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HEDL-TME 75-48 ADDENDUM
UC-79b

EVALUATION OF FFTF FUEL PIN DESIGN PROCEDURE VIS-A-VIS STEADY STATE IRRADIATION PERFORMANCE IN EBR II

MASTER

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November, 1975

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ABSTRACT

The FFTF fuel pin design analysis is shown to be conservation through comparison with pin irradiation experience in EBR-II. This comparison shows that the actual lifetimes of EBR-II fuel pins are either greater than 80,000 MWd/MTM or greater than the calculated allowable lifetimes based on thermal creep strain.

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EVALUATION OF FFTF FUEL PIN DESIGN PROCEDURE VIS-A-VIS STEADY STATE IRRADIATION PERFORMANCE IN EBR-II

I. INTRODUCTION

The objective of this addendum is to show that the FFTF fuel pin design analysis is conservative by comparing the design analysis with fuel pin irradiation experience in EBR-II. First we describe those assumptions and procedures used in Reference 1 to predict the thermal creep strain. The composite of assumptions, calculation methods, and the lifetime limiting thermal creep strain criterion, called the "design procedure," is then applied in the analysis of a selected group of prototypic fuel pins irradiated in EBR-II. This comparison shows that the actual lifetimes of EBR-II fuel pins are either greater than 80,000 MWd/MTM or greater than the calculated allowable lifetimes based on thermal creep strain.

The analysis of Reference 1 considered: (1) pin bundle-duct interaction, (2) wire-cladding interaction, (3) fuel-cladding mechanical interaction and (4) fission gas pressure as the sources for design lifetime limiting stresses or strains for the FFTF driver fuel pins. Fission gas pressure is the limiting internal driving pressure for thermal creep strain of the fuel pin cladding. Note that thermal creep is only one of several mechanisms that result in the total change in fuel pin diameter during its lifetime. Neither the irradiation creep nor swelling of the cladding are reported here because thermal creep strain calculations, alone, determine a cladding design lifetime limit[1]. It was determined in Reference 1 that for hot channel cladding inside surface temperature below 1200°F the calculated lifetime (based on thermal creep) is greater than the design lifetime of 80,000 MWd/MTM. For peak cladding temperatures greater than 1200°F, the design lifetime is limited by reaching a calculated thermal creep "strain" of 0.2% from fission gas pressure (Reference 1). As described below, a thermal creep value is calculated for the thermal history and fuel burnup encountered by EBR-II irradiated test pins. These values are compared with the design thermal creep strain criterion to show the conservatism of the FFTF fuel design lifetime.

II. DESCRIPTION OF DESIGN PROCEDURE

The design procedure consists of assumptions regarding cladding temperatures, thermal creep rates, cladding thinning due to "wastage", calculation of plenum pressure and a calculated steady state "strain" limit. This section will summarize a description of the design procedure which was used for the FFTF pin and will describe how it is applied to an analysis of selected fuel pins irradiated in EBR-II.

A. Cladding Temperature:

The thermal creep analyses in Reference 1 are based upon peak cladding temperatures for the hypothetical fuel pin with combined highest power and lowest coolant flow rate, i.e. the hot channel fuel pin. These temperatures were assumed to decrease linearly with time. This decrease was caused by a 13% decrease in fissile atom density at 80,000 MWd/MTM.

The EBR-II experimental fuel pins normally see both temperature increases and decreases with time. These temperature changes result from changes in core makeup, subassembly relocation within the core, subassembly reconstitution, and run by run core coolant flow redistributions. These changes are often larger than the pin power decrease from fissile atom depletion. Thus, there is not always a similar general decrease of cladding temperature with fuel burnup in EBR-II as compared with the design conditions for the FFTF fuel pins. The application of the design procedure to EBR-II experimental fuel pins is therefore based upon the calculated actual time varying nominal temperatures. This is conservative in the sense that the FFTF design procedure utilizes the cladding hot channel temperature and would therefore predict a shorter allowable lifetime.

B. Plenum Pressure:

The computation of plenum pressure cited in Reference 1 is based upon nominal cladding and hardware dimensions for the plenum volume, nominal fuel pellet dimensions, nominal fuel pellet density and nominal peak and average fuel burnup. A fission gas yield of 0.274 gas atoms per fission event, and an assumed 100% release of xenon and krypton fission gas from the fuel to the gas plenum was used with an average energy release of 210 Mev per fission to determine the amount of fission gas in the plenum. The maximum allowable offgas of 0.09 cubic centimeter per gram of oxide and the maximum allowable water vapor in a single pellet of 50 parts per million were also used. The fill gas was assumed to be at one atmosphere at room temperature. The plenum temperature was set equal to the coolant temperature at the top of the fuel column. For application of the design procedure to EBR-II, we will use the same values and assumptions.

Many of these values are higher than the present nominal values used for calculations other than design procedure. The fission gas release data, and the models derived from these data, predict less than 100% gas release.[2] Measured values of offgas and water vapor are always less than the specification of 0.09 cc/g offgas and the specified maximum 30 ppm fuel lot average water vapor. Similarly, the fission gas yields are conservative because the October 1974 ENDF/B files indicated a Xe + Kr yield of 0.256 for FFTF. Also, the assumption that the plenum temperature equals the coolant temperature at the top of the fuel is conservative because coolant cross mixing will reduce the coolant temperature in the plenum region of the hot pin in a bundle. Further, the conservative assumption is made that plenum pressure is based upon beginning of life plenum volume and ignores plenum volume increases from cladding swelling and creep.

C. Wastage:

The effective cladding thickness for the FFTF fuel pin design analysis in Reference 1 was reduced via wastage allowances as shown below and in Figure 1.

Category	Allowance (mils)	Application in the Fuel Pin Design Analysis
Fuel/Cladding Corrosion	2.0	Beginning of Life
Sodium/Cladding Corrosion	0.5 Min'm. 2.1 Max'm.	Temperature Dependent
Cladding Scratches	0.5†	Beginning of Life

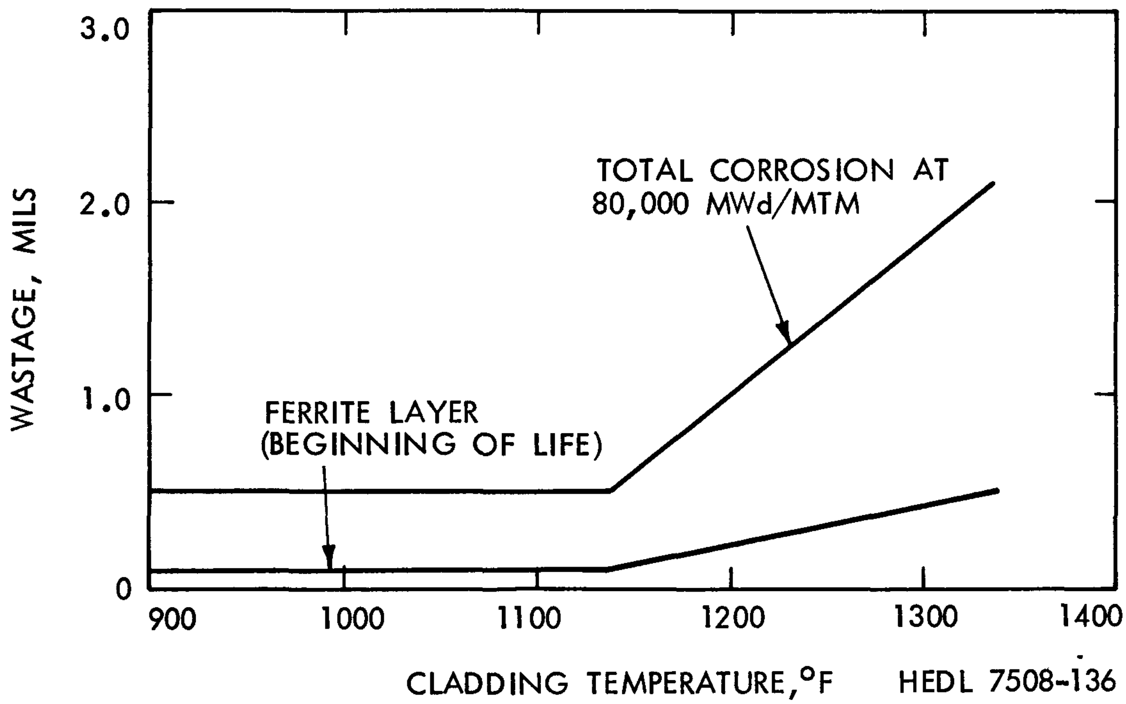

FIGURE 1. Sodium-Cladding Corrosion Allowance in FFTF Fuel Pin Design (After FCF213 A.1.3).

Category (Cont'd)	Allowance (mils)	Application in the Fuel Pin Design Analysis
Thickness Tolerance	0.5	Beginning of Life
Fretting Wear and Self-Welding	2.5†	2.0† Linearly with Life
Contingency	1.0	Beginning of Life

†0.5 mil scratch assumed to be removed by fretting and wear

Design life is 80000 MWd/Mt = 300 effective full power days

(Design life is between 300 and 306 days. Using 300 days here is conservative because it gives a higher wastage rate).

The time dependence of the sodium corrosion is put in terms of equivalent full power days (EFPD) for application of the design procedure to EBR-II experimental fuel pin irradiations.

