UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

JUN 2 0 1979

MEMORANDUM FOR: File

FROM: M. L. Picklesimer
Fuel Behavior Research Branch

M L Picklesimer
June 20, 1979

SUBJECT: BOUNDING ESTIMATES OF DAMAGE TO ZIRCALOY FUEL ROD CLADDING IN THE TMI-2 CORE AT THREE HOURS AFTER THE START OF THE ACCIDENT, MARCH 28, 1979

SUMMARY AND CONCLUSIONS

A set of simplified bounding calculations have been made in an attempt to set upper and lower limits on the damage produced in the TMI-2 core through the first three hours of the accident on March 28, 1979. The calculations use simplifying assumptions such as (1) the heat capacity of the fuel rod is constant with temperature, (2) the axial power profile in the assemblies is cosine, (3) the heat lost to the steam and surroundings is a constant fraction of the power developed in the rod by both decay heat and oxidation of the cladding, and (4) the core is uncovered at a constant rate. Also, it was assumed that the heat-up of the core was terminated at 50 minutes after the top was first uncovered by two-phase and slug flow of coolant from reflooding water. Radial and axial profiles of damage in the core were estimated from the calculations.

It is concluded that the maximum damage likely in the core was:

(a) All fuel rods burst with elevations ranging from about one foot from the top of the core in the center assembly to about three feet down in some of the peripheral assemblies.

(b) The total amount of Zircaloy reacted in the first three hours to produce hydrogen was "guestimated" to be between 25% and 30% of all Zircaloy in the core.

(c) Embrittlement of cladding by oxidation occurred to a depth of between 6 and 7 feet from the top of the core in the center assembly, down to about 5 feet to 6 feet in most of the assemblies, and did not occur on the lowest power corner assemblies on the periphery.

(d) A liquid phase was formed between molten Zr + ZrO_2 eutectic and the outer part of the UO_2 fuel pellets next to the cladding at depths from the top of the core down to 5 to 6 feet in most assemblies and between 6 and 7 feet in the center assembly. It did not form in the corner assemblies.

(f) No significant oxidation of cladding occurred in the bottom five feet of the core at any radial position.

It was concluded that the minimum damage that could have been produced was:

(a) All fuel rods burst, with burst ranging from 1 foot from the top of the core in the center assembly to about 3 feet from the top in peripheral corner assemblies.

(b) Embrittlement of cladding due to oxidation occurred to a depth of 6 feet from the top of the core in the center assembly, to 5 feet in most of the assemblies, and did not occur in the peripheral corner assemblies. Also, the top 1 to 2 feet of many of the outer assemblies was not oxidized to the embrittlement stage.

(c) None of the assemblies was oxidized significantly at depths below 6 feet from the top of the core.

(d) A liquid phase between molten Zr + ZrO_2 eutectic and the outer part of UO_2 fuel pellets was formed only in the center assembly and down to a depth of about 4 feet.

In view of the simplifications imposed to allow calculations to be made, and the assumptions required to establish a "scenario" of events from the quite limited data available it is concluded that the more realistic estimate of damage lies near the upper bound described by the "minimum" and "maximum" plots of core damage. The "realistic" estimate of core damage allows explanation of most of the reported observations of fission product emission, hydrogen generation, high temperatures in the core, etc., with the exception of the survival of the thermocouples that passed through the hot core to the upper end fitting of many of the assemblies.

The calculational procedures and many of the graphical plots can be used to improve the bounding estimates as new data are received and correlated to establish a better sequence of the events that actually occurred in the system.

INTRODUCTION

The data on the Three Mile Island, Plant No. 2 (TMI-2) accident on March 28, 1979 available to the Fuel Behavior Research Branch (FBRB), RES/NRC by about April 20, 1979 was examimed and discussed amongst the several members of the FBRB in an attempt to establish a "scenario" of events transpiring in the first three hours of the accident. Because the limited data available made difficult the establishment of a scenario that could provide a sound basis for calculations, the author decided to attempt a set of simplified, bounding calculations of damage to the core that could be modified relatively easily to produce better estimates and bounds for the extent of damage as new data or interpretations were developed.

