50-255

CEN - 189
APPENDIX D

EVALUATION OF PRESSURIZED THERMAL SHOCK EFFECTS DUE TO SMALL BREAK LOCA'S WITH LOSS OF FEEDWATER FOR THE PALISADES REACTOR VESSEL

Prepared for

CONSUMERS POWER COMPANY

NUCLEAR POWER SYSTEMS DIVISION
DECEMBER, 1981

POWER SYSTEMS
COMBUSTION ENGINEERING, INC.

8201130 485

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ABSTRACT

This Appendix to CEN-189 provides the plant-specific evaluation of pressurized thermal shock effects due to small break LOCA's with extended loss of feedwater for the Palisades reactor vessel. It is concluded that crack initiation would not occur for the transients considered for more than 32 effective full power years, which is assumed to represent full plant life.

TABLE OF CONTENTS

D1.0 PURPOSE

This Appendix provides the plant-specific evaluation of pressurized thermal shock effects of the SB LOCA + LOFW transients presented in the main body of the CEN-189 report for the Palisades reactor vessel.

D2.0 SCOPE

The scope of this Appendix is limited to the evaluation of the SB LOCA + LOFW transients presented in CEN-189, as applied to the Palisades reactor vessel.

Other C-E NSSS reactor vessels are reported in separate Appendices.

D3.0 INTRODUCTION

This Appendix to CEN-189 was prepared by C-E for Consumers Power Company for their use in responding to Item II.K.2.13 of NUREG-0737 for the Palisades reactor vessel.

This Appendix is intended to be a companion to the CEN-189 report. The transients evaluated in this Appendix are those reported in Chapter 4.0 of the main report. Chapter D5 of this Appendix reports the plant-specific fluence distributions developed as described in Chapter 5.0 of the main report. Chapter D6 reports the plant-specific material properties and change of properties due to irradiation, based on the methods of Chapter 6.0 of the report. Chapter D7 reports the results of comparing the fracture mechanics results of Chapter 7.0 of the report, to the material properties discussed in Chapter D6.

D4.0 THERMAL HYDRAULIC ANALYSES

The pressure-temperature transients used to perform the plant-specific vessel evaluation reported in this Appendix are those reported in Chapter 4.0 of CEN-189. As discussed in the body of the report, there are several plant parameter conservatisms included in the analyses to develop these transients due to the reference plant approach used which could be eliminated by performing more detailed plant-specific thermal-hydraulic system analyses. Removal of these available conservatisms by additional analyses was not performed due to the favorable conclusion achieved.

D5. Palisades Fluence Distribution

The fluence distribution applied to the Palisades reactor was based on the peak fluence and azimuthal distribution provided by Consumers Power plus radial and axial distributions which were calculated as described in Sections 5.2.3 and 5.2.4.

The peak fluence was quoted as 4.24×10^{18} n/cm^2 as December 31, 1981. This value assumes an integrated energy output of 4.215 Effective Full Power Years (EFPY) at 2530 Megawatts-thermal (Mwt). The azimuthal fluence distribution as transmitted by Consumers Power is shown in Table D5-1. The distribution shown for the interval between 0 and 2 centimeters from the inner surface of the vessel was used. Figure D5-1 shows a plot of the azimuthal distribution used for this analysis.

The axial and radial distributions were calculated using an RZ-DOT model based on a Millstone Point-Unit 2 design. Adjustments to account for differences in core lengths were made by using the top of the active core as a reference point. The resulting axial and radial fluence distributions are shown in Figures D5-2 and D5-3, respectively.

TABLE D5-1

FLUX** 1 Mev at Palisades Vessel as a Function of Angle and Distance from Surface

ZONE	ANGLE*(REVOLUTIONS)		FLUX VS. DISTANCE (CM) FROM INNER SURFACE				
	FROM	TO	0-2	2-4	4-6	6-8	8-10
1	0	0.0073	0.619	0.513	0.392	0.285	0.183
2	0.0073	0.0147	0.694	0.574	0.437	0.317	0.203
3	0.0147	0.0220	0.825	0.679	0.514	0.371	0.237
4	0.0220	0.0293	0.963	0.786	0.591	0.424	0.269
5	0.0293	0.0354	1.000	0.818	0.615	0.441	0.280
6	0.0354	0.0388	0.971	0.796	0.601	0.433	0.276
7	0.0388	0.0402	0.952	0.779	0.591	0.427	0.272
8	0.0402	0.0412	0.944	0.771	0.586	0.424	0.270
9	0.0412	0.0422	0.937	0.765	0.581	0.420	0.268
10	0.0422	0.0432	0.927	0.757	0.576	0.416	0.265
11	0.0432	0.0446	0.910	0.746	0.567	0.410	0.262
12	0.0446	0.0480	0.879	0.725	0.550	0.399	0.255
13	0.0480	0.0541	0.847	0.699	0.532	0.385	0.247
14	0.0541	0.0642	0.859	0.710	0.540	0.391	0.250
15	0.0642	0.0743	0.956	0.784	0.592	0.426	0.272
16	0.0743	0.0845	0.987	0.809	0.610	0.439	0.279
17	0.0845	0.0946	0.912	0.751	0.569	0.410	0.262
18	0.0946	0.1047	0.817	0.673	0.511	0.369	0.236
19	0.1047	0.1148	0.741	0.611	0.464	0.336	0.215
20	0.1148	0.1250	0.702	0.579	0.440	0.318	0.204

*Zero revolutions is at the 45° axis and 0.125 is at the principal axis. Octant symmetry assumed.