The specific mathematical model used to calculate the design procedure based cladding wastage for EBR-II tests is:

Wastage = Time Dependent Wastage + Time Independent Wastage

WAST = TDW + TIW

TDW = Wear + OD Scratch + Sodium Corrosion

TDW = WEAR + ODS + NACOR

WEAR = (2.5/300.0)(EFPD)

if EFPD > 60.0 ODS = 0.0 Because scratch is worn away in 60 days
if EFPD ≤ 60.0 ODS = 0.5 - WEAR

NACOR = Ferrite Layer + Corrosion

NACOR = FER + COR

if T ≤ 1125.0 FER = 0.1 and COR = (0.4/300.0)(EFPD) if T > 1125.0 FER = 0.1 + 0.002 (T - 1125.0) and

COR = $[2.0 \times 10^{-5} (T-1125.0) + (0.4/300)](EFPD)$

TIW = Fuel Cladding + Cladding Tolerance + Contingency

= 2.0 + 0.5 + 1.0 = 3.5

so

WAST = WEAR + ODS + FER + COR + 3.5

where WAST = Cladding thinning, mils

EFPD = Effective full power days, days.

T = Cladding outer surface temperature, F.

D. Stress

For EBR-II application of the design procedure, the hoop stress is calculated using the thin wall equation $\sigma = pd/2t$

where σ = hoop stress, psi

d = average cladding diameter, inch

t = cladding thickness, inch.

p = fission gas pressure, psi

The actual stress increases with a concave upward curve with time because of the increasing fission gas release fraction with burnup. This actual curve is always below the design curve from the assumed 100% gas release. In this computation, the design curve is approximated with a stair step series of constant stress values for a series of equal time increments. The time increment is less than 48 hours and is chosen to create an integral number of equal length increments for the irradiation history. The conservative end-of-increment plenum pressure during each time increment (of approximately 48 hours) is used in the calculation of the stress value. The cladding thickness, t, also varies with time because of wastage. Likewise, the effective cladding thickness end of increment is conservatively used for calculation of the stress value for that time increment.

E. Thermal Creep:

The design procedure uses the thermal creep properties of unirradiated solution annealed 316 stainless steel to make a conservative (higher creep rate) thermal creep strain computation for 20% cold work stainless steel clad fuel pins. The equation used is shown in Table 1 and is applicable to the temperature range 1000°F to 1500°F. For application of the design procedure to EBR-II fuel pin irradiations, this equation was used with the addition of values for coefficients below 1000°F in order to calculate thermal creep strains along the length of the fuel pins. These additional coefficients have been defined as

$$A = -4.1497 \times 10^{11} + 8.6281 \times 10^{9} T$$
$$B = 3.5853 \times 10^{14} - 4.3077 \times 10^{11} T$$
$$C = 0.2351 + 9.8098 \times 10^{-3} T$$
$$n = 1.8257 + 3.9644 \times 10^{-3} T$$
$$\beta = -4.257 \times 10^{-4} + 7.733 \times 10^{-4} T$$

The primary creep term. $\varepsilon_p = \varepsilon_t(1 - \exp(-rt)$ is put in the rate form $\dot{\varepsilon}_p = r(\varepsilon_t - \varepsilon_p)$ for purposes of summing up strain increments at different stresses. Secondary and primary creep strain increments are summed for time increments of approximately forty-eight hours each, during which time increment the stress is assumed constant.

III. DESCRIPTION OF EBR-II EXPERIMENTAL FUEL PINS

There have been approximately 600 FFTF prototypic fuel pins with 20% cold worked cladding irradiated in EBR-II. For purposes of confirming the conservation of the design procedure, it is appropriate to perform an analysis on a selected group of these fuel pins. Obviously, there is no merit in calculating design lifetimes on fuel pins from the P-19, P-20, F.20, PNL 17 and P-17A tests, which were designed for measurement of thermal performance at the beginning of life and accordingly were removed at a very low burnup. The re maining subassemblies which contained protypic fuel pins are listed in Table II with fuel pin parameters current through EBR-II run 75.

The fuel pins listed are, with one exception, those with the highest cladding temperature in each subassembly at the end of its irradiation. The

TABLE I

CREEP EQUATION FOR ANNEALED

316 STAINLESS STEEL IN TEMPERATURE RANGE 1000-1500°F

$$\varepsilon_c = \varepsilon_t \left\{ 1 - \exp (-rt) \right\} + \dot{\varepsilon}_m t \qquad (1)$$

$$\dot{\varepsilon}_m = A \left[\sinh \left(\frac{\beta}{n} \sigma \right) \right]^n \exp\left(- \frac{67{,}000}{1.987T} \right), \text{ \% per hour} \qquad (2)$$

$$r = B \left[\sinh \left(\frac{\beta}{n} \sigma \right) \right]^n \exp\left(- \frac{67{,}000}{1.987T} \right), \text{ hours}^{-1} \qquad (3a)$$

or

$$r = 3 \times 10^{-3}, \text{ hours}^{-1} \qquad (3b)$$

whichever yields the larger value of r

$$\varepsilon_t = C \frac{\dot{\varepsilon}_m}{r}, \text{ \%} \qquad (4)$$

TABLE I (Continued)

Parameter	Temperature Range 1000-1076°F	1077-1200°F	1201-1399°F	1400-1500°F
A	$-4.631\times10^{15}+5.719\times10^{12}T$	$2.447\times10^{-3}\exp\left(\frac{33,400}{T}\right)$	$6.279\times10^{10}\exp\left(\frac{4930}{T}\right)$	$7.4\times10^{1[illegible]}$
B	$-3.636\times10^{16}+4.485\times10^{13}T$	$7.2\times10^{-9}\exp\left(\frac{46,000}{T}\right)$	$5.35\times10^{8}\exp\ \frac{10,300}{T}$	1.15×10^{13}
C	8.19	$79.7-8.393\times10^{-2}T$	2.3	2.3
β	$-4.257\times10^{-4}+7.733\times10^{-7}T$	$-4.257\times10^{-4}+7.733\times10^{-7}T$	$-4.257\times10^{-4}+7.733\times10^{-7}T$	$-4.257\times10^{-4}+7.733\times10^{-7}T$
n	$-82.051+0.10741T$	$50.1-0.0482\ T$	$14.37-9.46\times10^{-3}T$	4.6

In using these parameters in equations 1 to 4, σ is stress in psi and T is temperature in °K

TABLE II

COMPARISON OF EBR-II EXPERIMENTAL FUEL PINS TO FFTF FUEL PINS

ITEM	FFTF (Initial)	PNL-9-39	PNL-10-66	PNL-11-71	NUMEC F -123	P-12A-01	P-23A-13	P-23B-9A	WSA 3-19
Fuel (Nominal)									
$^{235}U/U$ Total, %	.7	29.97	64.97	64.97	76.81	92.99	65.49	64.80	93.08
Pu/U + Pu), weight %	22 to 27	22.08	22.09	22.08	22.09	22.10	22.01	22.10	22.30
Off gas, cc/g (STP)	.02-.03	.028	.018	.020	.068	.009	.017	.007	.050
Water, ppm	<5	28.0	28.4	9.0	1.0	5.0	5.0	5.0	30.0
O/M	1.94-1.97	1.974	1.965	1.973	1.970	1.958	1.984	1.970	1.983
Column length, in.	36.0	13.395	13.460	13.587	13.395	13.581	13.420	13.415	13.423
Column diameter, in.	.1945	.1946	.1949	.1937	.1944	.1945	.1947	.1946	.1951
Peak power, beginning of life, kW/ft	12.7	5.4	8.8	12.1	11.5	12.5	12.2	12.2	10.0
Peak burnup, MWd/MTM	80000	83400	61100	110900	52200	79200	57500	53200	122400
Peak temperature, beginning of life, °F	3950.	2789.	3427.	4093.	3985.	4216.	4174.	4172.	3624.
Column smear density, %TD	85.5	83.3	83.5	84.3	86.6	86.7	85.7	85.9	90.5
Pin (Nominal)									
OD, in. BOL, in.	.2300	.2301	.2300	.2297	.2312	.2301	.2302	.2298	.2300
ID, in. BOL, in.	.2000	.2002	.2000	.1997	.1996	.1994	.1999	.1999	.2000
Thickness, in.	.015	.015	.015	.015	.015	.015	.015	.015	.015
Wire diameter, in.	.056	.040	.040	.040	.040	.056	.056	.056	.055
Peak ID cladding temperature, end of life, °F	1018 [α]	1060	1060	1069	1145	1293	1365	1420	1108
Effective plenum length, in.	37	11.1	11.1	11.1	10.1	11.7	11.7	13.5	16.
Fuel/Plenum volume ratio	1.03	.8263	.8239	.8187	.7511	.8649	.8699	1.0037	1.2621
Environment (Nominal)									
Coolant velocity, fps	21	8	12	18	14	7	7	6	9
Peak coolant temperature	1050	1017	1011	975	1015	1188	1320	1329	989
Peak flux, 10^{15} n/cm^2 sec E>.1 Mev	4.34	1.79	1.79	2.51	2.02	1.79	2.571	2.48	1.2
Peak fluence, 10^{22}n/cm^2 E>.1 Mev	12.4	10.2	4.83	10.3	3.82	5.22	5.14	4.75	7.23

[α] Hot spot temperature for design analysis = 1200°F, beginning of life nominal temperature is 1080°F.

one exception is P-23A, with P-23A-43 having a peak cladding ID temperature of 1367°F and P-23A-13 having a peak temperature of 1365°F. However, P-23A-43 was a replacement fuel pin at the first interim examination and has about 11000 MTd/MTM less burnup than P-23A-13.

These fuel pins (except for those in WSA 3) were built according to the same standards and specifications as apply to the FFTF fuel pins. WSA 3 fuel pins were built to the Westinghouse commercial standards which are essentially equivalent to the applicable RDT standards.

The fuel pin power, burnup, and temperature are consistent with the calculational scheme used in the SIEX computer code[2]. Plots of the temperature and power histories are shown in Figures 2 through 17.

