77 .878 0. 0. .668 .469
105R1. 1.065 1.11 1.19 1.16 1.02 .87 .83 .8 .75 .778 .79 .72 .57 .439
105R1. 1.03 .965 .95 .927 .89 .956 1. .969 .82 .677 .62 .554 .477 .401
105R1. .997 .93 .908 .893 .885 1.044 0. 0. .885 .659 .585 .516 .447 .387
   91R1. 1.228 1.198 1.210 1.201 1.163 1.127 1.097
         1.115 1.118 1.129 1.143 1.130 1.095 1.086
 .981 .91 .874 .85 .835 .98 0. 0. .855 .635 .563 .497 .432 .376
   91R1. 1.211 1.298 1.416 1.406 1.258 1.099 1.064
         1.073 1.078 1.205 1.319 1.302 1.165 1.048
 .972 .9 .87 .837 .9 .848 .884 .87 .733 .6 .542 .482 .415 .359
   91R1. 1.239 1.431 0.000 0.000 1.389 1.120 1.074
         1.071 1.086 1.312 0.000 0.000 1.262 1.047
 .968 .99 1.03 .989 .855 .722 .679 .66 .61 .626 .625 .56 .447 .344
   91R1. 1.246 1.437 0.000 0.000 1.398 1.133 1.092
         1.078 1.086 1.305 0.000 0.000 1.241 1.029
 .96 1.06 0. 0. .91 .688 .626 .607 .57 .64 0. 0. .47 .33
   91R1. 1.224 1.305 1.421 1.414 1.277 1.135 1.124
         1.100 1.079 1.179 1.271 1.238 1.092 0.976
 .925 1.02 0. 0. .855 .642 .579 .561 .527 .596 0. 0. .439 .306
   91R1. 1.205 1.159 1.166 1.164 1.151 1.242 1.335
         1.296 1.173 1.052 1.027 0.986 0.934 0.919
```

Table A.2. Continued

```
.867 .873 .9 .85 .71 .58 .53 .52 .48 .495 .504 .454 .357 .274
  91R1. 1.195 1.144 1.139 1.143 1.158 1.352 0.000
        0.000 1.273 1.052 0.998 0.941 0.886 0.863
.805 .72 .674 .63 .58 .532 .494 .48 .438 .404 .372 .333 .286 .248
 91R1.0 1.193 1.142 1.138 1.142 1.157 1.348 0.000
        0.000 1.246 1.022 0.965 0.917 0.868 0.832  14Z
 91R1.0 1.220 1.171 1.176 1.172 1.155 1.240 1.325
        1.279 1.143 1.011 0.973 0.920 0.850 0.794  14Z
 91R1.0 1.256 1.333 1.448 1.436 1.290 1.138 1.118
        1.081 1.041 1.115 1.174 1.113 0.939 0.771  14Z
 91R1.0 1.295 1.484 0.000 0.000 1.423 1.143 1.092
        1.055 1.037 1.213 0.000 0.000 1.026 0.757  14Z
 91R1.0 1.300 1.429 0.000 0.000 1.425 1.139 1.081
        1.042 1.027 1.204 0.000 0.000 1.012 0.743  14Z
 91R1.0 1.280 1.364 1.481 1.464 1.301 1.125 1.078
        1.036 1.010 1.094 1.156 1.090 0.905 0.724  14Z
 91R1.0 1.292 1.262 1.274 1.261 1.209 1.156 1.111
        1.062 1.031 1.008 0.964 0.923 0.833 0.747  14Z
 91R1. 1.294 1.261 1.271 1.256 1.201 1.145 1.084 1.05 1.027 1.004 .977
    .915 .825  .741   14Z
 91R1. 1.265 1.351 1.465 1.444 1.280 1.099 1.039 1.002 .981 1.058 1.109
  1.037 .858 .689  14Z
 91R1. 1.273 1.466 0.0 0.0 1.39 1.1 1.028 .992 .976 1.136 0.0 0.0 .923
 .675  14Z
 91R1. 1.259 1.45 0.0 0.0 1.377 1.094 1.028 .992 .969 1.121 0. 0. .9
 .654  14Z
 91R1. 1.217 1.297 1.408 1.391 1.24 1.082 1.047 1.012 6 1.01 1.042
   .963 .785 .622  14Z
 91R1. 1.179 1.134 1.137 1.128 1.104 1.197 1.277 1.234 1.065 .897 .837
   .674 .598  14Z
91R1.  1.147 1.098 1.093 1.092 1.1 1.312 0.0 0.0 1.16 .887 .805 .73 .654
   .59  14Z
91R1. 1.147 1.095 1.088 1.086 1.093 1.302 0. 0. 1.152 .882 .8 .725 .649
   .584  14Z
91R1. 1.172 1.121 1.119 1.107 1.081 1.17 1.242 1.202 1.037 .87 .808 .735
   .647 .573  14Z
91R1. 1.204 1.272 1.371 1.348 1.197 1.04 .999 .969 .915 .956 .979 .9 .73
   .575   14Z
91R1. 1.239 1.41 0. 0. 1.314 1.035 .763 .933 .904 1.036 0. 0. .812 .583
 14Z
```

Table A.2. Continued

```
91R1. 1.243 1.414 0. 0. 1.308 1.024 .945 .914 .89 1.027 0. 0. .807 .578
 14Z
91R1. 1.222 1.29 1.387 1.355 1.186 1.005 .937 .904 .874 .932 .967 .891
    .722 .564  14Z
91R1. 1.232 1.188 1.185 1.158 1.094 1.029 .965 .928 .894 .861 .823 .754
    .662 .577  14Z
 91R1.