**Relative to peak flux.

PALISADES AZIMUTHAL FLUENCE VARIATION

AT VESSEL CLAD INTERFACE

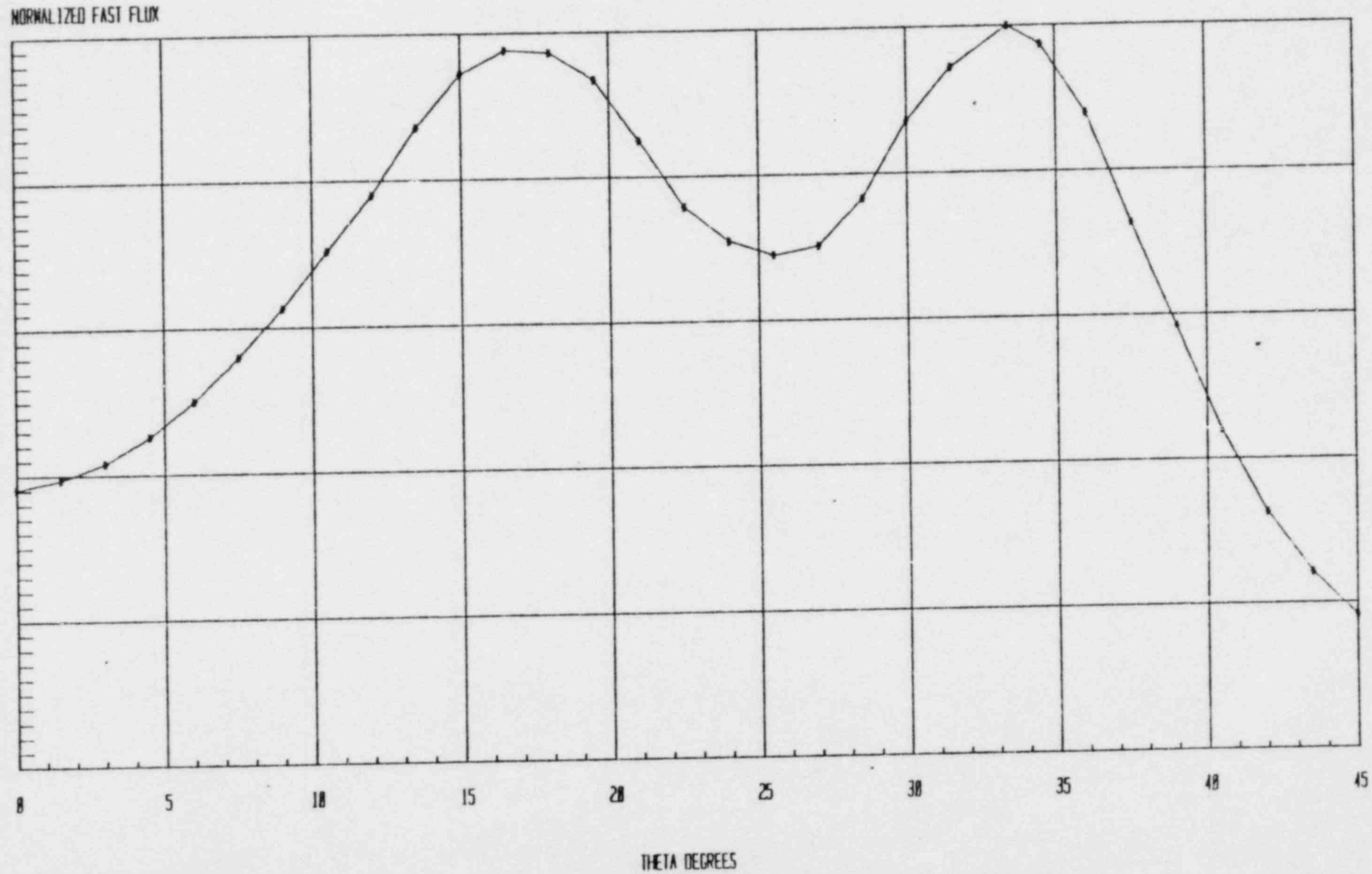


FIGURE D5-1

PALISADES AXIAL FLUENCE VARIATION

AT VESSEL CLAD INTERFACE

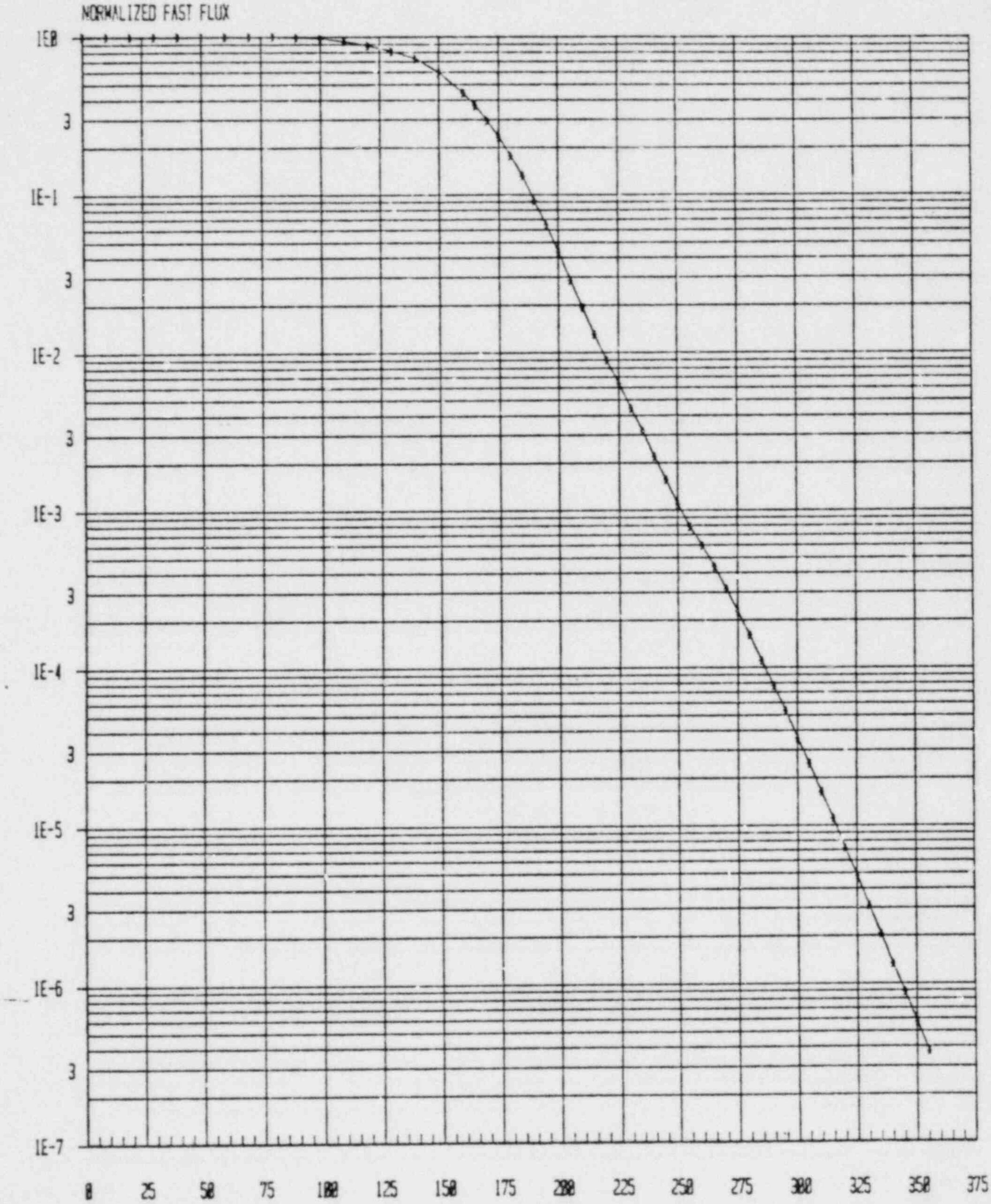
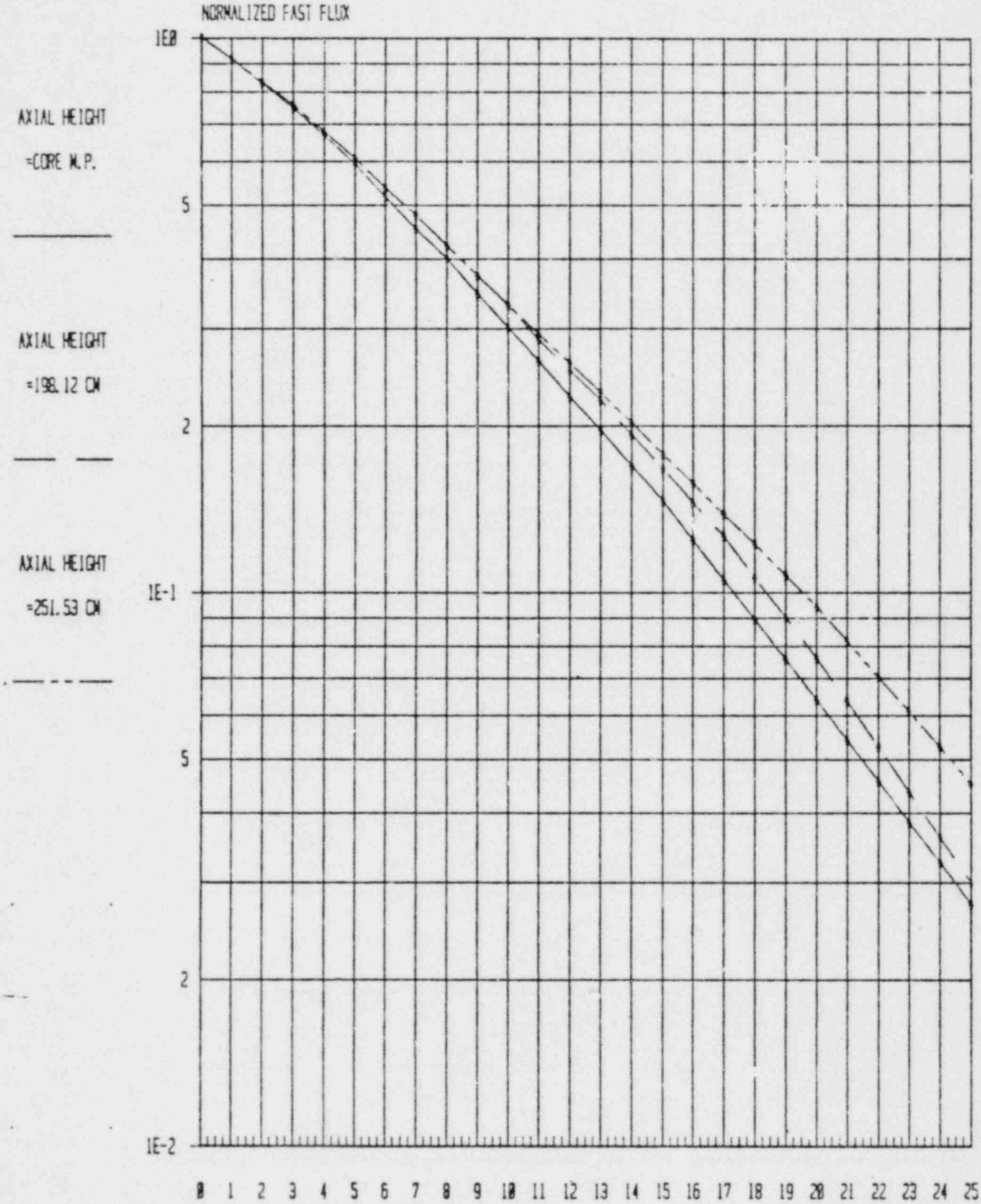


FIGURE D5-2

PALISADES RADIAL FLUENCE VARIATION

AT VESSEL CLAD INTERFACE



Distance From V.C. Interface - CM

FIGURE D5-3

D.6 MATERIAL PROPERTIES

The methods used to develop and evaluate the materials for the Palisades reactor vessel are described in Section 6.0 in the main body of the report. The chemistry data (nickel, copper, and phosphorus content) and initial (pre-irradiation) toughness properties of the reactor vessel shell course plates and welds are summarized in Table D6-1. The copper content for weld seams 1-112 and 2-112 was estimated using the highest measured value for the other weld seams.