IV. RESULTS OF DESIGN ANALYSIS

Table III shows the results of using the design procedure on the peak temperature pin in each subassembly. The pins are grouped according to cladding temperature in order to show the effect of temperature on fuel pin performance.

Those pins operating with peak cladding temperatures above 1200°F have design lifetimes less than 80,000 MWd/MTM. The design procedure is indicated to be conservative because the actual lifetime is greater than the design lifetime. Correspondingly, the CALCULATED thermal creep strain at end of life is more than an order of magnitude greater than the design criterion value of 0.2%. For example, P-23A-3, with a design lifetime of 39200 MWd/MTM, has attained a burnup of 57,500 MWd/MTM and a calculated thermal creep strain of 4.6%. It is important to realize that this calculated value of "strain" is not a measurable quantity. It is a result of a design procedure which includes several conservative assumptions regarding material properties. Therefore, the actual thermal creep strain is something less, and may be very much less, than this value calculated by the design procedure. In contrast, for fuel pins operating with peak cladding temperatures below 1200°F, the design life of 80,000 is reached long before a calculated thermal creep strain of 0.2%.

The subassemblies with cladding wear present a special problem in this analysis. These fuel pins were designed to fit loosely in the subassembly

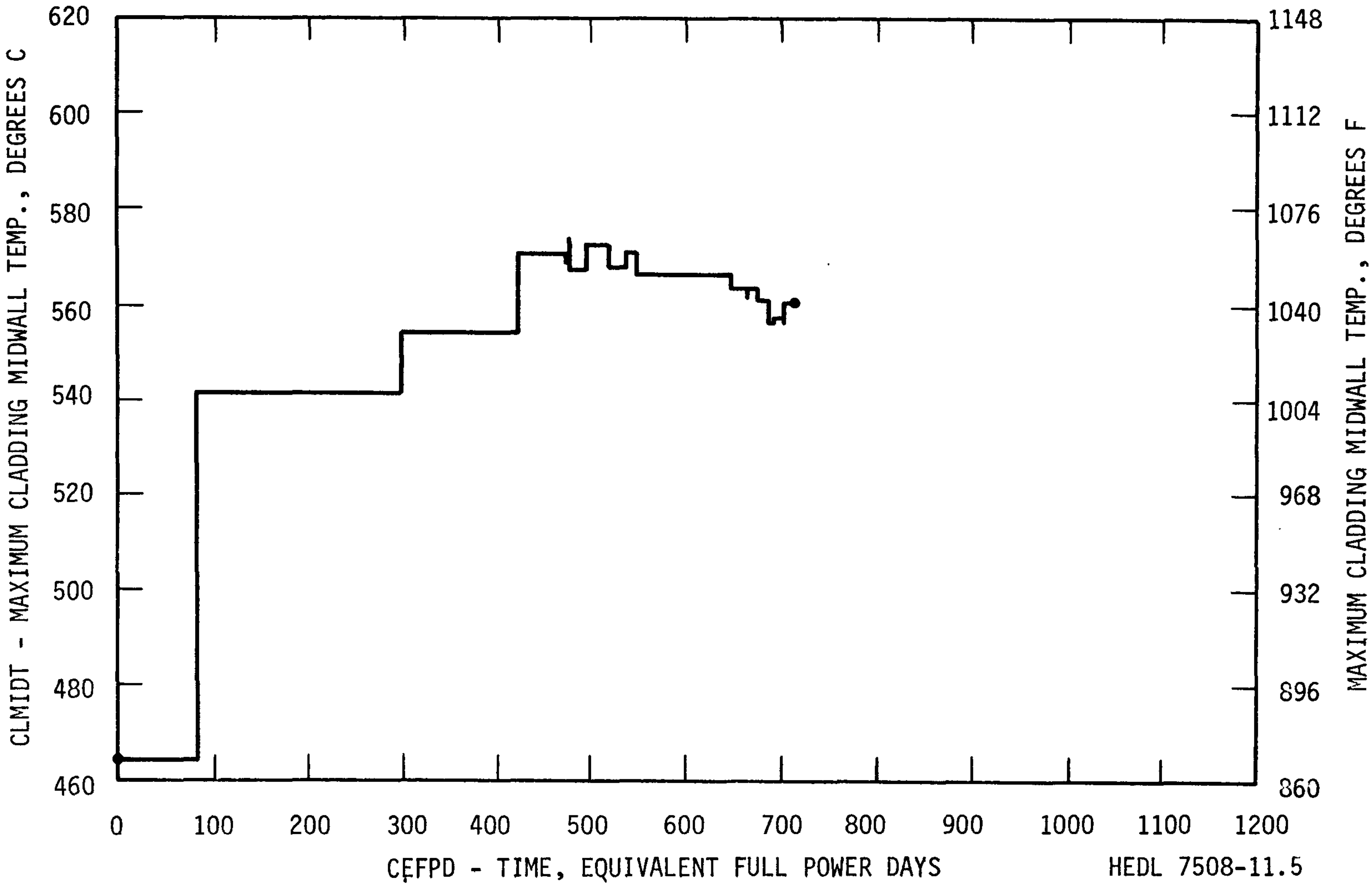

FIGURE 2. Cladding Temperature PNL 9-39.

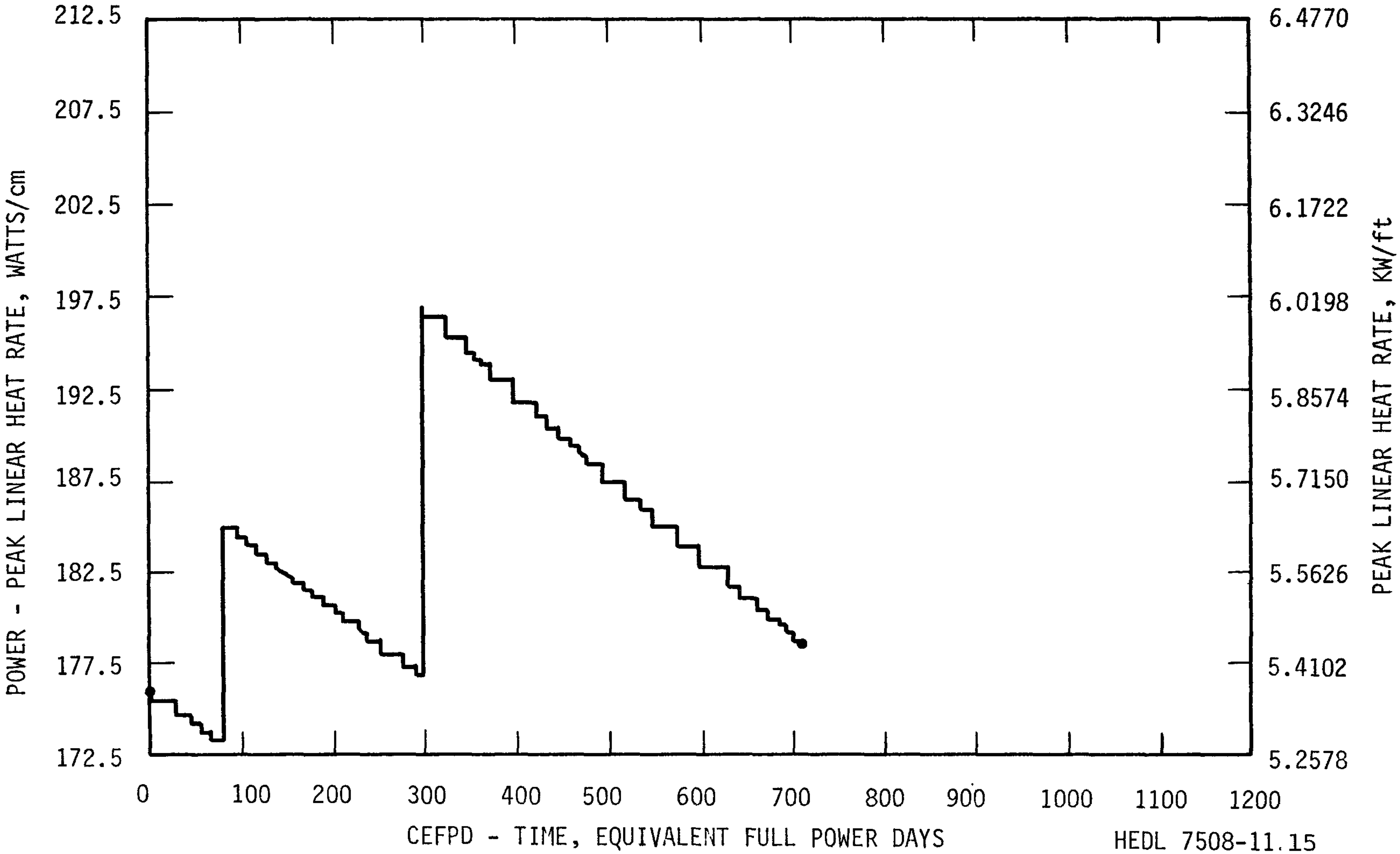

FIGURE 3. Pin Power PNL 9-39.