 1.206 1.169 1.167 1.14 1.077 1.013 0.951 0.915 0.879 0.843 0.805 0.737
 0.649 0.567
 14Z   91R1.0
 1.179 1.268 1.338 1.304 1.139 0.964 0.899 0.865 0.83 0.88 0.906 0.833
 0.675 0.529
 14Z   91R1.
 1.184 1.348 0.0 0.0 1.228 0.955 0.882 0.847 0.815 0.933 0.0 0.0 0.723
0.516
 14Z   91R1.
 1.166 1.324 0.0 0.0 1.204 0.938 0.87 0.834 0.797 0.907 0.0 0.0 0.696
.495
 14Z   91R1.0
 1.117 1.173 1.254 1.218 1.065 0.911 0.869 0.833 0.774 0.802 0.817 0.74
 0.594 0.461
 14Z   91R1.0
 1.069 1.011 0.994 0.967 0.928 0.991 1.041 0.996 0.842 0.694 0.636 0.57
 0.493 0.429
 14Z   91R1.0
 1.024 0.964 0.94 0.921 0.909 1.069 0.0 0.0 0.899 0.669 0.594 0.525 .457
 0.399
14Z   91R1.0
 1.002 0.94 0.913 0.89 0.876 1.028 0.0 0.0 0.877 0.652 0.577 0.51 0.444
 0.39
 14Z   91R1.0
 0.993 0.929 0.902 0.87 0.83 0.883 0.921 0.893 0.752 0.613 0.557 0.496
 0.431 0.376
 14Z   91R1.0
```

Table A.2. Continued

```
 0.987 1.016 1.064 1.01? 0.883 0.747 0.703 0.6   0.626 0.641 0.642 0.58
 0.464 0.363
  14Z  91R1.0
 0.98 1.082 0. 0. 0.926 0.706 0.643 0.617 0.582 0.655 0. 0. 0.49 .348
   14Z  91R1.0
 0.943 1.034 0.0 0.0 0.868 0.653 0.59 0.564 0.534 0.605 0.0 0.0 0.455
.322
   14Z  91R1.0
 0.8?9 0.878 0.907 0.853 0.716 0.585 0.535 0.513 0.478 0.499 0.511 0.46
 0 360 0.286
   14Z  91R1.0
 .813 .713 .669 .629 .575 .529 .491 .472 .434 .403 .374 .337
 0.293 0.258   14Z
77R1. 1.29 1.25 1.25 1.22 1.17 1.12 1.08 1.05 1.03 1.01 1.00 .96 .90 .83
28Z
77R1. 1.25 1.32 1.43 1.40 1.24 1.07 1.03 .99 .97 1.05 1.12 1.07 .90 .73
28Z
77R1. 1.25 1.43 0.00 0.00 1.33 1.06 1.01 .97 .95 1.12 0.00 0.00 .94 .69
28Z
77R1. 1.22 1.40 0.00 0.00 1.31 1.04 .99 .95 .92 1.07 0.00 0.00 .89 .65
28Z
77R1. 1.17 1.24 1.33 1.31 1.16 1.01 .98 .94 .89 .94 .98 .92 .75 .60
28Z
77R1. 1.12 1.07 1.06 1.04 1.01 1.06 1.13 1.07 .93 .80 .76 .70 .62 .56
28Z
77R1. 1.07 1.02 1.00 .99 .98 1.13 0.00 0.00 .97 .77 .70 .64 .58 .52
28Z
77R1. 1.05 .99 .97 .96 .94 1.08 0.00 0.00 .95 .74 .69 .62 .55 .51
28Z
77R1. 1.03 .97 .95 .92 .89 .94 .98 .95 .82 .69 .64 .59 .52 .47
28Z
77R1. 1.02 1.05 1.11 1.07 .94 .81 .77 .74 .69 .72 .73 .67 .55 .44
28Z
77R1. 1.01 1.12 0.00 0.00 .98 .76 .70 .68 .64 .53 0.00 0.00 .57 .42
28Z
77R1. .97 1.07 0.00 0.00 .92 .70 .64 .62 .59 .67 0.00 0.00 .53 .38
28Z
77R1. .90  .90 .94 .89 .76 .62 .58 .55 .52 .55 .57 .53 .42 .34
28Z
77R1. .83 .74 .69 .66 .61 .56 .52 .51 .47 .44 .42 .38 .39 .30
   28Z
```

Table A.3. Relative Pin Powers for 24 Month Cycle

```
105R1.0    1.063 1.047 1.039 1.009 0.956 0.899 0.849
  0.805 0.766 0.731 0.691 0.632 0.551 0.458
105R1.0    1.071 1.076 1.179 1.146 0.982 0.900 0.843
  0.798 0.764 0.748 0.786 0.722 0.569 0.465
105R1.0    1.087 1.200 0.000 0.000 1.096 0.906 0.839
  0.793 0.766 0.832 0.000 0.000 0.540 0.474
105R1.0    1.090 1.196 0.000 0.000 1.089 0.902 0.838
  0.793 0.763 0.826 0.000 0.000 0.634 0.471
105R1.0    1.075 1.057 1.149 1.116 0.960 0.891 0.846
  0.802 0.757 0.729 0.759 0.694 0.549 0.456
105R1.0    1.053 1.006 0.984 0.955 0.919 0.899 0.954
  0.907 0.768 0.700 0.646 0.584 0.512 0.439
105R1.0    1.035 0.980 0.947 0.921 0.903 0.987 0.000
  0.000 0.846 0.689 0.620 0.557 0.492 0.426
105R1.0    1.016 0.967 0.935 0.908 0.890 0.972 0.000
  0.000 0.833 0.675 0.606 0.544 0.480 0.416
105R1.0    1.009 0.972 0.950 0.919 0.862 0.862 0.913
  0.866 0.729 0.661 0.607 0.547 0.479 0.411
105R1.0    1.017 1.005 1.088 1.051 0.899 0.830 0.784
  0.739 0.693 0.663 0.686 0.625 0.493 0.410
105R1.0    1.025 1.121 0.000 0.000 0.995 0.816 0.751