In cases where the weld metal nickel content was not determined, it was conservatively estimated using information on the type of wire (eg, high MnMo versus MnMoNi wire) or the weld process (inclusion of Ni-200 wire during weld deposition). For the Palisades weldments, the weld inspection records and welding certification reports indicated that all the welds could be expected to contain high nickel (greater than 0.30 w/o), so the nickel content was conservatively estimated to be 0.99 w/o as indicated in Table D6-1.

The toughness properties given in Table D6-1 are the drop weight NDTT (if determined) and the initial reference temperature, RT_{NDT}. For the plate materials, the RT_{NDT} was determined using transversely oriented Charpy impact specimens or by converting longitudinal impact data using Branch Technical Position MTEB 5-2*. For the weld material, the RT_{NDT} was estimated using the weld qualification test results benchmarked to the Fort Calhoun surveillance weld. (RT_{NDT} was not determined for the Palisades surveillance weldment, so data from a similar weldment were used instead.) The methodology used is discussed in Section 6.0 and described below.

The individual weld qualification test results (three Charpy impact specimens tested at +10F) are listed in Table D6-2. Each weld which exhibited an average Charpy energy of 57 ft-lb or greater (the average Charpy energy for the benchmark weld at 10F) was considered to be at least as tough as the benchmark weld; i.e., that weld seam RT_{NDT} was

* "Fracture Toughness Requirements for Older Plants," U.S. Atomic Energy Commission, Regulatory Standard Review Plan.

-50F or less. For those weld qualification test results exhibiting an average Charpy energy less than 57 ft-lb, the RT_{NDT} was increased by an amount equivalent to the temperature difference between the average Charpy energy transition curve for the benchmark weld and the average Charpy energy for the vessel weld test results. In effect, the temperature at which 50 ft-lb or better exists was determined, and the RT_{NDT} was established at a temperature 60F below that value.

A "map" of the cylindrical portion of the Palisades reactor vessel is given in Figure D6-1. It shows the locations of the plates and welds listed in Table D6-1 and their corresponding values of initial RT_{NDT} (F) located within a rectangle on the Figure. RT_{NDT} values for the vertical weld seams (designated 1-112, 2-112, and 3-112) are shown at a single seam but apply to all three vertical seams in a given shell course. Included in the Figure are the locations of the inlet and outlet nozzles, the core midplane, and the extremities of the active core.

Figure D6-2 is a map of adjusted RT_{NDT} values for important locations at the inner surface of the Palisades vessel predicted for December 31, 1981. The predictions are based on the best estimate neutron fluence, 0.424×10^{19} n/cm (E>1MeV), (corresponding to 4.215 effective full power years at peak flux location on the inside surface of the reactor vessel), the initial RT_{NDT} and copper, phosphorus, and nickel contents given in Table D6-1, and the normalizd neutron flux profiles given in Section D.5. The values of adjusted RT_{NDT} (initial RT_{NDT} plus predicted shift) are located in rectangles adjacent to the plate and weld designations. The RT_{NDT} values apply to the inner surface of the vessel in the region indicated by a circle. The circled regions generally represent areas of peak neutron flux for a given weld seam or plate.

TABLE D6-1 PALISADES REACTOR VESSEL MATERIALS

Product Form	Material Identification	Drop Weight NDTT (°F)	Initial RTNDT (°F)	Chemical Content (%) Nickel	Copper	Phosphorus
Plate	D-3802-1	10	20 [a]	0.49	0.25 [b]	0.012
Plate	D-3802-2	0	30 [a]	0.48	0.25 [b]	0.015
Plate	D-3802-3	10	20 [a]	0.55	0.25 [b]	0.011
Plate	D-3803-1	-10 [c]	-5 [c]	0.53	0.25	0.011
Plate	D-3803-2	-30	-30 [a]	0.50	0.25	0.011
Plate	D-3803-3	-30	0 [a]	0.48	0.25	0.013
Plate	D-3804-1	-30	0 [a]	0.45	0.25 [b]	0.017
Plate	D-3804-2	-40	-30 [a]	0.50	0.25 [b]	0.018
Plate	D-3804-3	-30	-25 [a]	0.54	0.25 [b]	0.010
Weld	1-112 A,B,&C	N/A	-25 [d]	1.20	0.28 [e]	0.021
Weld	2-112 A,B,&C	N/A	-25 [d]	1.20	0.28 [e]	0.021
Weld	3-112 A,B,&C	N/A	-45 [d]	0.99 [f]	0.28	0.018
Weld	8-112	N/A	-45 [d]	0.99 [f]	0.28	0.018
Weld	9-112	N/A	-25 [d]	1.27 [c]	0.22 [c]	0.011 [c]

N/A Not Available
a Determined using Branch Technical Position MTEB 5-2
b Estimated based on average for Palisades plates having reportedanalyses
c Surveillance program data
d Estimated (see text and Table D6-2)
e Estimated (highest measured value for other weld seams)
f Estimated Ni content (high nickel type wire or weld process)

TABLE D6-2

PALISADES
REACTOR VESSEL WELD SEAM TOUGHNESS DATA

Weld Seam	Charpy Qualification Test Results at 10°F (ft-lb)	Average Energy at 10°F (ft-lb)	Estimated[d] RT_{NDT} (°F)
1-112 A/C	35, 39, 48	40.7	-25
2-112 A/C	35, 39, 48	40.7	-25
3-112 A/C	46, 56, 59	53.7	-45
8-112	46, 56, 59	53.7	-45
9-112	35, 48, 42	41.7	-25
	71, 57, 42	56.7	-45
Benchmark Weld[a]	51, 55[b]	57.0	-50[c]