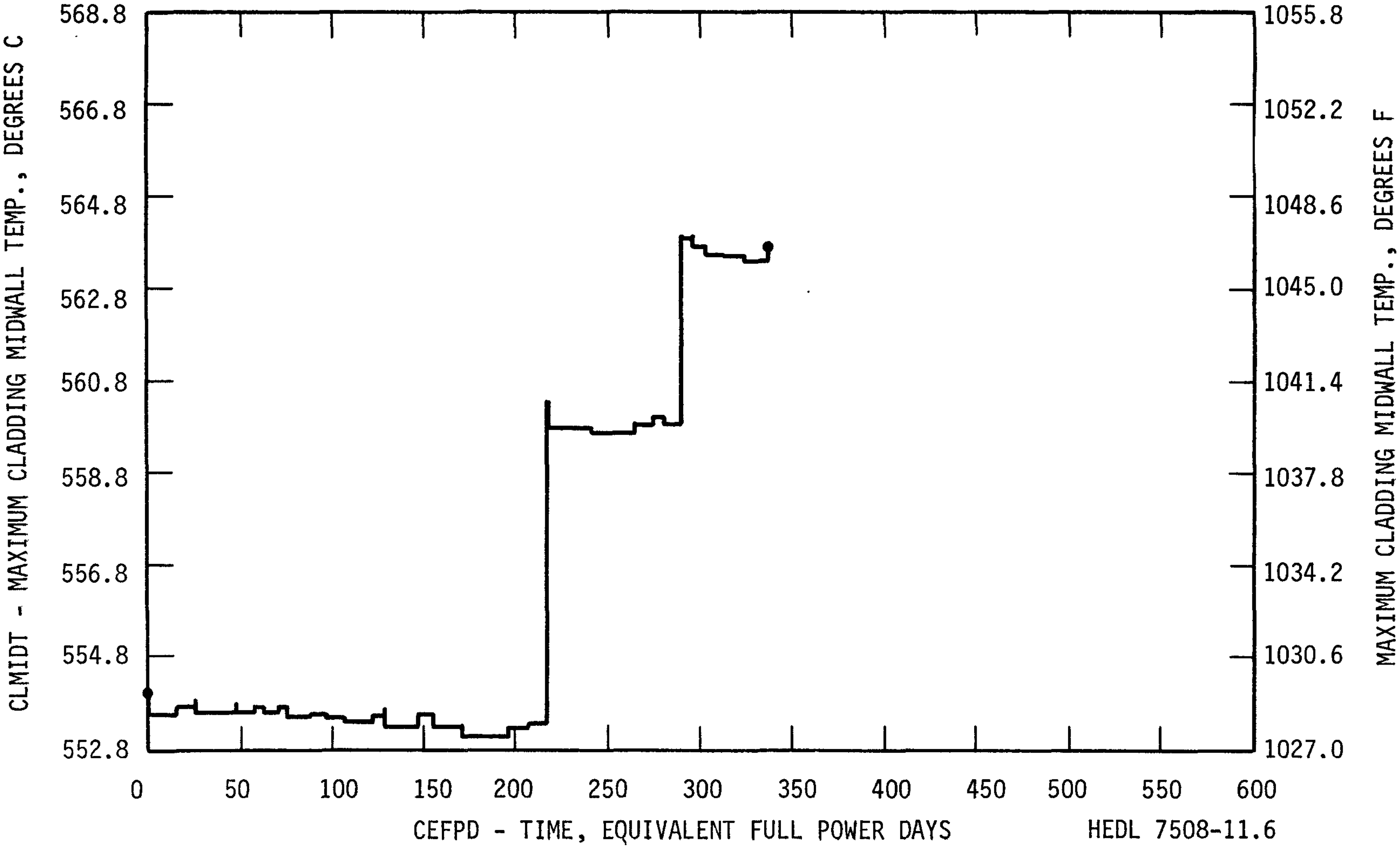

FIGURE 4. Cladding Temperature PNL 10-66.

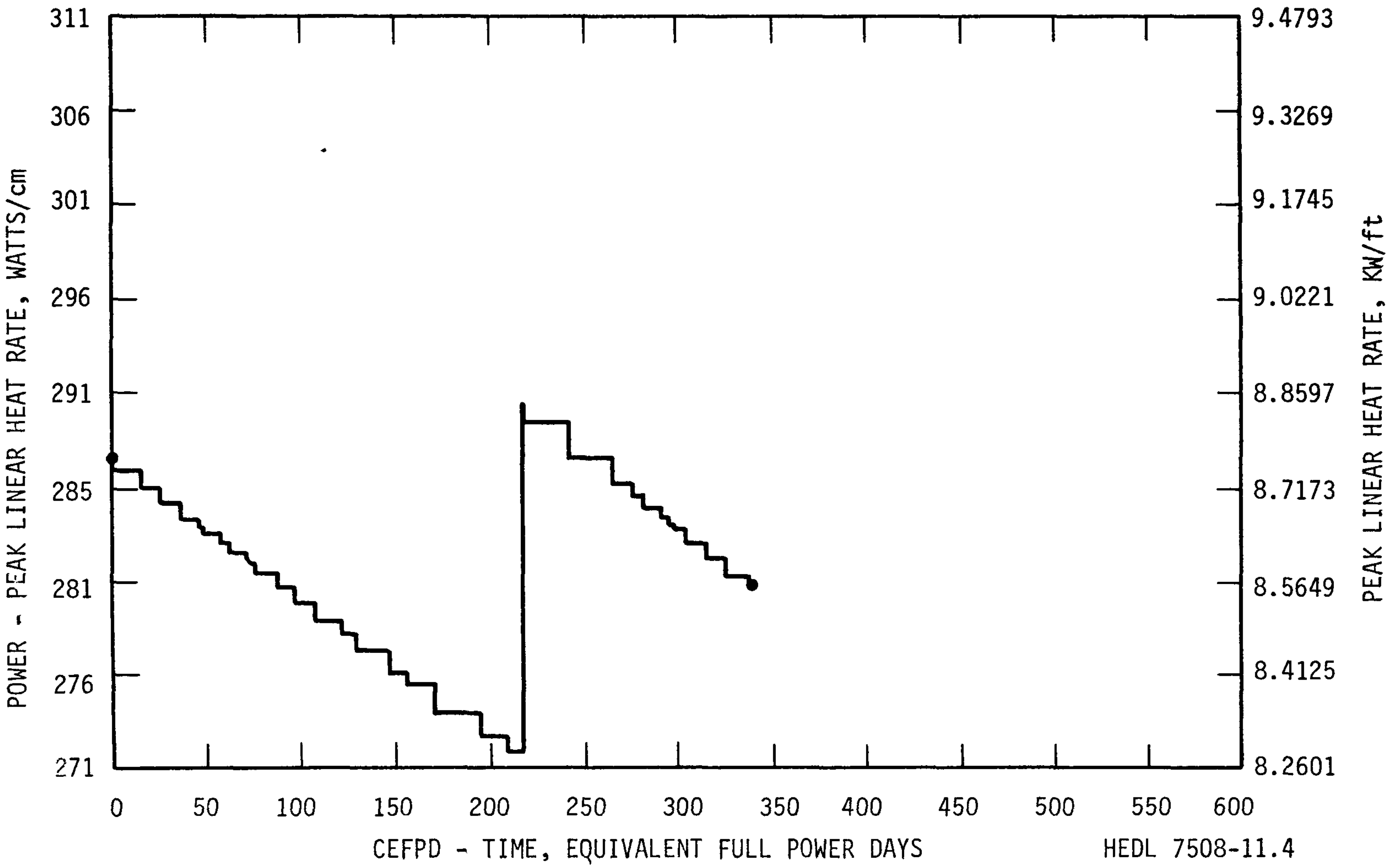

FIGURE 5. Pin Power PNL 10-66.

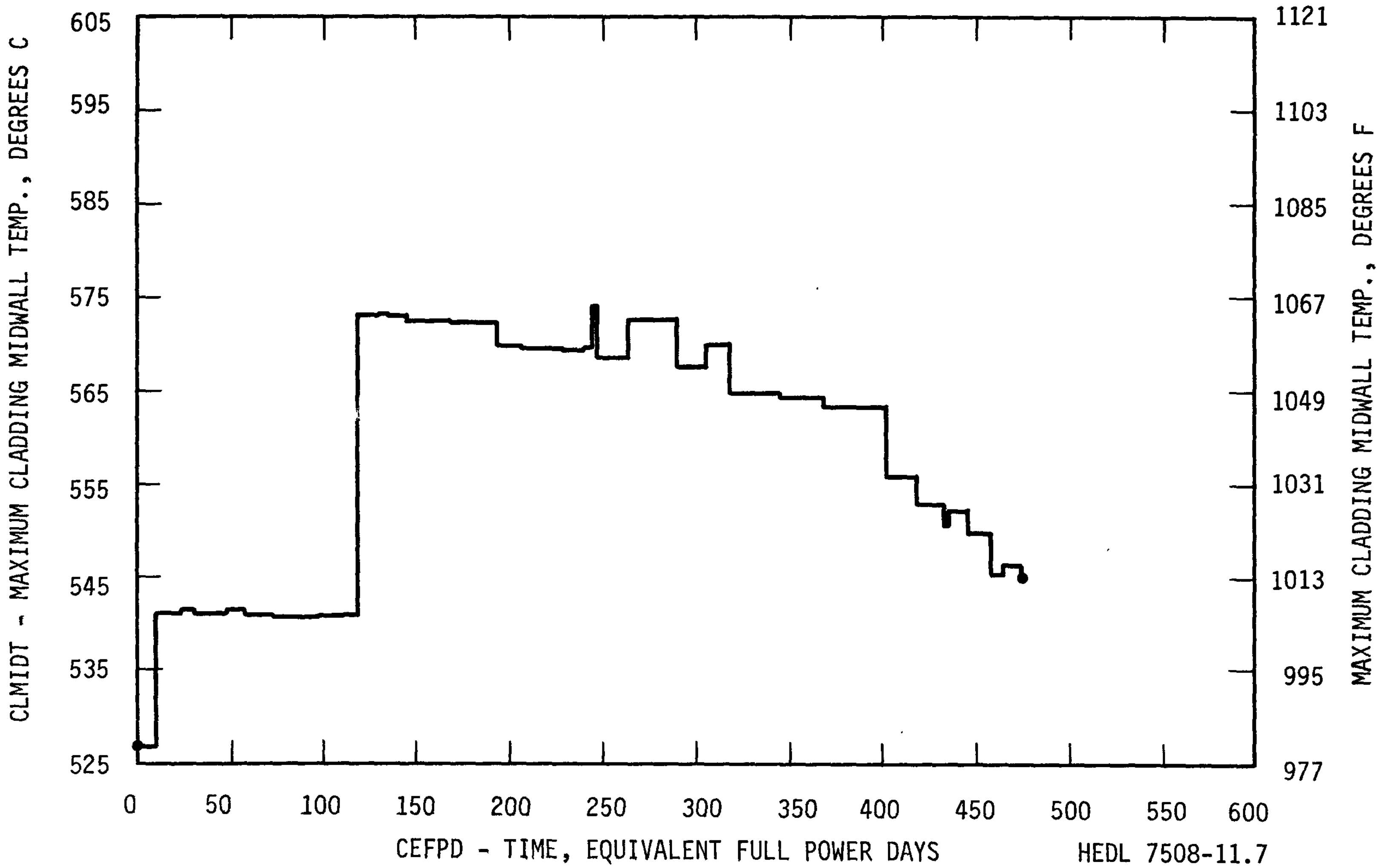

FIGURE 6. Cladding Temperature PNL 11-71.