A simple scenario was developed to have the following features: (a) although the coolant in the core was probably a two-phase mixture of flowing water and steam at the time, the core was adequately cooled and was not uncovered at any position until after the second set of primary coolant pumps were turned off at 100 minutes after turbine trip, (b) the top of the core was exposed (i.e., above the liquid coolant level) within a few minutes afterwards, (c) the water level in the core decreased at a constant rate of 12 feet per hour after the top was uncovered, (d) no position on a fuel rod could begin heating up above saturation temperature (T_{sat}) until it has been exposed by the dropping water level in the core, (e) the decay heat in a fuel rod at any level was a fraction (to be chosen as a parameter) of the operating power at that position in the specific assembly at the start of the accident (i.e., a function of the radial and axial power profiles in the core), (f) although known to be an approximation, such variables as heat capacities, steam flow rates, heat generation rates by oxidation, etc., would be taken as constant with temperature or time, or were approximated by linear interpolation over small temperature or time increments, and (g) the minimum damage would be determined by using only decay heat as the heat source while the maximum would be approximated by including an estimate of the heat generated by oxidation that would be made always on the high side of any interpolation.

ASSUMPTIONS

The following assumptions have been made to allow simplified calculations to be made, even though several are known to be in error by as much as 10-15%, and others are not adequately supported by data or other information from the plant. Improvements can be made when justified by additional data or a need for better estimates of the damage to the core.

1. The voiding of the water in the immediate volume of the core started at or "very shortly" after the shut-down of the second set of primary coolant pumps at 100 minutes into the accident.

2. The voiding of the water in the core ended during the rapid repressurization of the primary system shortly after 2.3 hours into the accident, and refill-reflood of the core began.

3. The level of coolant in the core decreased linearly with time after the top was first uncovered, at a rate of 12 feet per hour.

4. The heat capacities of UO_2 and Zircaloy are approximately constant with temperature (they increase by 10-15% with increasing temperature, and phase changes are ignored).

5. Since the heat losses from the fuel rods to steam and to the neighboring control, poison, axial power shaping, and instrumentation rods/tubes can not be estimated with any precision, the losses can be approximated by setting them equal to some arbitrary fraction of the heat developed in or by the fuel rod after the water level has fallen below the specific elevation of the calculation. For the first estimation of damage, the fraction chosen is 25%.

6. The total power peaking factor map of the core is the same as that reported for Rancho Seco (1/29/75) and shown in Figure 1. The axial power peaking factor is assumed to be 1.3 and the axial power profile to be cosine.

7. The heat generated by steam oxidation of the Zircaloy cladding can be calculated using the Cathcart-Pawel rate equations,(1,2) the oxidation is one-sided, and the oxidation heat and amount can be calculated by linear ramps over 100°F increments, using linear heating ramp calculations developed with the BUILD-5 code.

8. The decay heat in the middle of the period of calculations is 1% of the power developed at the start of the accident.

9. Oxidation of the Zircaloy fuel rod locally by steam stops when the molten α-Zr + ZrO_2 eutectic reacts with the UO_2 fuel(3) to produce a liquid phase at about 3480°F. The oxidation of the zirconium metal contained in the liquid phase continues, but it no longer contributes heat to raise the temperature of the rod at the spot where it had been before it melted.

10. Embrittlement of the Zircaloy cladding to thermal shock (quenching) by oxidation can be predicted for one-sided oxidation from the studies of Kassner and Chung (ANL)(4,5) for embrittlement by two-sided oxidation. They found that embrittlement was present if the beta phase contained 0.9-1.0 weight precent oxygen or was less than about 0.004 inches thick. The code (BUILD-5) developed by Pawel(6) was used by Marino(7) to calculate the oxygen distribution and content in the beta phase for linear temperature ramps at rates encompassing the ones predicted for several positions in the TMI-2 core. The temperature determined for the embrittlement conditions ranged between about 2500 and 2600°F depending on the ramp rate. The lower temperature, 2500°F was chosen.

11. The burst temperature for the fuel rods can be estimated from the pressure-burst temperature data of Chapman (MRBT, ORNL),(8) a temperature ramp rate of about 1°F per second, and a knowledge of the cold fill pressure for the rods of 445psi. Calculations show that if the pressure drop across the cladding is 400psi, the fuel rod will burst when it reaches a temperature between 1450 and 1500°F. If it is 500psi, the burst temperature is between 1400 and 1450°F.

CALCULATIONS

The details of the procedures used in the calculations are given in the attached appendix. The formulations and results are given below.