a Benchmark Weld - Fort Calhoun surveillance weld

b Test results at 0°F

c Actual RT_{NDT} based on drop weight and Charpy test results

d Estimated using the method described in the text

FIGURE D6-1

PALISADES REACTOR PRESSURE VESSEL MAP
INITIAL RT_{NDT} IN °F

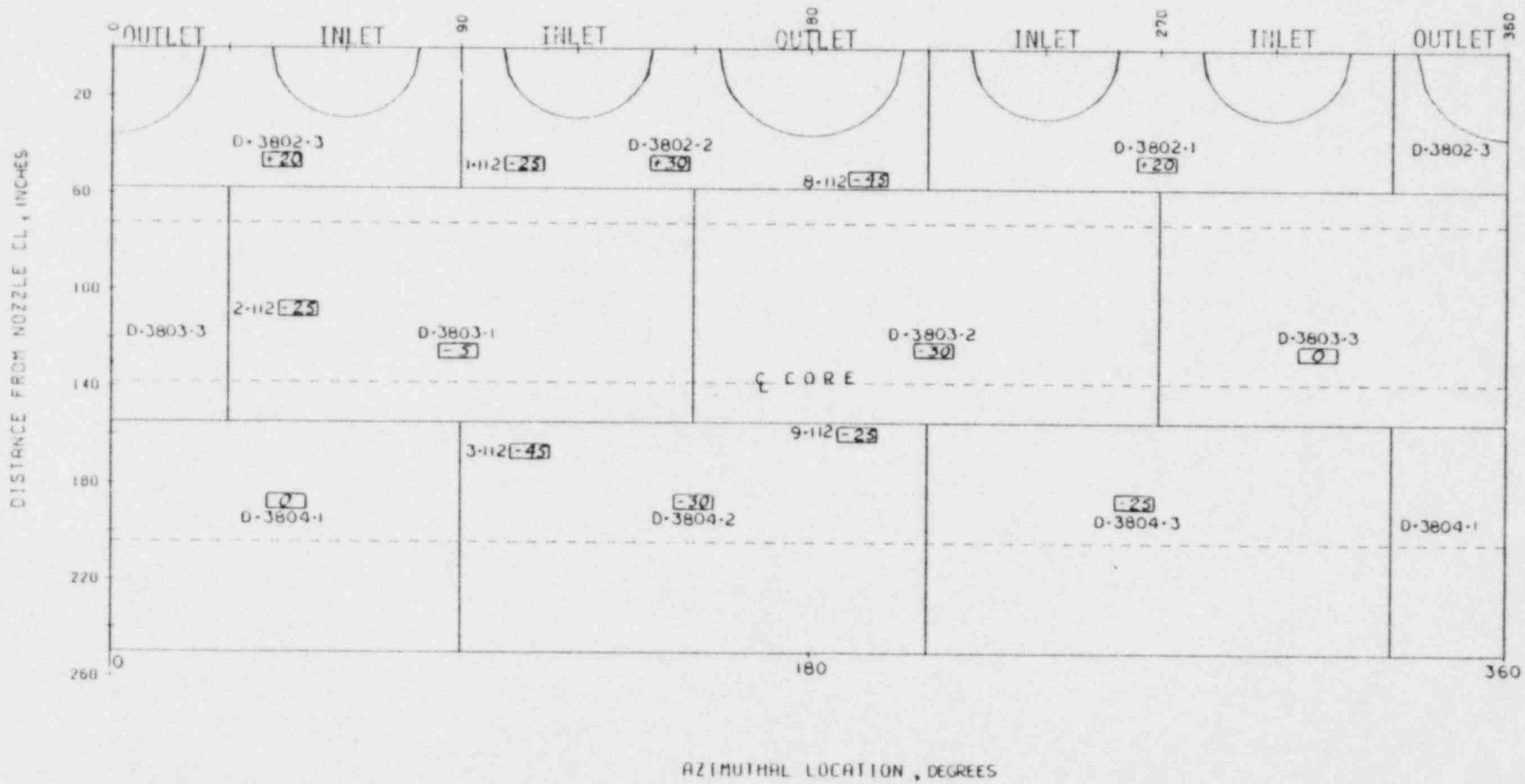


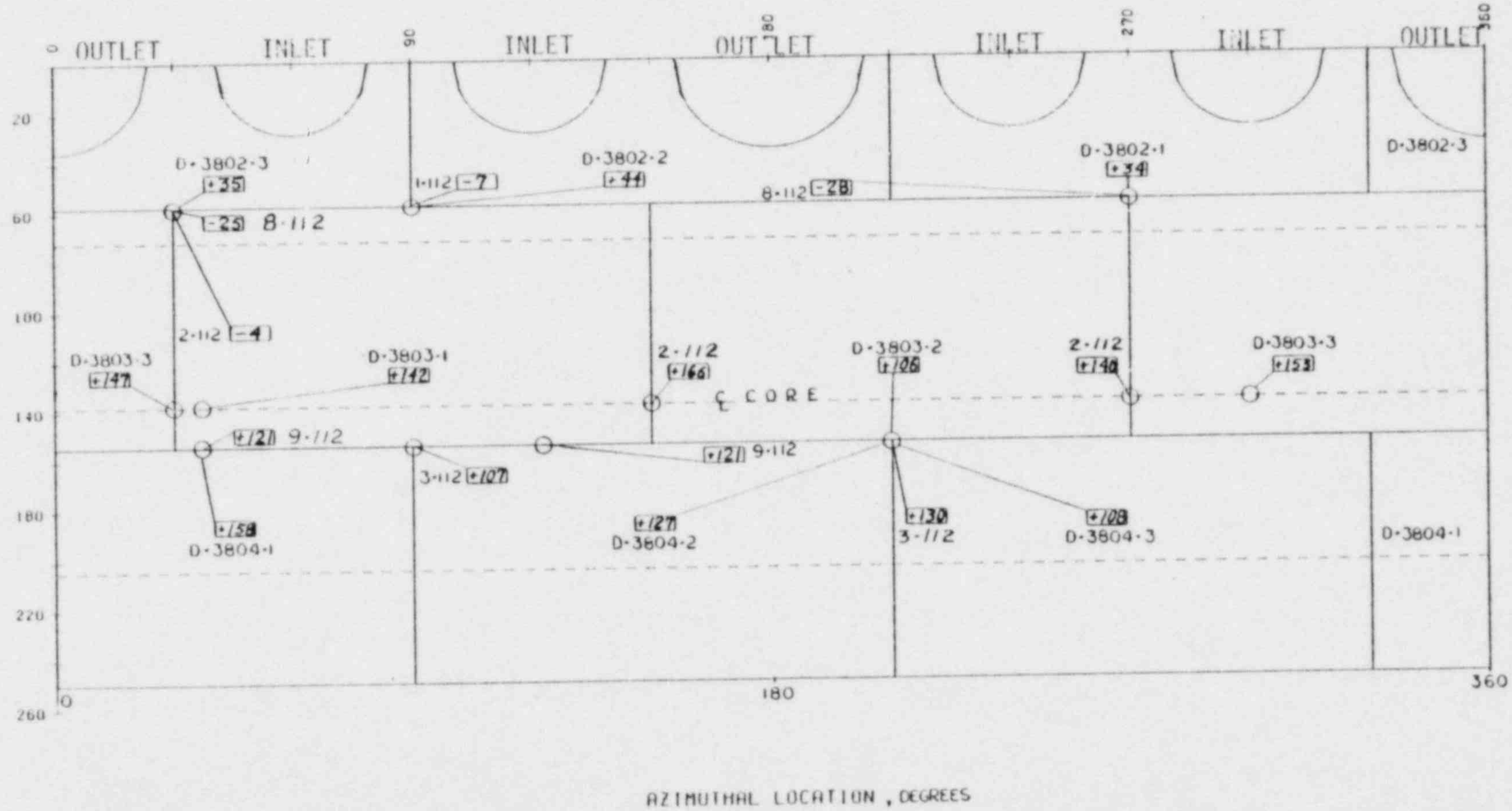
FIGURE D6-2

PALISADES REACTOR PRESSURE VESSEL MAP

ADJUSTED RT_{NDT} IN °F (12/31/81)

4.215 Effective Full Power Years

0.424×10^{19} n/cm^2 Peak Surface Fluence



D.7.0 Palisades Vessel Integrity

The fracture mechanics analysis is performed using the plant specific properties of the Palisades vessel. The attenuation of the peak fluence value is considered in three dimensions (r, z, θ), and the superposition of the fluence profile and the weld geometry map is used in calculating the predicted RT_{NDT} value at all points in the vessel as a function of Effective Full Power Years (EFPY). This information is used in locating the points in the vessel having the highest RT_{NDT} at each of the three axial sections of interest:

1)	middle of core, z	=	138.63 in.
2)	top of core, z	=	72 in.
3)	above-core, z	=	43.5

where z is the axial distance below the centerline of the nozzle. From the predicted RT_{NDT} values, the material toughness properties K_{IC} and K_{Ia} are determined from the calculated temperatures for the SBLOCA + LOFW transients using the method described in Section 7.6. Critical crack depth diagrams are constructed from the applied K_I vs crack depth curves and the calculated material toughness curves. By performing the same fracture mechanics analysis a number of times for increasing plant life (EFPY) the integrity of the Palisades vessel for the SBLOCA + LOFW transient is evaluated.

D.7.1 Summary of Physics and Materials Data Input to Fracture Mechanics Analysis

A detailed survey was performed on the combined fluence and material properties in terms of radiation embrittlement. The properties are considered independently at the three axial sections. At each section, the combination of fluence and materials data were evaluated for a large number of points around the circumference. The adjusted RT_{NDT} values at the inner vessel radius were compared, and the location with the highest RT_{NDT} value was used in the fracture mechanics analysis.