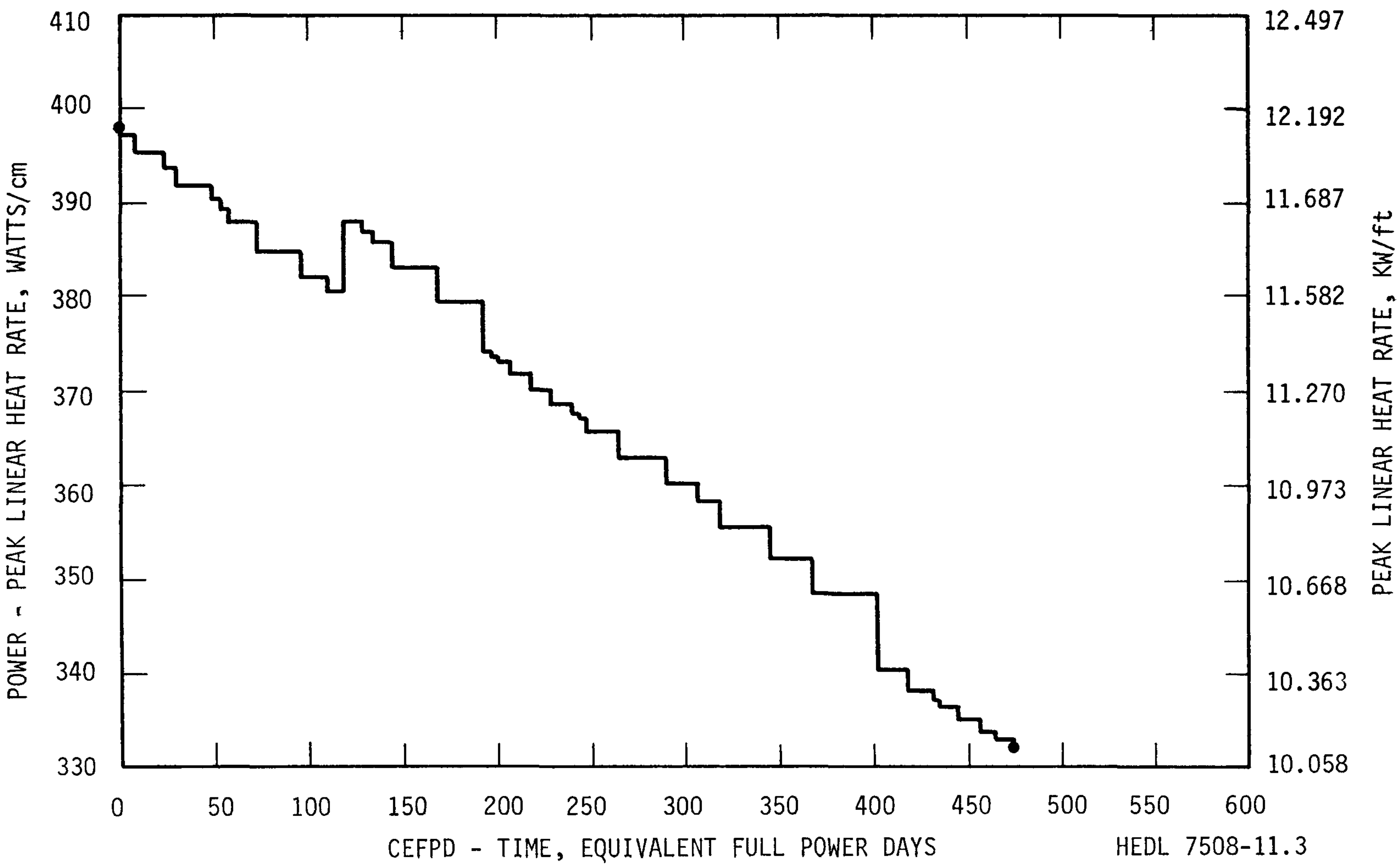

FIGURE 7. Pin Power PNL 11-71.

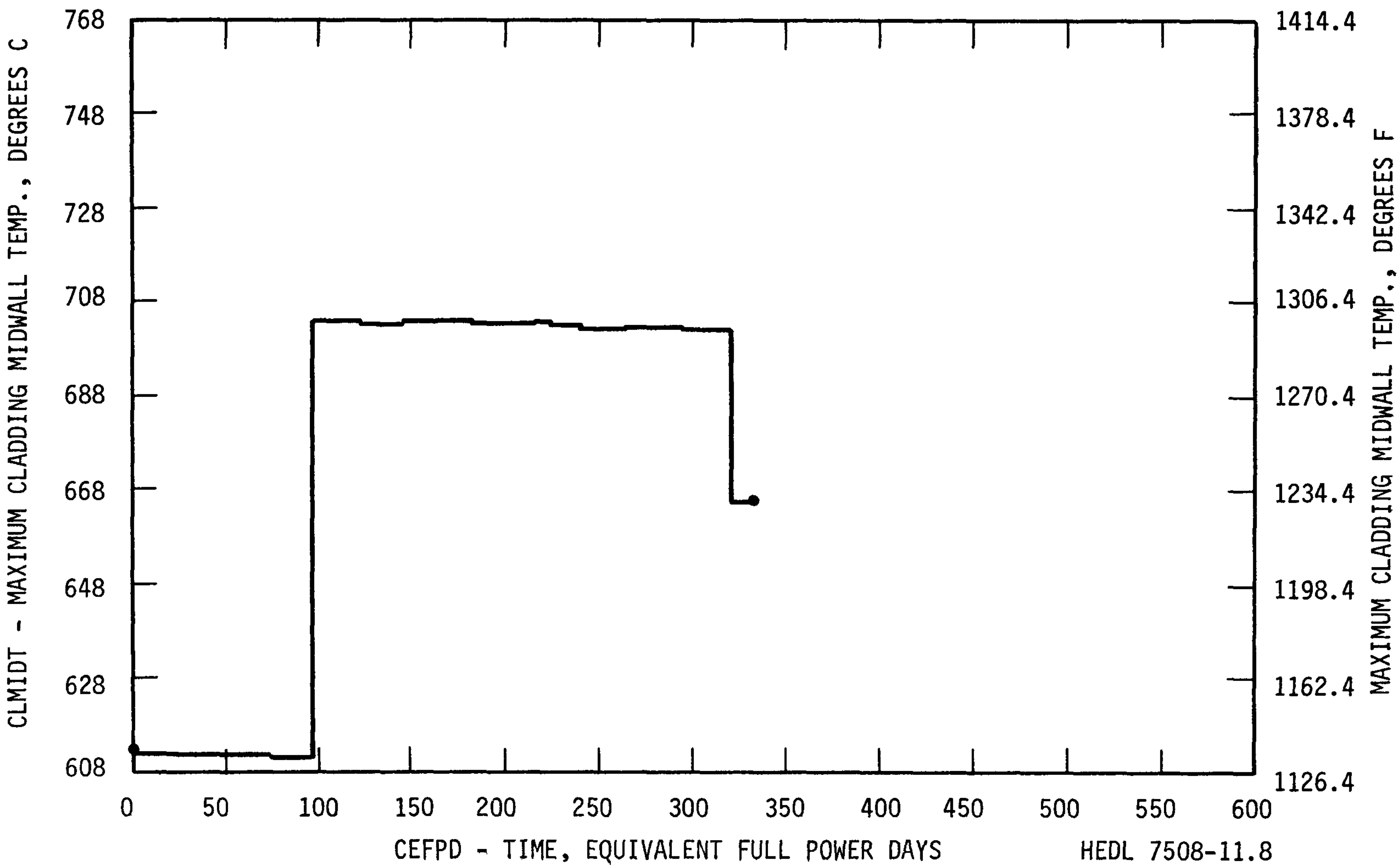

FIGURE 8. Cladding Temperature P-12A-1A.