  0.705 0.673 0.723 0.000 0.000 0.548 0.407
105R1.0    1.013 1.110 0.000 0.000 0.977 0.796 0.727
  0.680 0.651 0.703 0.000 0.000 0.534 0.396
105R1.0    0.989 0.982 1.060 1.015 0.853 0.768 0.707
  0.660 0.626 0.609 0.637 0.582 0.458 0.376
105R1.0    0.976 0.951 0.925 0.878 0.812 0.747 0.692
  0.645 0.607 0.575 0.541 0.494 0.430 0.361
105R1.0    .711 .685 .646 .603 .562 .521 .482
  .444 .407 .372 .338 .304 .267 .224
105R1.0    .697 .000 .661 .615 .547 .506 .465
  .427 .391 .356 .336 .304 .000 .217
105R1.0    .670 .672 .000 .000 .550 .486 .444
  .406 .371 .351 .000 .000 .254 .205
105R1.0    .648 .637 .000 .000 .530 .465 .423
  .386 .353 .335 .000 .000 .238 .192
105R1.0    .612 .581 .573 .541 .000 .442 .399
  .365 .336 .000 .288 .256 .214 .180
```

Table A.3. Continued

```
105R1.0    .586 .553 .520 .488 .453 .412 .389
  .357 .316 .289 .260 .230 .200 .167
105R1.0    .563 .526 .491 .457 .421 .400 .000
  .000 .308 .270 .242 .213 .185 .156
91R1.0    1.14 1 [illegible] 1.09 1.06 1.02 .97 .93
  .90 .86 .84 .80 .76 .72 .67
  .539 .500 .463 .429 .395 .376 .000
  .300 .288 .250 .223 .196 .170 .143
91R1.0    1.13 1.12 1.17 1.14 1.02 .96 .91
  .87 .84 .83 .85 .80 .71 .66
  .516 .477 .441 .409 .378 .344 .325
  .296 .259 .233 .207 .182 .158 .132
91R1.0    1.14 1.20 0.00 0.00 1.08 .95 .89
  .85 .83 .86 0.00 0.00 .74 .64
  .492 .454 .437 .406 .000 .328 .296
  .267 .241 .000 .198 .175 .146 .122
91R1.0    1.13 1.18 0.00 0.00 1.07 .93 .88
  .84 .81 .84 0.00 0.00 .72 .63
  .467 .449 .000 .000 .353 .308 .276
  .247 .221 .205 .000 .000 .140 .113
91R1.0    1.10 1.08 1.13 1.09 .97 .92 .87
  .83 .80 .77 .78 .74 .65 .60
  .442 .427 .000 .000 .327 .284 .254
  .226 .202 .187 .000 .000 .129 .103
91R1.0    1.08 1.04 1.01 .98 .94 .91 .92
  .88 .79 .74 .70 .65 .61 .57
  .414 .000 .363 .329 .286 .257 .230
  .205 .182 .162 .150 .133 .000 .093
91R1.0    1.06 1.02 .98 .95 .92 .95 0.00
  0.00 .82 .72 .67 .62 .57 .53
  .366 .331 .300 .273 .247 .223 .200
  .178 .158 .140 .124 .109 .095 .079
91R1.0 1.06 1.01 .97 .94 .91 .94 0.00
  0.00 .81 .71 .65 .60 .55 .49
14Z  91R1.0    1.06 1.01 .98 .94 .90 .87 .88
  .84 .74 .69 .64 .59 .53 .46
14Z  91R1.0    1.07 1.03 1.07 1.03 .91 .86 .81
  .77 .72 .69 .68 .63 .53 .45
14Z  91R1.0    1.07 1.11 0.00 0.00 .98 .85 .79
  .75 .71 .72 0.00 0.00 .56 .44
```

Table A.3. Continued

```
14Z  91R1.0   1.06 1.10 0.00 0.00 .97 .84 .78
 .74 .70 .71 0.00 0.00 .55 .44
14Z  91R1.0   1.05 1.02 1.05 1.01 .90 .83 .78
 .73 .69 .66 .66 .60 .50 .42
14Z  91R1.0   1.04 1.00 .97 .93 .87 .82 .77
 .73 .68 .64 .60 .55 .47 .41
    14Z  91R1.0 1.137 1.102 1.083 1.048 0.990 0.93 0.878
     0.833 0.794 0.761 0.723 0.666 0.589 0.506
    14Z 91R1.0  1.128 1.113 1.209 1.171 1.002 0.918 0.859
     0.814 0.781 0.766 0.808 0.745 0.594 0.497
    14Z 91R1.0  1.127 1.230 0.000 0.000 1.113 0.920 0.852
     0.807 0.780 0.849 0.000 0.000 0.661 0.495
    14Z 91R1.0  1.106 1.211 0.000 0.000 1.102 0.914 0.851
     0.806 0.776 0.840 0.000 0.000 0.648 0.482
    14Z 91R1.0  1.066 1.058 1.155 1.124 0.969 0.903 0.861
     0.817 0.770 0.741 0.771 0.795 0.556 0.457
    14Z 91R1.0  1.027 0.996 0.980 0.956 0.925 0.914 0.981
     0.935 0.786 0.711 0.653 0.590 0.514 0.433
    14Z 91R1.6  1.001 0.962 0.938 0.917 0.907 1.008 0.000
     0.000 0.871 0.699 0.625 0.560 0.491 0.417
    14Z 91R1.0  0.986 0.947 0.922 0.901 0.891 0.990 0.000
     0.000 0.854 0.684 0.610 0.546 0.479 0.408