At the mid-core level, the location of highest RT_{NDT} occurs in the weld material at an azimuthal angle of 30 degrees. The fluence factor at this location is .93 of the peak fluence in the vessel.

The materials data at this point are as follows:

PCT.	Ni	=	1.2
PCT.	Cu	=	.28
PCT.	P	=	.021
Initial RT_{NDT}		=	$-20^{o}F$

At the 12/31/81 level of 4.2 EFPY, and peak fluence of $.422 \times 10^{19}$ n/cm^2 ($E > 1$ MeV), this corresponds to a point fluence of $.392 \times 10^{19}$ n/cm^2 and an adjusted surface RT_{NDT} value of $171^{o}F$.

At the top of core level the location of highest RT_{NDT} occurs in the weld material at an azimuthal angle of 30 degrees. The fluence factor at this location in the vessel is .29 of the peak fluence. The materials data at this point are as follows:

PCT.	Ni	=	1.2
PCT.	Cu	=	.28
PCT.	P	=	.021
Initial RT_{NDT}		=	$-20^{o}F$

At the 12/31/81 level of 4.2 EFPY, and peak fluence of $.422 \times 10^{19}$ n/cm^2 ($E > 1$ MeV), this corresponds to a point fluence of $.124 \times 10^{19}$ n/cm^2 and an adjusted surface RT_{NDT} value of $88^{o}F$.

At the above core level (about halfway between the top of core and the inlet nozzle), the location of highest RT_{NDT} occurs in the plate material at an azimuthal angle of 123 degrees. The fluence factor at this point is .002 of the peak fluence in the vessel. The materials data for this point are as follows:

PCT.	Ni	=	.48
PCT.	Cu	=	.25
PCT.	P	=	.015
Initial RT_{NDT}		=	$30^{o}F$

At the 12/31/81 level of 4.2 EFPY, and peak fluence of $.422 \times 10^{19}$ n/cm^2 (E >1 MeV), this corresponds to a point fluence of $.001 \times 10^{19}$ n/cm^2 and an adjusted surface RT_{NDT} value of 37^oF.

This represents the materials information available at the time of the analysis. Lower initial weld metal RT_{NDT} values were subsequently justified by additional testing. The use of the present values therefore provides a conservative evaluation of vessel integrity.

D.7.2 Results of Fracture Mechanics Analysis for SBLOCA + LOFW ⟶ Open PORV's (Case 4)

The stress analysis for this case is presented in Section 7.8.1 of the report. The fracture mechanics analyses were performed for this case using the Palisades vessel properties and predicted fluence levels up to the assumed end-of-life condition of 32 EFPY. The critical crack depth diagram at the mid-core level of the vessel for 32 EFPY is given in Figure D.7-1. For times greater than 65 minutes in the transient, K_I is calculated to exceed the initiation toughness, K_{IC}, for a range of initial flaw sizes. However, from the plot of K_I vs time shown in Figure 7.14 of the report it is seen that warm-prestressing would occur after 10 minutes in the transient, beyond which time K_I is continually decreasing. Thus, no crack initiation would occur under these circumstances. The upper shelf toughness line indicates the flaw depths for which $K_I = 200 \text{ ksi}\sqrt{\text{in.}}$. This represents the upper limit of applicability for linear elastic fracture mechanics. A ductile failure mechanism would be expected for crack sizes above this limit The fact that warm-prestressing precludes crack initiation prevents initially small flaws from extending into that range.

The critical crack depth diagram for the top of core level at 32 EFPY is shown in Figure D.7-2. For this case, also, initial flaws within a certain range of depth are calculated to exceed the level of initiation toughness after 85 minutes in the transient. From the plot of K_I vs time for the top of core level in Figure 7.15 it is seen that warm-prestressing occurs after 10 minutes in the transient. Thus, no crack initiation would occur under these conditions at the top of core level of the vessel.

Figure D.7-3 shows the critical crack depth diagram at the above core level of the vessel for 32 EFPY. It is apparent from this figure that the calculated stress intensities are below both the initiation and arrest toughness levels, thus there is no potential for brittle crack initiation in the vessel above the top of the core for this transient. This is because of the relatively low fluences at this height on the vessel wall.

D.7.3 Results of Fracture Mechanics Analysis for SBLOCA + LOFW ⟶ Restoration of Feedwater (Case 5)

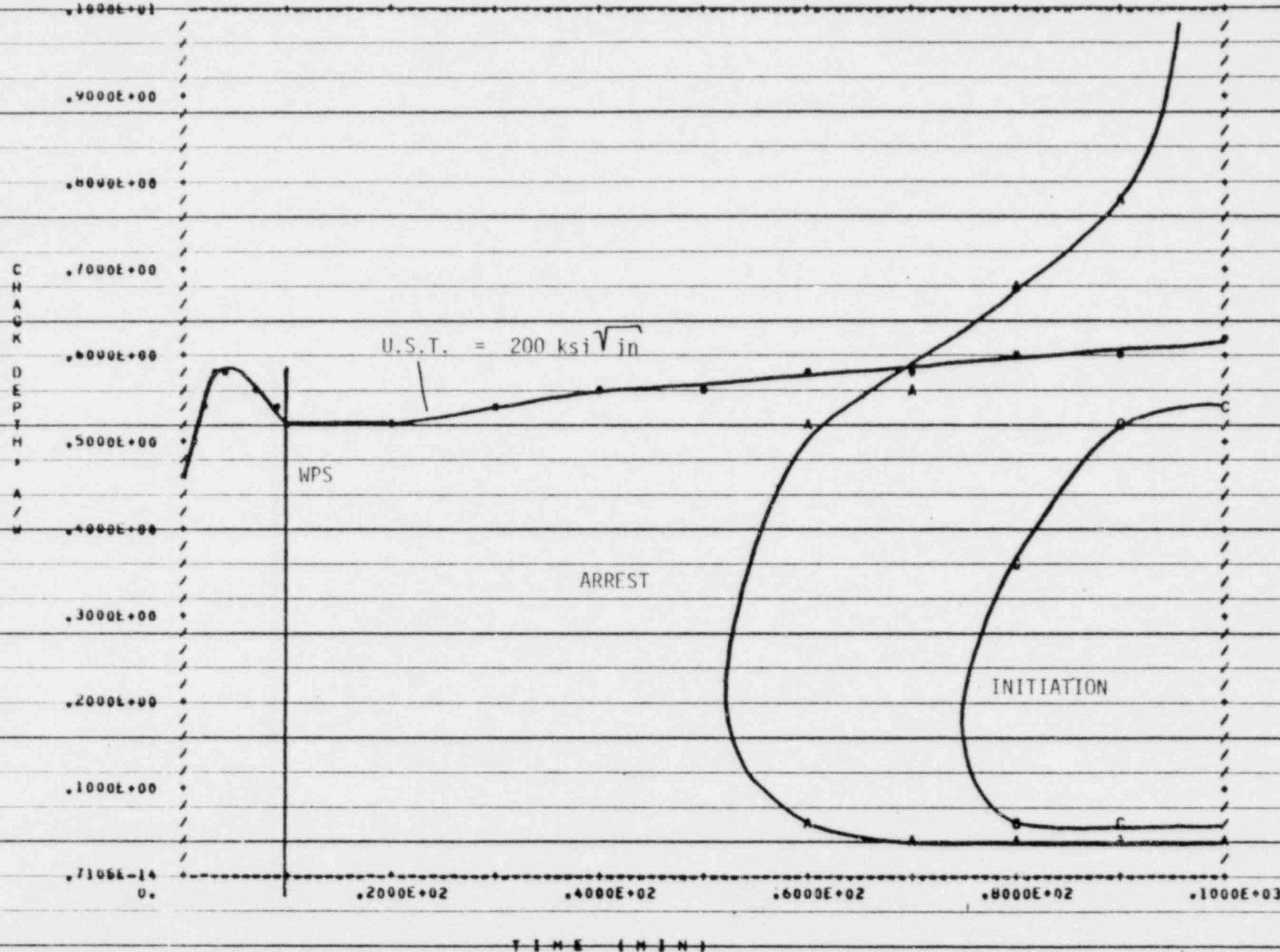
The stress analysis for this transient is presented in Section 7.8.2 of the report. Fracture mechanics analyses were performed using the Palisades vessel properties with various levels of accumulated fluence up to the assumed end-of-life condition of 32 EFPY. The critical crack depth diagram at the mid-core level of the vessel for 32 EFPY is given in Figure D.7-4. The calculated stress intensity values exceed the arrest toughness after 72 minutes, and a small initiation region is apparent at 100 minutes in the transient. The fact that warm-prestressing occurs for this transient after 78 minutes, as shown in the plot of K_I vs time in Figure 7.17 of the report, indicates that crack initiation would not occur under these conditions. The upper shelf toughness line for K_I = 200 ksi$\sqrt{in.}$ represents the upper limit of applicability of LEFM. A ductile failure mechanism would be expected for crack sizes above this limit. In this case, warm-prestressing prevents initially small flaws from extending into that range.