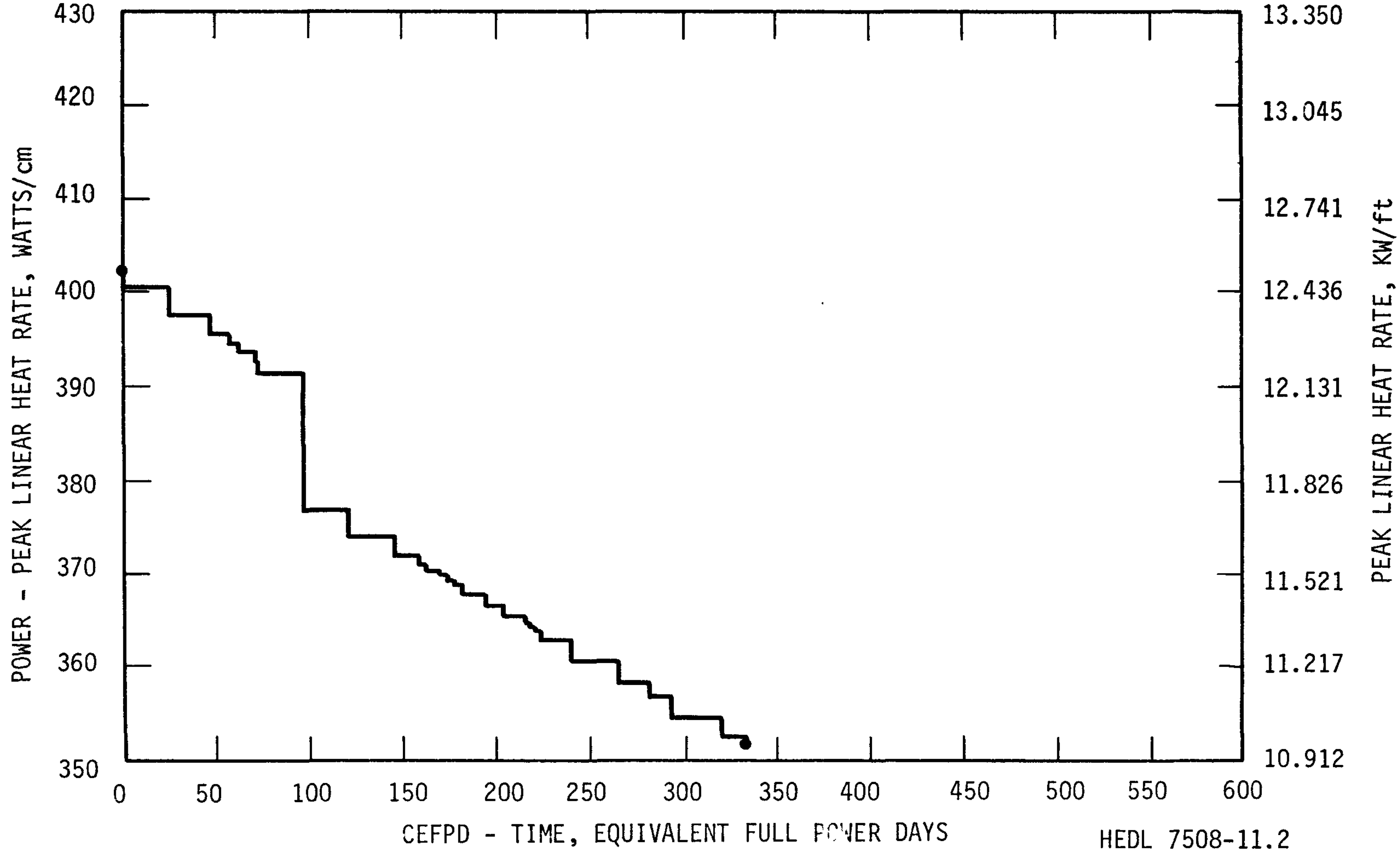

FIGURE 9. Pin Power P-12A-1A .

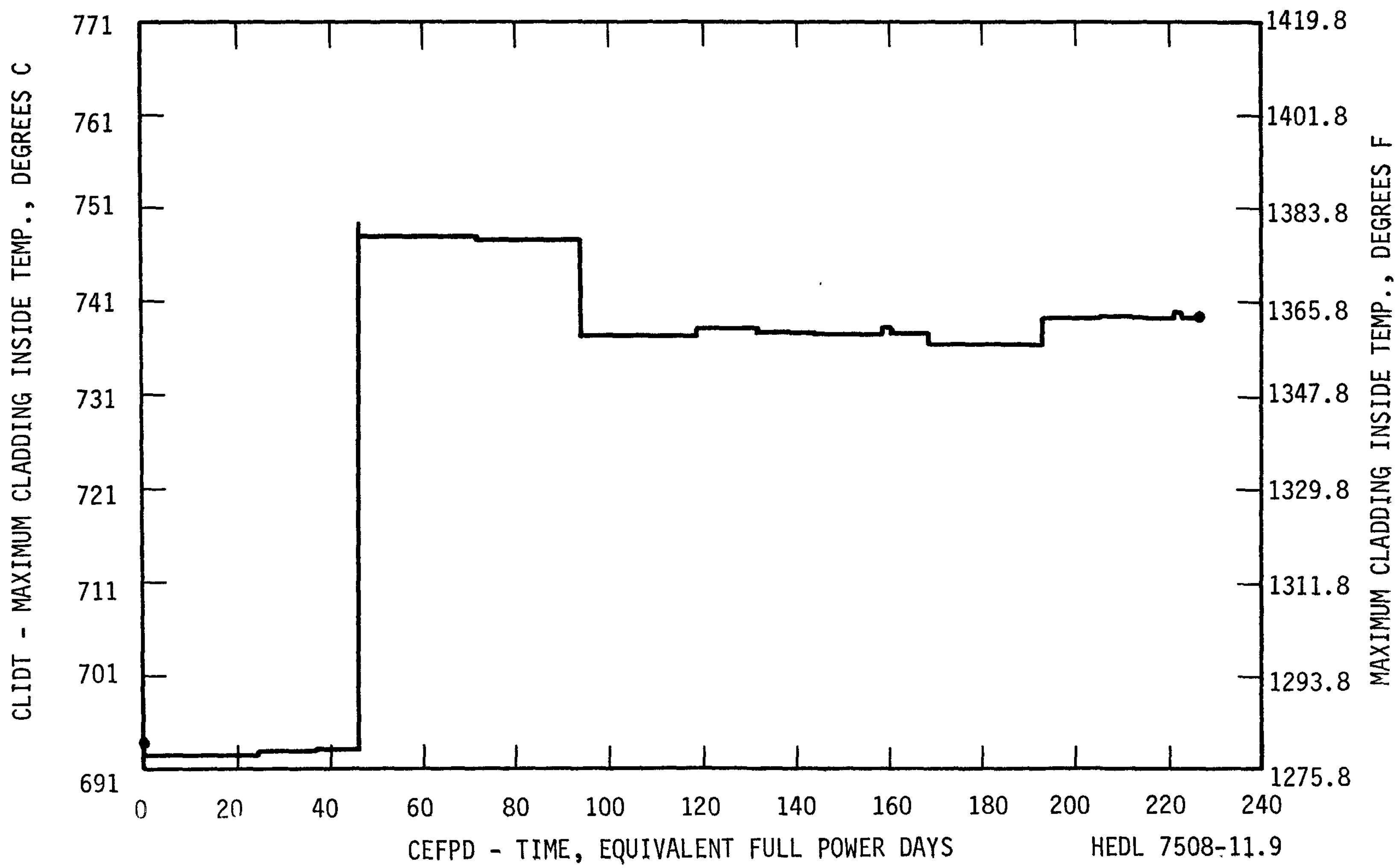

FIGURE 10. Cladding Temperature P-23A-13.

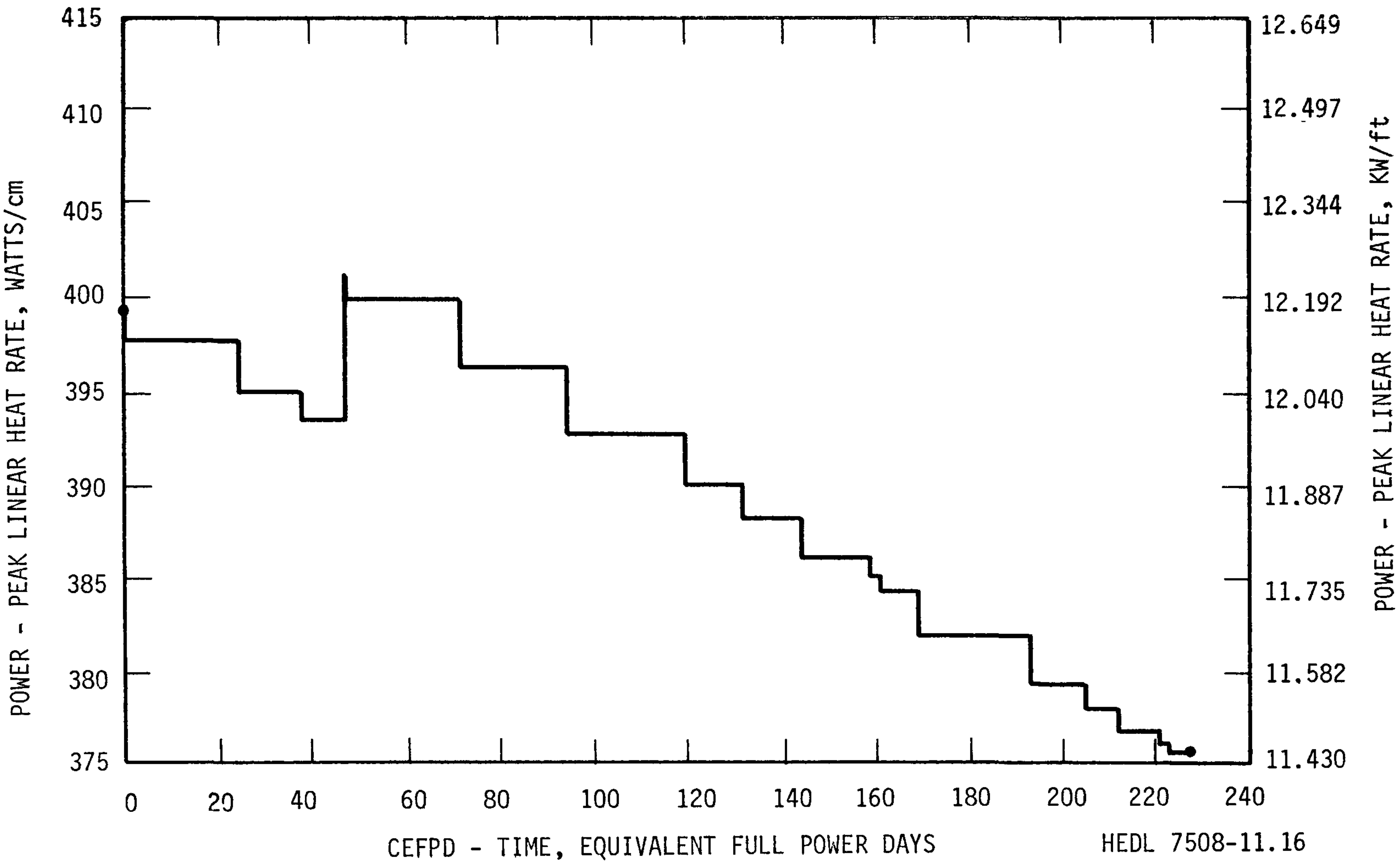

FIGURE 11. Pin Power P-23A-13.