    14Z 91R1.0  0.963 0.950 0.931 0.906 0.876 0.866 0.930
     0.884 0.739 0.664 0.607 0.547 0.477 0.404
    14Z 91R1.0  0.991 0.979 1.063 1.030 0.885 0.823 0.783
     0.740 0.693 0.661 0.683 0.621 0.489 0.404
    14Z 91R1.0  1.000 1.089 0.000 0.000 0.973 0.801 0.741
     0.697 0.666 0.716 0.000 0.000 0.542 0.401
    14Z 91R1.0  0.990 1.075 0.000 0.000 0.949 0.775 0.711
     0.667 0.640 0.692 0.000 0.000 0.525 0.389
    14Z 91R1.0  0.964 0.943 1.016 0.974 0.822 0.742 0.686
     0.642 0.610 0.594 0.622 0.568 0.446 0.367
    14Z 91R1.0  0.945 0.906 0.880 0.840 0.782 0.723 0.672
     0.629 0.592 0.561 0.527 0.479 0.417 0.351
 14Z  91R1.0  .676 .640 .605 .570 .534 .497 .461
.425 .390 .356 .322 .288 .253 .212
 14Z  91R1.0  .652 .618 .608 .572 .514 .476 .439
.403 .369 .335 .315 .283 .239 .201
 14Z  91R1.0  .632 .622 0.0 0.0 .513 .455 .417
.382 .348 .328 0.0 0.0 .235 .190
 14Z  91R1.0  .612 .600 0.0 0.0 .490 .432 .395
```

Table A.3. Continued

```
.361 .329 .310 0.0 0.0 .221 .178
 14Z  91R1.0  .590 .553 .539 .502 .446 .408 .373
.341 .311 .283 .265 .237 .199 .167
 14Z  91R1.0  .565 .527 .491 .455 .419 .384 .366
.335 .294 .267 .240 .213 .185 .155
 14Z  91R1.0  .541 .501 .464 .429 .394 .376 0.0
0.0 .288 .251 .224 .198 .171 .144
 14Z  91R1.0  .517 .477 .440 .405 .372 .355 0.0
0.0 .270 .234 .208 .183 .158 .133
 14Z  91R1.0  .493 .453 .417 .383 .351 .322 .306
.278 .242 .216 .191 .169 .146 .123
 14Z  91R1.0  .468 .429 .410 .376 .331 .302 .274
.248 .222 .197 .182 .161 .135 .113
 14Z  91R1.0  .441 .420 0.0 0.0 .323 .281 .253
.227 .203 .187 0.0 0.0 .129 .104
 14Z  91R1.0  .412 .392 0.0 0.0 .299 .259 .231
.207 .184 .170 0.0 0.0 .118 .094
 14Z  91R1.0  .378 .344 .326 .298 .259 .232 .208
.185 .165 .147 .136 .121 .101 .084
 14Z  91R1.0  .338 .301 .272 .248 .225 .203 .182
.162 .145 .129 .114 .100 .087 .072
14Z  77R1.0 .841 .791 .752 .714 .673 .631 .592
  .554 .517 .482 .448 .408 .367 .322
28Z 77R1.0 .815 .772 .767 .725 .650 .604 .562
  .524 .488 .454 .436 .400 .345 .296
28Z 77R1.0 .793 .784 .000 .000 .653 .577 .532
  .494 .459 .443 .000 .000 .336 .275
28Z 77R1.0 .767 .754 .000 .000 .621 .546 .502
  .465 .431 .415 .000 .000 .313 .256
28Z 77R1.0 .734 .685 .673 .630 .558 .512 .472
  .436 .404 .373 .357 .325 .270 .237
28Z 77R1.0 .697 .643 .600 .560 .518 .478 .460
  .426 .378 .348 .318 .287 .254 .218
28Z 77R1.0 .658 .604 .560 .521 .483 .466 .000
  .000 .368 .323 .293 .263 .232 .199
28Z 77R1.0 .618 .568 .526 .480 .452 .436 .000
  .000 .342 .298 .269 .240 .211 .182
28Z 77R1.0 .582 .537 .497 .460 .425 .392 .376
  .346 .303 .273 .245 .219 .193 .165
```

Table A.3. Continued

```
28Z 77R1.0 .549 .508 .491 .453 .399 .365 .334
  .305 .276 .248 .231 .207 .176 .150
28Z 77R1.0 .516 .498 .000 .000 .389 .330 .306
  .277 .250 .233 .000 .000 .166 .135
28Z 77R1.0 .479 .462 .000 .000 .357 .309 .277
  .250 .225 .210 .000 .000 .150 .121
28Z 77R1.0 .437 .401 .385 .353 .306 .275 .247
  .222 .200 .180 .169 .151 .127 .107
28Z 77R1.0 .389 .347 .317 .289 .263 .238 .214
  .193 .173 .155 .139 .124 .108 .091
  28Z
```

APPENDIX B

Description of the 3D Flux Synthesis Method

Appendix B. Description of the 3D Flux Synthesis Method

A 3D (RθZ) flux distribution is synthesized using the following well established approximation:

$$\phi(R,\theta,Z) = \phi_{R\theta}(R,\theta)\frac{\phi_{RZ}(R,Z)}{\phi_R(R)} = \phi_{R\theta}\, A(R,Z) \qquad B.1$$

where $\phi_{R\theta}$ is the flux obtained from the Rθ DOT calculation; and