The critical crack depth diagram for the top of core level at 32 EFPY is given in Figure D.7-5. Similarly, the diagram for the above the core level of the vessel at 32 EFPY is shown in Figure D.7-6. Both of these figures indicate that the initiation toughness level is not exceeded at these locations in the vessel throughout the expected plant life for this transient loading condition.

D.7.4 Conclusion

These results demonstrate that the integrity of the Palisades vessel would be assured throughout the assumed plant life for the SBLOCA + LOFW transient with recovery of feedwater, and for the SBLOCA + LOFW transient where the PORV's are opened.

CRITICAL CRACK DEPTH VS. TIME



FLUENCE = .30E+20 N/SQ. CM EFPY = 32.0
INIT RTNDT = -20. DEG. F
PCT. CU = .28
PCT. P = .021
RTNDTS = 329. DEG. F

PALISADES - CASE 4 - MIDDLE OF CORE

UPPER SHELF TOUGHNESS = 200. **

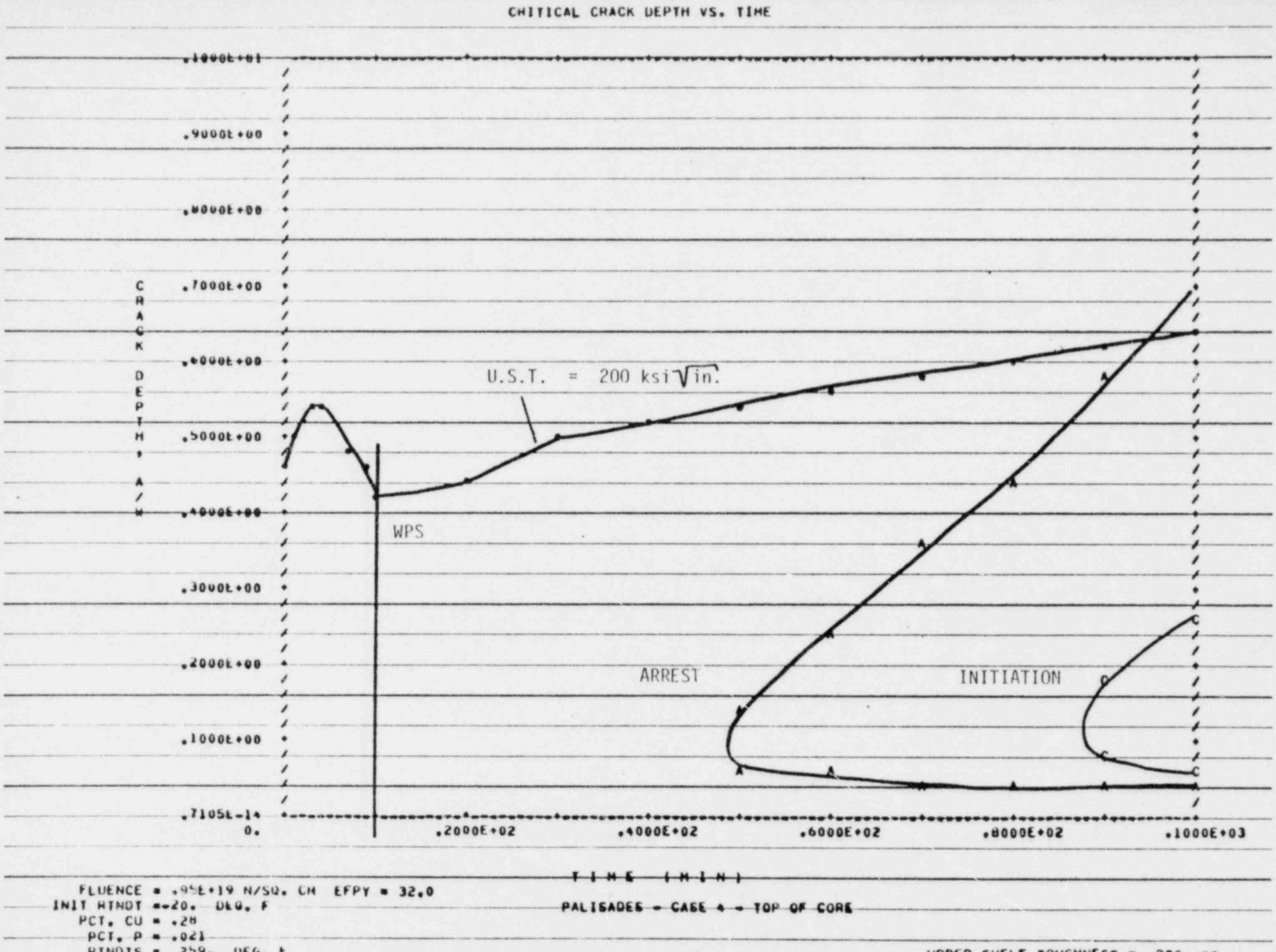
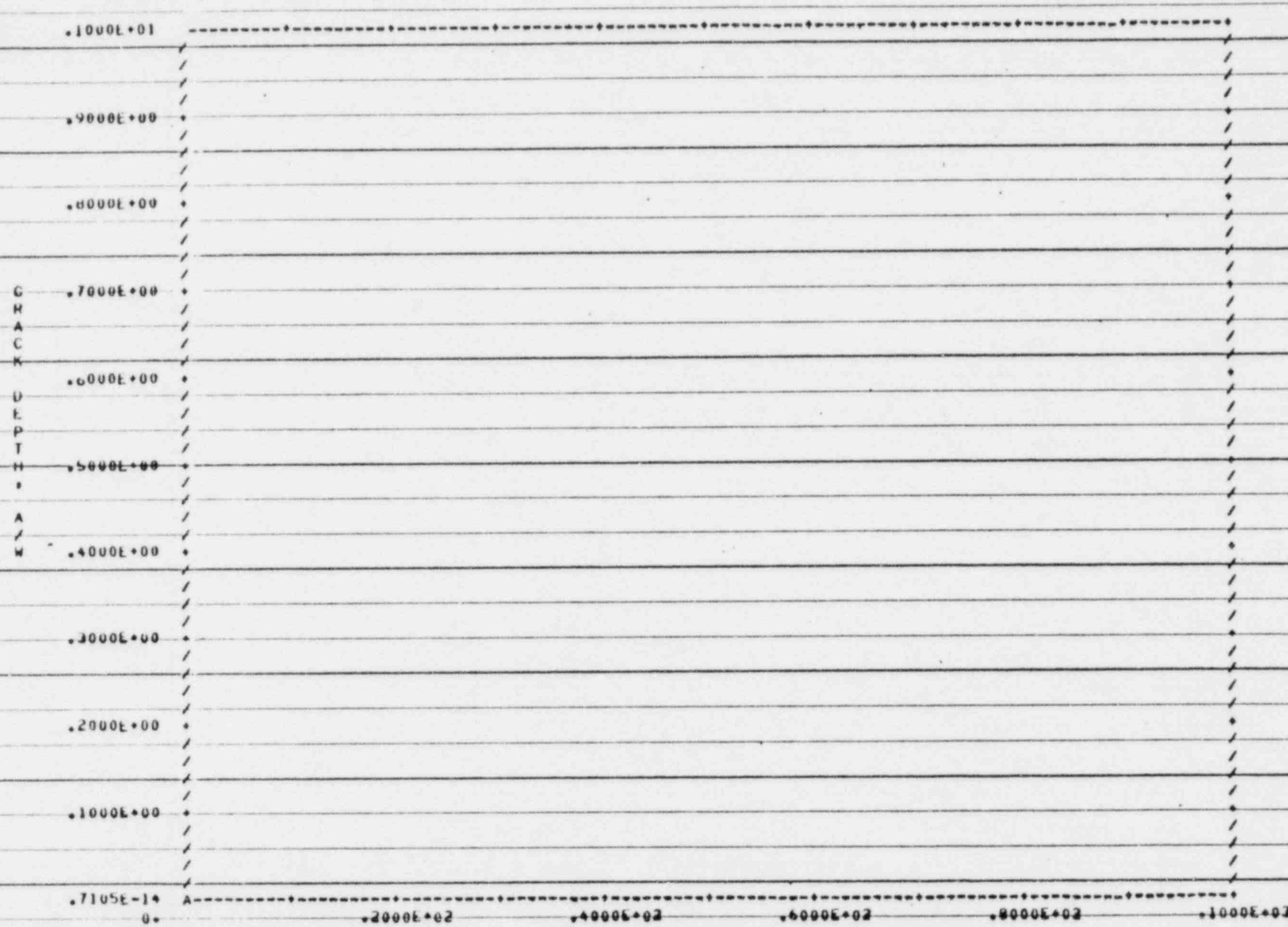