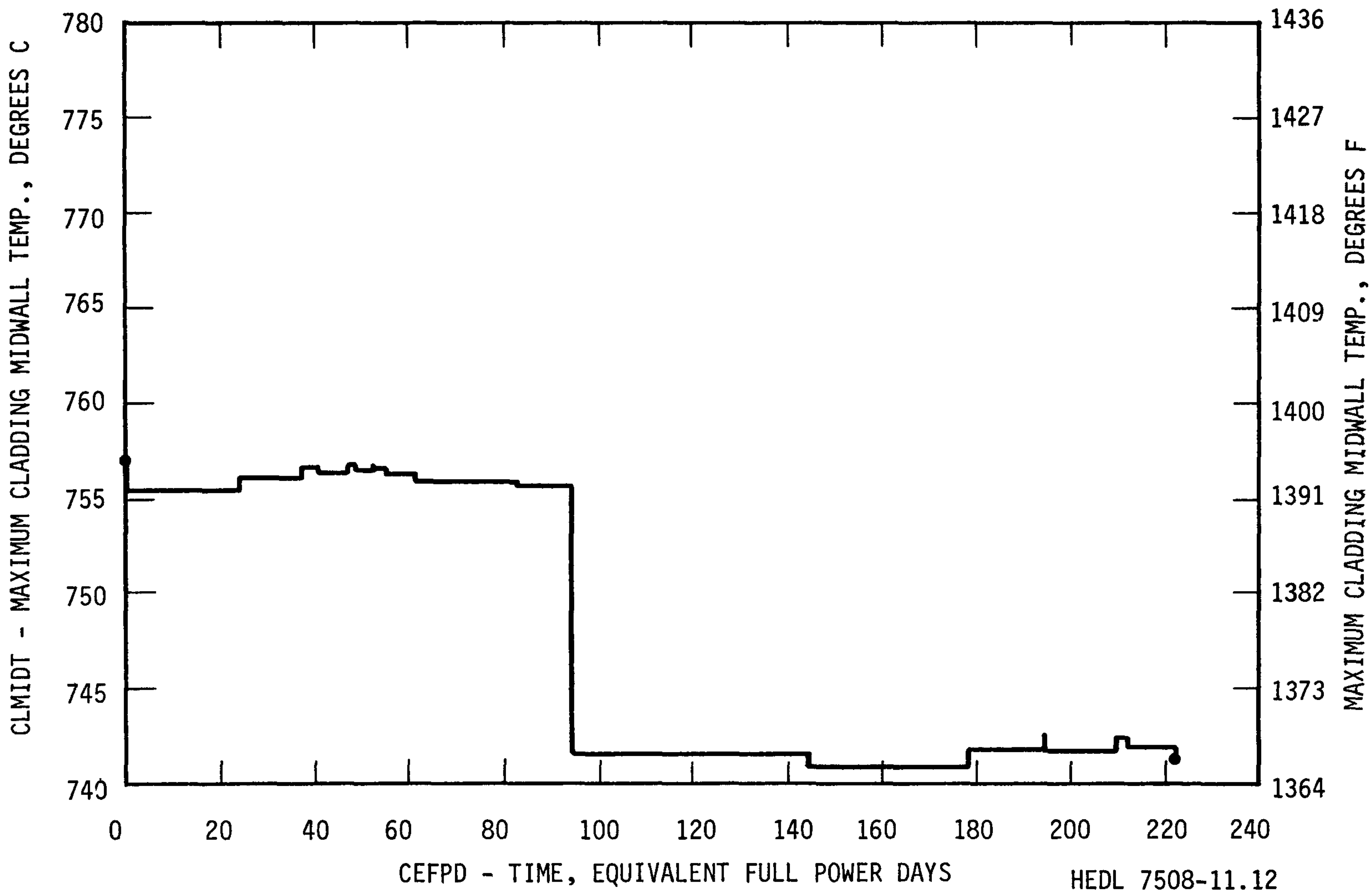

FIGURE 12. Cladding Temperature P-23B-9A.

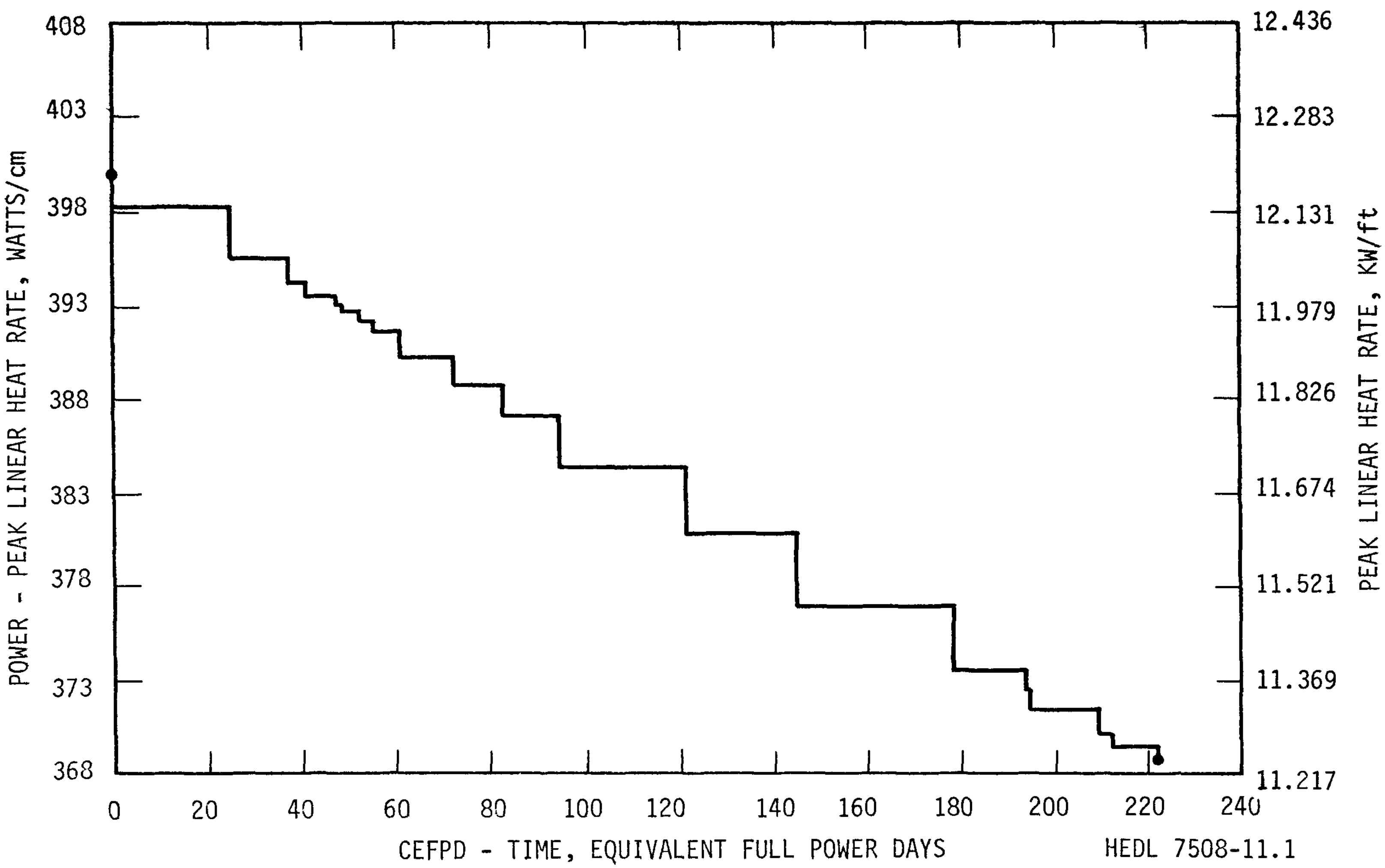

FIGURE 13. Pin Power P-23B-9A.