$A(R,Z) = \frac{\phi_{RZ}}{\phi_R}$ = axial distribution function obtained by representing the RZ flux = (ϕ_{RZ}) distribution and dividing it by the integral over Z of the RZ flux, i.e.,

$$\phi_R = \int_Z \phi_{RZ}\, dZ.$$

In some previous studies the RZ flux distribution was represented by the results obtained from a DOT RZ calculation, while the radial flux ϕ_R was obtained from a one-dimensional calculation. However, it has been discovered that a simplier approximation gives similar results (within a few percent) as the results of these transport calculations for locations not outside of the RPV and near the reactor midplane. In this approach we represent

$$A(R,Z) = \frac{\phi_{RZ}\,(RZ)}{\phi_R} \approx \frac{P_{(Z)}}{\int_Z P(Z)dZ} \qquad B.2$$

where P(Z) is the average axial distribution of power in the core. The function P(Z) has been represented by discrete nodal values corresponding to the core-average axial power distribution at MOC, which was provided by Baltimore Gas and Electric. The relative axial power values were provided at 51 points for the 12 and 18 month cycles, and at 24 points for the 24 month

A 3D ($R\theta Z$) flux distribution is synthesized using the following well established approximation:

$$\phi(R,\theta,Z) = \phi_{R\theta}(R,\theta)\frac{\phi_{RZ}(R,Z)}{\phi_R(R)} = \phi_{R\theta}\, A(R,Z) \qquad B.1$$

where $\phi_{R\theta}$ is the flux obtained from the $R\theta$ DOT calculation; and

$A(R,Z) \equiv \frac{\phi_{RZ}}{\phi_R}$ = axial distribution function obtained by representing the RZ flux = (ϕ_{RZ}) distribution and dividing it by the integral over Z of the RZ flux, i.e.,

$$\phi_R \equiv \int_Z \phi_{RZ}\, dZ.$$

In some previous studies the RZ flux distribution was represented by the results obtained from a DOT RZ calculation, while the radial flux ϕ_R was obtained from a one-dimensional calculation. However, it has been discovered that a simplier approximation gives similar results (within a few percent) as the results of these transport calculations for locations not outside of the RPV and near the reactor midplane. In this approach we represent

$$A(R,Z) \equiv \frac{\phi_{RZ}\,(RZ)}{\phi_R} \approx \frac{P_{(Z)}}{\int_Z P(Z)dZ} \qquad B.2$$

where P(Z) is the average axial distribution of power in the core. The function P(Z) has been represented by discrete nodal values corresponding to the core-average axial power distribution at MOC, which was provided by Baltimore Gas and Electric for the peripheral assemblies. The relative axial power values were provided at 51 points for the 12 and 18 month cycles, and at 24 points for the 24 month cycle.

Therefore employing the expression eq. B.2 for axial point k, we find

$$A(R,Z) \approx A(Z) \rightarrow A_k = \frac{P_k}{\int P(Z)dZ} \text{ ; k=1, \# of axial points}$$

There are 51 points used for the 12 and 18 month cycles, in the axial dimension. The 51 points define 50 nodes (i.e., intervals). To calculate the integrated axial power we use the expression

$$\int_0^H P(Z)dZ \sim \sum_{k=1}^{50} \bar{P}_k \Delta Z_k \qquad \text{B.3}$$

where $\bar{P}_k$ is the average power (relative) in the kth axial node. This value is approximated by $\bar{P}_k = \dfrac{P_k + P_{k+1}}{2}$, where P_k and $P_{k=1}$ are the point powers taken from the axial power data provided by BG&E.

Equation B.3 was used to approximate the denominator of eq. B.2, for the 12 and 18 month cycles.