CRITICAL CRACK DEPTH VS. TIME
CRACK DEPTH, A/W
.1000E+01
.9000E+00
.8000E+00
.7000E+00
.6000E+00
.5000E+00
.4000E+00
.3000E+00
.2000E+00
.1000E+00
.7105E-14
0.
.2000E+02
.4000E+02
.6000E+02
.8000E+02
.1000E+03
TIME (MIN)
U.S.T. = 200 ksi$\sqrt{in.}$
WPS
ARREST
INITIATION
FLUENCE = .95E+19 N/SQ. CM EFPY = 32.0
INIT RTNDT =-20. DEG. F
PCT. CU = .28
PCT. P = .021
RTNDTS = 259. DEG. F
PALISADES - CASE 4 - TOP OF CORE
UPPER SHELF TOUGHNESS = 200. **

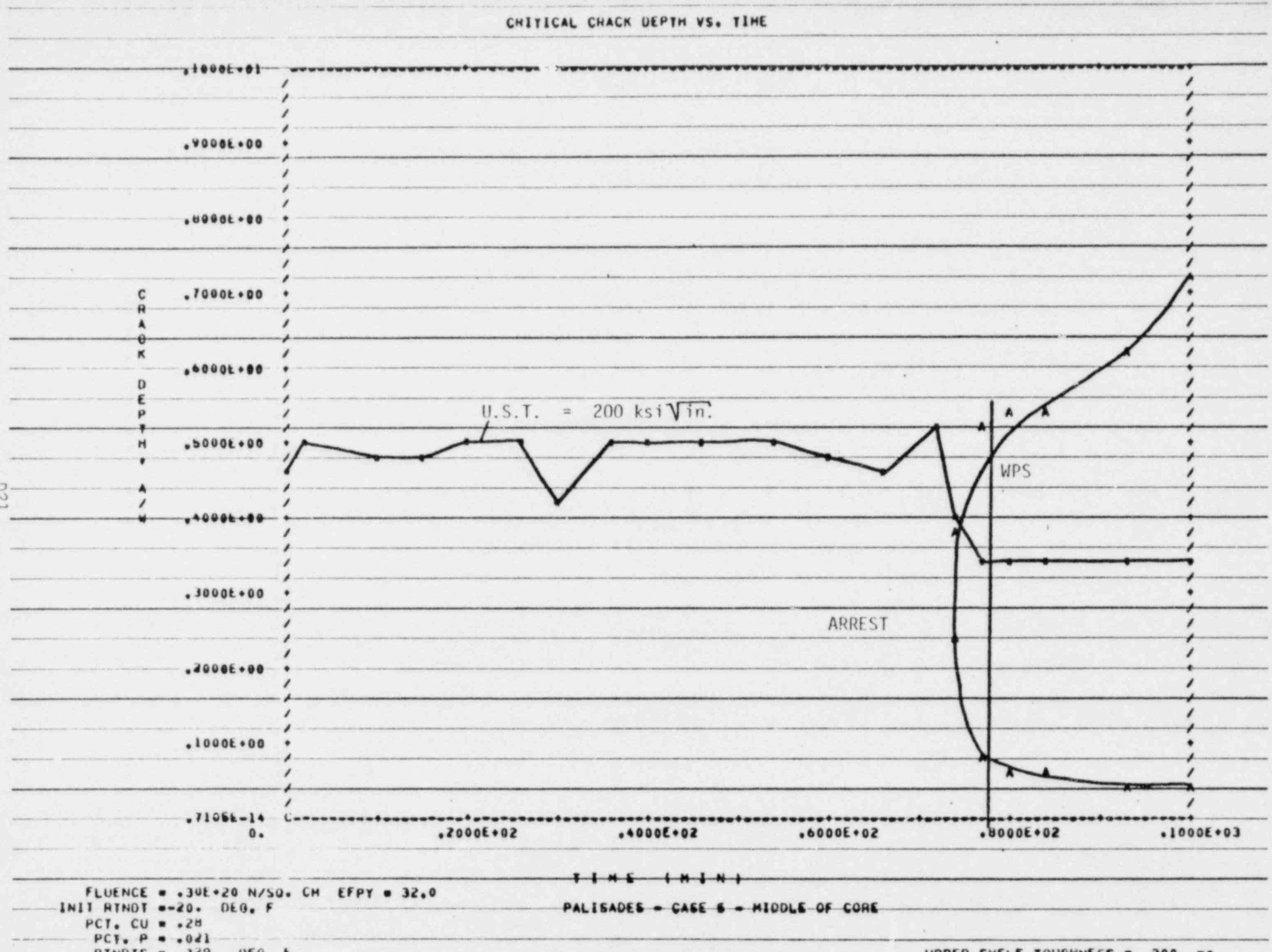
Figure D.7-2

CRITICAL CRACK DEPTH VS. TIME



FLUENCE = .60E+17 N/SQ. CM EFPY = 32.0
INIT RTNDT = 30. DEG. F
PCT. CU = .25
PCT. P = .015
RTNDTS = 40. DEG. F

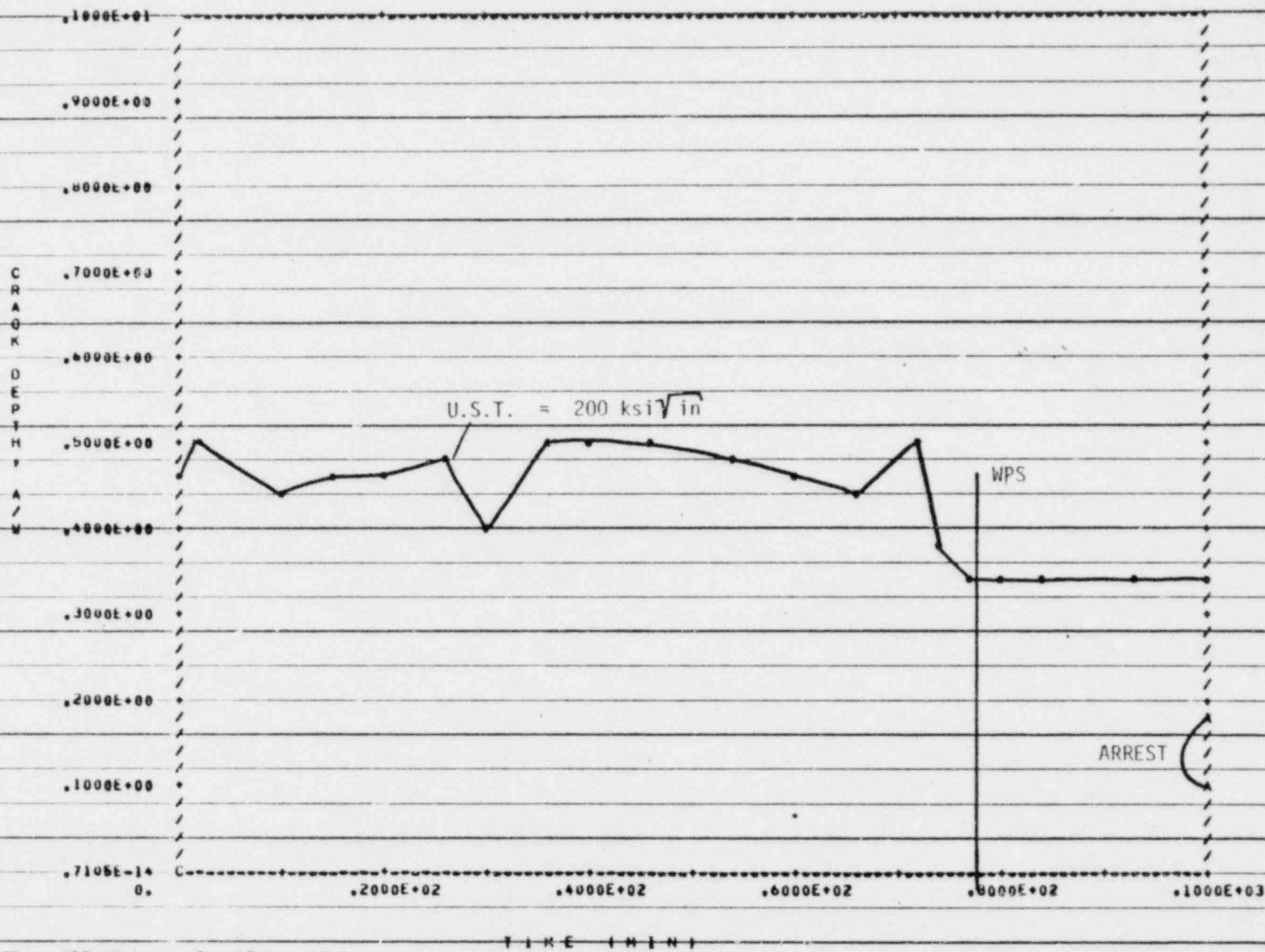
PALISADES - CASE 4 - ABOVE CORE



CRITICAL CRACK DEPTH VS. TIME
CRACK DEPTH A/W
.1000E+01
.9000E+00
.8000E+00
.7000E+00
.6000E+00
.5000E+00
.4000E+00
.3000E+00
.2000E+00
.1000E+00
.7105E-14
0.
.2000E+02
.4000E+02
.6000E+02
.8000E+02
.1000E+03
U.S.T. = 200 ksi$\sqrt{in.}$
WPS
ARREST
TIME (MIN)
FLUENCE = .30E+20 N/SQ. CM EFPY = 32.0
INIT RTNDT =-20. DEG. F
PCT. CU = .28
PCT. P = .021
RTNDTS = 329. DEG. F
PALISADES - CASE 6 - MIDDLE OF CORE
UPPER SHELF TOUGHNESS = 200.

Figure D.7-4

CRITICAL CRACK DEPTH VS. TIME



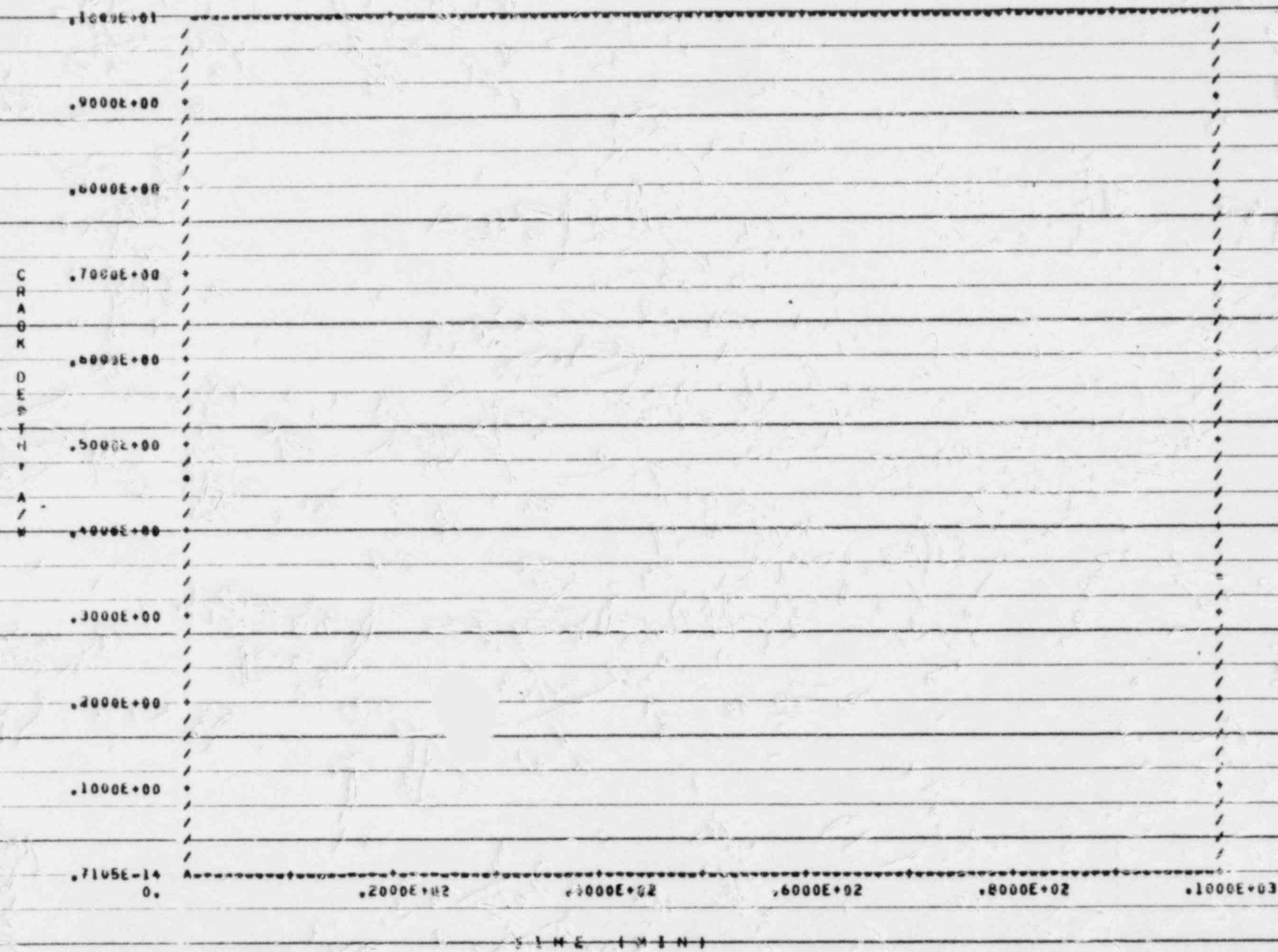
FLUENCE = .55E+19 N/SQ. CM EFPY = 32.0
INIT RTNDT =-20. DEG. F
PCT. CU = .28
PCT. P = .021
RTNDTS = 259. DEG. F

PALISADES - CASE 5 - TOP OF CORE

UPPER SHELF TOUGHNESS = 200. **

Figure D.7-5

CRITICAL CRACK DEPTH VS. TIME



FLUENCE = .60E+17 N/SQ. CM EFPY = 32.0
INIT RTNDT = 30. DEG. F
PCT. CU = .25
PCT. P = .015
RTNDTS = 49. DEG. F

PALISADES - CASE 5 - ABOVE CORE

Figure D.7-6

D 8.0 CONCLUSIONS