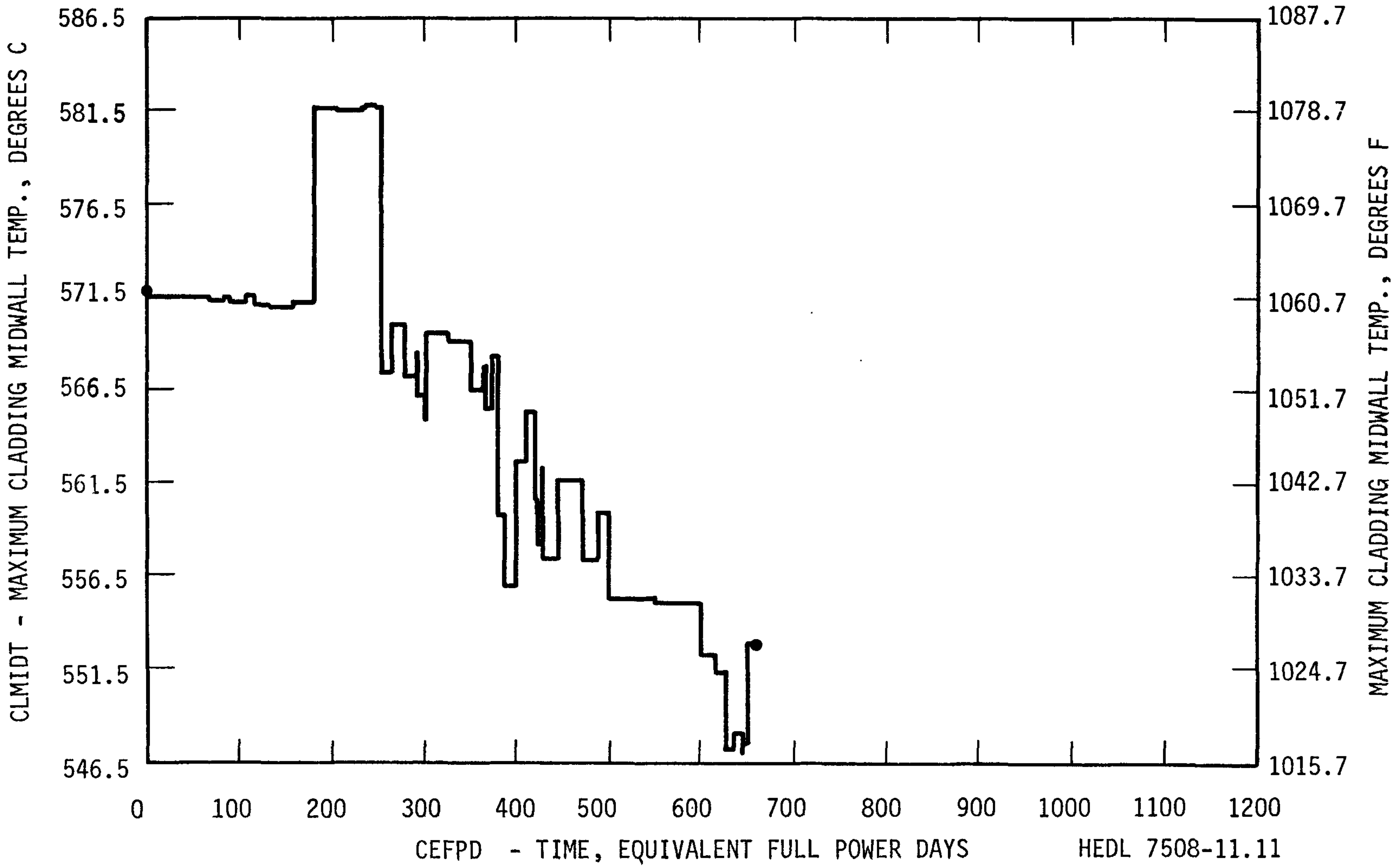

FIGURE 16. Cladding Temperature, WSA3-19.

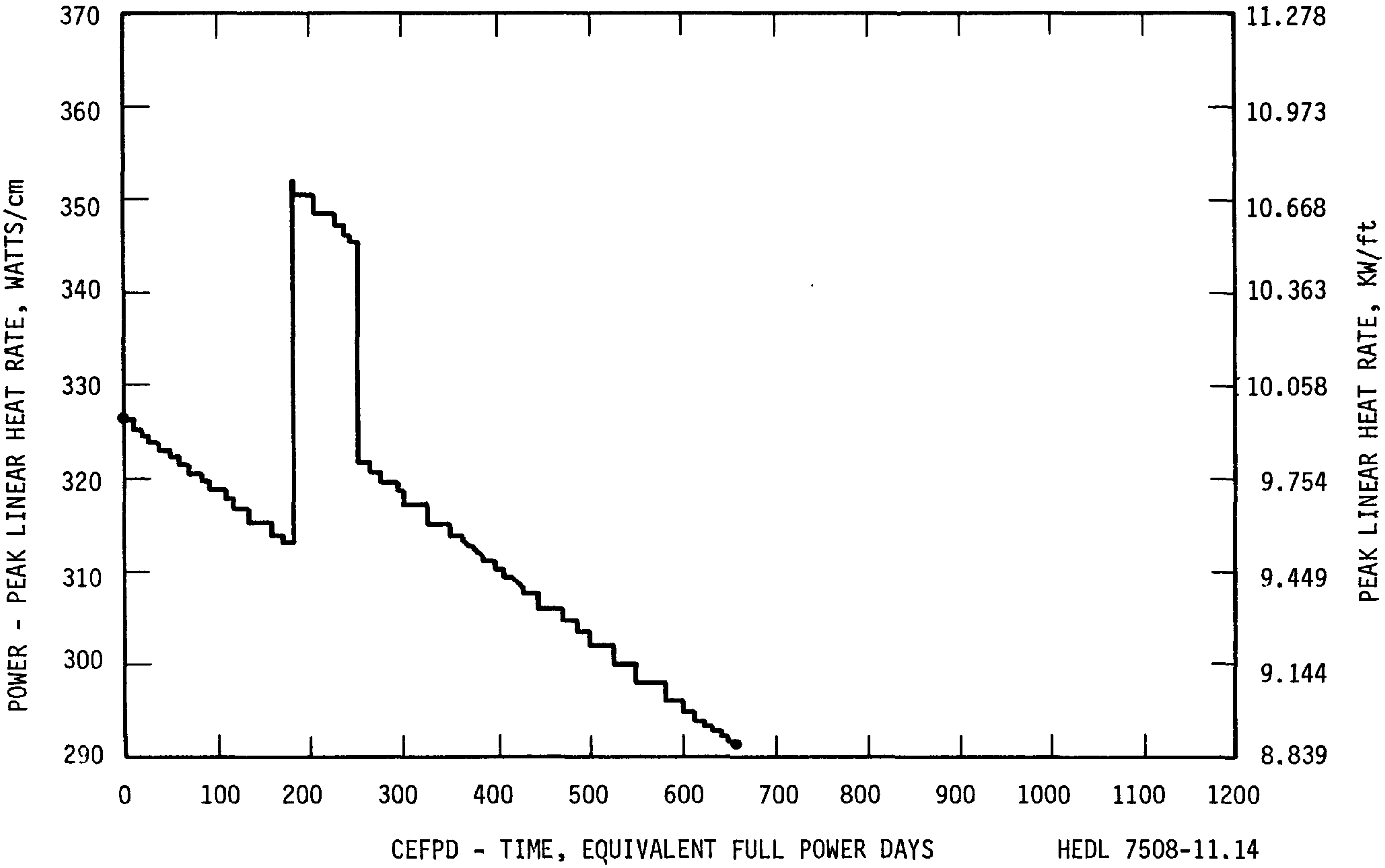

FIGURE 17. Pin Power WSA3-19.

TABLE III

RESULTS OF ANALYSIS USING FFTF DESIGN PROCEDURE

SUBASSEMBLY IDENTIFICATION	PEAK ID CLADDING TEMPERATURE AT END OF LIFE °F	BURNUP ATTAINED MWd/MTM	DESIGN ALLOWABLE LIFETIME MWd/MTM	RATIO OF BURNUP ATTAINED TO DESIGN LIFETIME	CALCULATED THERMAL CREEP %	STATUS
			CLADDING TEMPERATURE ABOVE 1200°F			
P12A	1260	79,200	49,500	1.6	4.8	Failed Pin
P23A	1383	57,500	39,200	1.5	4.6	Continuing
P23B	1391	53,200	35,200	1.5	3.3	Failed Pin
			CLADDING TEMPERATURE BELOW 1200°F			
WSA 3	1052	122,400	80,000	1.5	.059	Completed
PNL 9*	1055	83,400	80,000	1.0	.16	Continuing
PNL 10*	1070	61,100	80,000	.8	.0001	Failed Pin
PNL 11*	1039	110,900	80,000	1.4	.02	Failed Pin
NUMEC E/F*	1085	52,200	80,000	.7	1×10^{-5}	Failed Pin

*Subassemblies With Cladding Wear

with fuel bundle porosities approximately three times greater than current designs in order to accommodate greater expected cladding swelling than actually occurred. The looseness of the bundles resulted in nonprototypic cladding wear on these pins. Some of these pins failed prematurely. However, there is no indication that thermal creep strain was a factor in this premature failure. For example, PNL 11 attained a peak burnup of 110,900 MWd/MTM while PNL 10 failed at 61,100 MWd/MTM. The cause of the premature failures in these pins is not known at this time. Postirradiation examination of the failed pins is underway to determine cause of failure.

V. CONCLUSIONS

From this study, consisting of analyzing fuel pins irradiated in EBR-II through January 1975, use of the FFTF design procedure including a .2% thermal creep strain limit is shown to predict a conservative design lifetime.

VI. REFERENCES

1. FCF 213, "FFTF Fuel pin Final Design Support Document," December 10, 1971. (Updated via FCF 272. February 28, 1972).

2. D. S. Dutt and R. B. Baker "SIEX: A Correlated Code for the Prediction of Liquid Metal Fast Breeder Reactor (LMFBR) Fuel Thermal Performance." HEDL TME-75-55.

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