The axial distribution provided by BG&E for the 24 month cycle only has 24 intervals insteac of 51 as for the 12 and 18 month cycles. A similar development for this gives

$$\int_0^H P(Z)dZ \sim \sum_{k=1}^{24} \bar{P}_k \Delta Z_k \qquad \text{B.4}$$

Equation B.4 was used to approximate the denominator of eq. B.2 for the 24 month cycle.

The final axial synthesis factors for the 12 and 18 month cycles are given in Table B.1, and for the 24 month cycle in Table B.2.

In order to compute the 3D flux or activity at some axial location (corresponding to a height Z in Table B.1 and B.2), for some Rθ location one must

(a) find the flux or activity at the appropriate (R_I, θ_J) location in the DOT run

(b) find the axial flux factor at the appropriate node K

(c) compute the 3D value using expression

$$\phi(R_I,\ \theta_J,\ Z_K) = \phi_{R\theta}(R_I,\ \theta_J)^{*}A_K.$$

(*) For example, in the 18 month cycle the peak power corresponds approximately to Z = 3.20 feet [illegible] the bottom of the core. From Table B.1 it can be seen that the axial [illegible] the location is equal to 3.17 x 10^{-3}. Therefore all activities [illegible] the DOT Rθ output should be multiplied by this factor in order [illegible] corresponding peak values.

Table B.1 Calvert Cliffs Unit 2 Axial Distribution Factors for Flux Synthesis: 12 and 18 Month Cycles

Height (feet)	A_k, 12 Month	A_k, 18 Month
11.4300	1.84446E-03	1.74971E-03
11.2000	2.02698E-03	1.94625E-03
10.9700	2.19258E-03	2.12788E-03
10.7400	2.34726E-03	2.29373E-03
10.5100	2.48415E-03	2.44322E-03
10.2800	2.60497E-03	2.57607E-03
10.0500	2.70972E-03	2.69199E-03
9.8300	2.79898E-03	2.79155E-03
9.6800	2.87331E-03	2.87734E-03
9.3700	2.93329E-03	2.94277E-03
9.1400	2.97978E-03	2.99642E-03
8.9100	3.01393E-03	3.03659E-03
8.6800	3.03718E-03	3.06471E-03
8.4500	3.05095E-03	3.00221E-03
8.2300	3.05640E-03	3.09053E-03
8.0000	3.05554E-03	3.09139E-03
7.7700	3.04952E-03	3.08652E-03
7.5400	3.03976E-03	3.07734E-03
7.3100	3.02739E-03	3.06528E-03
7.0800	3.01565E-03	3.05208E-03
6.8500	3.00388E-03	3.03889E-03
6.6300	2.99355E-03	3.02569E-03
6.4000	2.98500E-03	3.01737E-03
6.1700	2.98150E-03	3.01077E-03
5.9400	2.98093E-03	3.00761E-03
5.7100	2.98437E-03	3.00886E-03
5.4800	2.99097E-03	3.00388E-03
5.2600	3.00274E-03	3.03688E-03
5.0300	3.01823E-03	3.02856E-03
4.8000	3.03689E-03	3.04663E-03
4.5700	3.05784E-03	3.06959E-03
4.3400	3.07994E-03	3.08967E-03
4.1100	3.12499E-03	3.11234E-03
3.8800	3.12270E-03	3.13357E-03
3.6600	3.14049E-03	3.15194E-03
3.4300	3.15628E-03	3.16571E-03
3.2000	3.16144E-03	3.17317E-03
2.9700	3.16144E-03	3.17231E-03
2.7400	3.15226E-03	3.16169E-03
2.5100	3.13246E-03	3.13960E-03
2.2800	3.10031E-03	3.10431E-03
2.0600	3.05497E-03	3.05467E-03
1.8300	2.99499E-03	2.98925E-03
1.6000	2.91923E-03	2.90690E-03
1.3700	2.82739E-03	2.80733E-03
1.1400	2.71891E-03	2.68940E-03
0.9100	2.59321E-03	2.55369E-03

0.6900	2.45029E-03	2.39960E-03
0.4600	2.29072E-03	2.22773E-03
0.2300	2.11480E-03	2.06160E-03
0.0	1.92367E-03	1.83349E-03

Table B.2 Calvert Cliffs Unit 2 Axial Distribution Factors for Flux Synthesis: 24 Month Cycles

Height (feet)	A_k, 24 Month
11.2500	1.48084E-03
10.9600	2.02411E-03
10.6600	2.43010E-03
10.3700	2.68129E-03
10.0800	2.87990E-03
9.6200	3.02594E-03
8.9700	3.08728E-03
8.3100	3.10188E-03
7.8300	3.10188E-03
7.3500	3.10188E-03
6.6900	3.09896E-03
6.0300	3.10188E-03
5.5500	3.10773E-03
5.0700	3.11649E-03
4.4100	3.13109E-03
3.7600	3.14278E-03
3.2700	3.15446E-03
2.7900	3.15738E-03
2.1300	3.11941E-03
1.4800	3.01134E-03
1.0220	2.84485E-03
0.7300	2.61703E-03
0.4380	2.23149E-03
0.1460	1.69990E-03

APPENDIX C

Energy Group Structure and Dosimeter Activation Cross Sections Used in Transport Calculations

Energy Group Structure and Dosimeter Activation Cross Sections Used in Transport Calculations are presented in Tables C.1 and C.2.