This Appendix to CEN-189 provides the results of analytical evaluations of pressurized thermal shock effects on the Palisades reactor vessel for cases of a SBLOCA + LOFW, in response to the requirements of Item II.K.2.13 of NUREG-0737. Two different scenarios were chosen for evaluation based on remedial actions to prevent inadequate core cooling:

1. SBLOCA + LOFW + PORV's opened after 10 minutes
2. SBLOCA + LOFW + Aux. FW reinstated after 30 minutes

Thermal-hydraulic system transient calculations were performed on a reference-plant basis, as reported in CEN-189 with the parameter variations over the range representing all operating plants. Four different cases were analyzed for each of the two different scenarios defined above, for a total of eight cases. The most challenging of each of the two different scenarios was analyzed using linear elastic fracture mechanics methods to determine the critical crack tip stress intensity values for comparison to plant specific materials properties at various times in plant life. The effect of the warm prestress phenomenon is identified where applicable for each transient, and credited where appropriate.

In this Appendix, the results of plant specific neutron fluence profile calculations are superimposed on plant specific material properties to define vessel capability versus plant life. The results of the generic LEFM analyses were evaluated using the plant specific material properties. It is concluded that crack initiation would not occur due to the SBLOCA + LOFW transients considered, for more than 32 effective full power years of operation, which is assumed to represent full plant life.

COMBUSTION ENGINEERING, INC.