1. Heat capacity of the fuel rod:

$$\Delta H_{UO_2} = 30.42 \times 10^{-4}\text{ Btu/inch of rod/°F}$$

$$\Delta H_{Zr} = 6.24 \times 10^{-4}\text{ Btu/inch of rod/°F}$$

$$\Delta H_{rod} = 36.66 \times 10^{-4}\text{ Btu/inch of rod/°F}$$

2. The axial power profile, $P(z)$, in the fuel rod is calculated by the equation(9);

$$P(z) = [\frac{B + A\cos(\pi z/2L)}{B + 2A/\pi}]\,P_{avg} \quad ; A, B = \text{constants related to the power levels in the core}$$

$$P_{max} = A + B,\ P_{avg} = B + 2A/\pi \quad ; \frac{P_{max}}{P_{avg}} = \text{axial peaking factor}$$

$$P_{avg}\ (rod) = [\frac{\text{total peaking factor (rod)}}{\text{axial peaking factor (rod)}}]\,P_{avg}\ (core)$$

then for axial peaking factor = 1.3, and $P_{avg\ core}$ = 6.0 kw/ft,

$$P(z) = [\frac{0.5746 + \cos(\pi z/2L)}{0.5746 + 2/\pi}]P_{avg} = [0.4744 + 0.8256\cos(\pi z/2L)]\,P_{avg}$$

3. $T(z) = T_{sat} + \Delta T$

for decay heat only, $\Delta T = [\frac{D.H.(\Delta t)\ (1-hlf)}{\Delta H_{rod}}]$

for decay heat plus oxidation heating,

and $T(z) \leq 1500°F$, $T(z) = T_{sat} + \Delta T$, $\Delta T = \frac{D.\ H.\ (\Delta t)\ (1-hlf)}{\Delta H_{rod}}$

and $T(z) > 1500°F$, $T(z,i) = T_{(z,i-1)} + 100$

$$t_{(z,i)} = t_{(z,i-1)} + \Delta t'\ ,\ \Delta t' = \frac{100}{(1-hlf)\ [\frac{D.H.+O.H.}{\Delta H_{rod}}]}$$

and the time increment, $\Delta t'$, is calculated for the time required to heat 100°F above the last $T(z)$ for all temperatures above 1600°F with the value of oxidation heat (O.H.) appropriate for $T(z)$

where $T(z)$ = temperature of rod at elevation z

T_{sat} saturation temperature at time of uncovering by coolant

ΔT = temperature increase durine time increment Δt

Δt = time of calculation from start of core uncovering minus time of uncovering at elevation z

$\Delta t'$ = time required to heat from $T_{(z,i-1)}$ to $T(z)$ with oxidation

D.H. = decay heat

hlf = heat loss fraction

O.H. = oxidation heat

ΔH_{rod} = heat capacity of fuel rod

4. Axial power profiles are shown in Figure 2 for total peaking factors of 1.9, 1.6, 1.3, 1.19, and 0.66, values representative of several areas in the core.

RESULTS

Time-temperature curves for the fuel rod cladding are shown in Figures 3-7 for total peaking factors from 1.9 to 0.66 and a heat loss factor of 25% to steam and non-fueled structures as functions of distance from the top of the core as the core was uncovered at a constant rate of 12 feet per hour. The straight lines are for heating by decay heat only, and the curved lines are for heating by both decay heat and by oxidation of the cladding. The latter allows for the increase of oxide thickness with both time and temperature. The details of the calculations are given in Table A-I of the Appendix.

Radial and axial core maps of damage to fuel rod cladding are shown in Figures 8-11 for the maximum and minimum amounts of damage estimated. The damage is graded into levels of (1) no significant oxidation, (2) significant oxidation but no embrittlement, (3) oxidation embrittlement of the cladding to thermal shock such as produced by reflooding coolant, (4) burst location, and (5) formation of liquid phase by reaction of the molten Zr + ZrO_2 eutectic with the outer surfaces of fuel pellets.

The curves of Figures 3-7 are read by starting at the time of uncovery for a given level from the top of the core and following it upwards. At 1600°F the choice must be made between inclusion or exclusion of the heat of oxidation. In Figure 3 (total peaking factor 1.9), the curves plotted show that the fuel rods in the center assembly at the one foot level reached the burst temperature range of 1400-1500°F first, and the rods burst at that level at 18-20 minutes after the top of the core was first uncovered. If only decay heat is included in the calculation (straight lines), the fuel rods reached the Zr + ZrO_2 eutectic temperature of about 3480°F first at the 3 foot level, followed within 1-2 minutes by the 2 and 4 foot levels. However, if oxidation heat is included (maximum damage, curved lines), then this temperature was first reached at the 1 and 2 foot levels essentially simultaneously and the 3 foot level did not reach that temperature until about two minutes later. The German core melt work of Hagan(3) has shown that the eutectic liquid immediately reacts with the UO_2 fuel to form a lower melting liquid phase. The liquid formed flows down from the region of formation, and oxidation of the cladding no longer occurs at that specific elevation. The heatup at that point then continues only by decay heat. No allowance has been made in the plots for the decrease in decay heat generation caused by the loss of fuel at that position.