Table C.1 SAILOR 47-Group Library Energy Structure

Group	Lower energy (MeV)	Group	Lower energy (MeV)
1	14.19*	25	0.183
2	12.21	26	0.111
3	10.00	27	0.0674
4	8.61	28	0.0409
5	7.41	29	0.0318
6	6.07	30	0.0261
7	4.97	31	0.0242
8	3.68	32	0.0219
9	3.01	33	0.0150
10	2.73	34	7.10×10^{-3}
11	2.47	35	3.36×10^{-3}
12	2.37	36	1.59×10^{-3}
13	2.35	37	4.54×10^{-4}
14	2.23	38	2.14×10^{-4}
15	1.92	39	1.01×10^{-4}
16	1.65	40	3.73×10^{-5}
17	1.35	41	1.07×10^{-5}
18	1.00	42	5.04×10^{-6}
19	0.821	43	1.86×10^{-6}
20	0.743	44	8.76×10^{-7}
21	0.608	45	4.14×10^{-7}
22	0.498	46	1.00×10^{-7}
23	0.369	47	1.00×10^{-11}
24	0.298		

*The upper energy of Group 1 is 17.33 MeV.

Table C.2 Reaction Cross Sections (Barns) Used in Calculations for Calvert Cliffs Unit 2

Group	Energy (MeV)	U-238 (n,f)	Np-237 (n,f)	Fe-54 (n,p)	Ni-58 (n,p)	Cu-63 (n,α)
1	1.733E+01	1.275E+00	2.535E+00	2.686E+01	2.962E-01	3.682E-02
2	1.419E+01	1.086E+00	2.320E+00	4.137E-01	4.416E-01	4.540E-02
3	1.221E+01	9.844E-01	2.334E+00	5.276E-01	6.103E-01	5.357E-02
4	1.000E+01	9.864E-01	2.329E+00	5.781E-01	6.588E-01	3.811E-02
5	8.607E+00	9.891E-01	2.248E+00	5.888E-01	6.553E-01	1.906E-02
6	7.408E+00	8.574E-01	1.965E+00	5.590E-01	6.285E-01	9.277E-03
7	6.065E+00	5.849E-01	1.520E+00	4.697E-01	5.365E-01	2.915E-03
8	4.966E+00	5.615E-01	1.538E+00	3.199E-01	3.917E-01	4.437E-04
9	3.679E+00	5.475E-01	1.638E+00	1.762E-01	2.287E-01	3.568E-05
10	3.012E+00	5.463E-01	1.680E+00	1.155E-01	1.658E-01	5.831E-06
11	2.725E+00	5.527E-01	1.697E+00	7.755E-02	1.131E-01	1.707E-06
12	2.466E+00	5.521E-01	1.695E+00	5.111E-02	9.308E-02	6.834E-07
13	2.365E+00	5.512E-01	1.694E+00	4.756E-02	9.232E-02	4.637E-07
14	2.346E+00	5.504E-01	1.693E+00	4.484E-02	8.614E-02	3.430E-07
15	2.231E+00	5.390E-01	1.677E+00	2.008E-02	4.661E-02	1.150E-07
16	1.920E+00	4.685E-01	1.645E+00	4.771E-03	2.660E-03	1.536E-08
17	1.653E+00	2.706E-01	1.604E+00	6.335E-04	1.337E-02	0
18	1.353E+00	4.502E-02	1.543E+00	1.311E-05	4.438E-03	0
19	1.003E+00	1.102E-02	1.389E+00	0	5.023E-04	0
20	8.208E-01	2.881E-03	1.205E+00	0	1.729E-04	0
21	7.427E-01	1.397E-03	9.845E-01	0	4.914E-05	0
22	6.081E-01	5.378E-04	6.437E-01	0	7.673E-06	0
23	4.979E-01	1.502E-04	2.642E-01	0	8.903E-07	0
24	3.688E-01	8.333E-05	8.800E-02	0	4.070E-08	0
25	2.972E-01	6.168E-05	3.552E-02	0	1.832E-15	0
26	1.832E-01	4.668E-05	2.043E-02	0	0	0
27	1.111E-01	4.015E-05	1.542E-02	0	0	0
28	6.738E-02	4.000E-05	1.228E-02	0	0	0
29	4.087E-02	6.176E-05	1.088E-02	0	0	0
30	3.183E-02	8.610E-05	1.023E-02	0	0	0
31	2.606E-02	8.700E-05	1.002E-02	0	0	0
32	2.418E-02	8.700E-05	9.906E-03	0	0	0
33	2.188E-02	8.700E-05	9.723E-03	0	0	0
34	1.503E-02	5.650E-05	1.004E-02	0	0	0
35	7.102E-03	4.860E-11	6.506E-03	0	0	0
36	3.355E-03	7.439E-10	8.716E-03	0	0	0
37	1.585E-03	4.199E-04	2.303E-02	0	0	0
38	4.540E-04	1.464E-08	3.701E-02	0	0	0
39	2.144E-04	1.044E-08	6.129E-02	0	0	0
40	1.013E-04	1.243E-08	9.027E-02	0	0	0
41	3.727E-05	1.955E-08	2.296E-02	0	0	0
42	1.068E-05	3.086E-08	1.014E-02	0	0	0
43	5.043E-06	4.770E-08	4.011E-03	0	0	0
44	1.855E-06	7.171E-08	9.350E-03	0	0	0
45	8.764E-07	5.067E-08	1.407E-02	0	0	0
46	4.140E-07	1.881E-08	4.328E-03	0	0	0
47	1.000E-07	1.182E-09	8.332E-02	0	0	0

APPENDIX D

Definition of "Measured Saturated Activity" Used in Calvert Cliffs-2 Capsule Analysis

Appendix D. Definition of "Measured Saturated Acitivity" Used in Calvert Cliffs-2 Capsule Analysis"

The term "measured saturated activity" is a somewhat ambiguous term which is extensively used, but often misunderstood. In this appendix we will discuss the definition of saturated activity and derive the expressions used in the present analysis.

In the Calvert Cliffs-2 263° capsule analysis following cycle 4, most dosimeters did not remain in the core long enough to reach "saturation conditions" (i.e., the activity at which the rate of decay is equal to the rate of production). This is often the case for dosimeters removed relatively early in the life of a plant. Thus the "time-of-removal" activity (A_{TOR}) which is physically measured does not actually correspond to a saturated activity. However it is common to define a "measured saturated activity" (A_{SAT}) by the relation:

(1) $A_{TOR} = h\, A_{SAT}$,

(2) $A_{SAT} = A_{TOR}/h$

where h is the non-saturation factor given by

(3) $$h = \sum_j P_j \,(1-e^{-\lambda T_j})\, e^{-\lambda(T-t_j)}$$

In reality the saturated activity is not measured at all —— only the TOR activity is measured, and a "measured saturated activity" is then calculated using eq.(1).

As shown in reference (1), eq. (1)-(3) are rigorous only if the core power distribution does not change with time. If the distribution is time-dependent, then the idea of a saturated activity is ambiguous, since the different power distributions may cause the dosimeters to saturate at different activities. We encounter this difficulty in analyzing the surveillance capsule from Unit 2, which was exposed to cycles 1-3 having a power distribution representative of a 12 month cycle, and to cycle 4 having an 18 month cycle distribution. Which cycle type should be used in defining the saturated activity? Obviously the simplistic expression in eq.(1) breaks down whenever several different power distributions are involved; and it is no longer clear how to define a "measured saturated activity" in terms of A_{TOR}. In the following development we derive an alternate expression to eq.(2) for defining a "measured saturated activity" in terms of A_{TOR} for the Calvert Cliffs-2 analysis. [This derivation is easily generalized.]

We assume that a single power distribution can be used to represent all 12 month cycles; and another to represent 18 month cycles. If the dosimeter were exposed to either of these distributions for a long enough period of time, it would obtain a saturated activity equal to A_{SAT}^{12} and A_{SAT}^{18}, respectively. Note that in general

$$A_{SAT}^{12} \neq A_{SAT}^{18} ;$$

and that the A_{TOR} value should represent some combined effect of the two power distributions.

The value for A_{TOR} at the end of cycle 4 will be given by

(4) $A_{TOR} = h_{1\to3} A^{12}_{SAT} e^{-\lambda T_{3\to4}} + h_4 A^{18}_{SAT}$

where $h_{1\to3}$ = non-saturation factor from beginning of cycle 1 to end of cycle 3.

h_4 = non-saturation factor from beginning of cycle 4 to end of cycle 4.

$T_{3\to4}$ = time from the end of cycle 3 to the end of cycle 4.

A^{12}_{SAT} and A^{18}_{SAT} = saturated activity associated with the power distribution for the 12 and 18 month cycles, respectively.

λ = dosimeter decay

Equation (4) can be written as

(5) $A_{TOR} = [\, h_{1\to3} e^{-\lambda T_{3\to4}} + h_4 \left(\frac{A^{18}_{SAT}}{A^{12}_{SAT}}\right)] \cdot A^{12}_{SAT}$

From this relation we define the "measured saturated activity" for the 12 month cycle to be

(6) $(A^{12}_{SAT})_{meas.} = \dfrac{A_{(TOR)meas.}}{\left[h_{1\to3} e^{-\lambda T_{3\to4}} + \cdot \left(\frac{A^{18}_{SAT}}{A^{12}_{SAT}}\right)_{CALC.} \right]}$

Note that eq.(6) allows us to obtain a "measured" saturated activity by utilizing the A_{TOR} measurements; however it also requires knowing the ratio

$\frac{A_{SAT}^{18}}{A_{SAT}^{12}}$ which must be obtained from the transport calculations.

In a similar way we obtain the measured saturated activity for the 18 month cycle:

$$(7) \quad (A_{SAT}^{18})_{meas.} = \frac{(A_{TOR})_{meas.}}{\left[h_4 + h_{1\to3} e^{-\lambda T_{3\to4}} \left(\frac{A_{SAT}^{12}}{A_{SAT}^{18}}\right)\right]_{CALC}}$$

The results called measured saturated activities in Tables 6a and 6b were obtained using eqs.(6) and (7) respectively.

REFERENCES

R. E. Maerker, M. L. Williams, B. L. Broadhead, "Accounting for Changing Source Distributions in Light Water Reactor Surveillance Dosimetry Analysis," *Nucl. Science Engr. 94*, 291-308 (1986).