The plots then show that by the maximum damage estimate for the assembly having a total peaking factor (tpf) of 1.9 the rods burst at 18-20 minutes after core uncovery started at the 1 foot level, and reached the eutectic reaction temperature after 34 minutes at both the 1 and 2 foot levels, followed by the 3 foot level at 36 minutes the 4 foot at 39-40 minutes, the top of the core (0 foot) at 41 minutes, the 5 foot at 43 minutes, and the 6 foot at 47-1/2 minutes.

If the "turnover" occurred at 50 minutes after the top was uncovered, the rods at the 7 foot level reached a maximum temperature of about 2300°F and were not embrittled by oxidation. The embrittlement boundary was then just above the 7 foot level and below the 6 foot. The lowest level of the eutectic reaction was just above the 6-1/2 foot level. No significant oxidation occurred below the 7-1/2 foot level.

For the minimum damage estimate for this center assembly (tpf = 1.9) the rods burst at the 1 foot level at 18-20 minutes, and only the 2, 3, and 4 foot levels reached the eutectic temperature. All rods were embrittled down to the 6-6-1/2 foot level, and no significant oxidation occurred below the 7-1/4 to 7-1/2 foot level.

The same procedure can be followed for the remaining assemblies in the core, with interpolations being made proportionately to differences between the peaking factor values. These results are presented in Table I as depths of penetration from the top of the core in feet for the several radial peaking factor values used in the damage estimate. These results were then interpolated and plotted in Figures 8-12 as pictographic core maps of the damage.

DISCUSSION

The detailed conclusions drawn from the analysis and the scenario used are somewhat sensitive to the details of the scenario used. However, the general conclusions as to the types of damage present in the core are not. Acceleration of the rate of change of level in the core does not drastically change the types of damage estimated, and preliminary calculations (to be reported in a subsequent, updating Memo to File) indicate that the depth of damage is changed only a little. Extension of the time that upper part of the core is uncovered increases significantly the extent and depth of damage estimated and increased heat losses to steam and other heat sinks decreases or delays the damage estimated.

The calculations are relatively easily repeated or the heat-up curves can simply be moved to different uncovery times as new data or interpretations are obtained to modify the scenario of the events occurring during the time the core was uncovered during the first three hours. A faster rate of uncovery will cause the burst zone to move down the fuel rods, to a lower level, since the higher power regions will overtake the upper, lower powered regions sooner in the time-temperature ramp, and they will reach the critical temperature region of 1400-1500°F first. Increased steam generation and flow will slow the rate of temperature rise by removing more heat from the fuel rod and delay the bursting. An axial power profile different from the cosine shape assumed may cause a faster rate of boil-off and uncovery of the first few feet from the top, which will simultaneously decrease the rate of temperature rise of an assembly and decrease the time to uncovery at any specific level. These are compensating effects, and whether the damage estimate changes will depend on the detailed calculations.

The minimum damage estimated is shown by the time-temperature plots using decay heat only (the straight lines). The maximum damage estimated is shown by the curved lines departing from the decay heat lines at about 1600°F. The actual damage occurring for the scenario used for the plots should lie between the curve (oxidation included) and the straight line (decay heat only) for each core level, since the heat of oxidation has been approximated on the "high side" for the curved line and made zero for the straight line.

An estimate of Zircaloy cladding converted to oxide can be obtained by using a modification of BUILD-5 to extend it to temperatures above its proven validity, making several assumptions as to the effects of phase changes in the oxide and geometry of the specimens on the oxidation rate. This was done by R. E. Pawel (ORNL)(10) at the writer's request and the results transmitted to him. The results obtained for oxide thickness, alpha layer thickness, and total consumed for several different linear ramp rates and sets of assumptions lead to the estimate that the thickness of cladding converted to oxide is, in the first approximation, a function of temperature reached in the ramp, and a function of time to reach that temperature only in the second order of approximation. Thus, the calculations indicate that between 1/4 and 1/5 of the original wall thickness has not been converted to oxide (but to oxygen-stablized alpha phase) at the time the $Zr + ZrO_2$ eutectic temperature has been reached. Further, only 1/6 of the wall thickness has been converted to oxide when embrittlement is reached. From the core maps of damage and Table I, it can be seen that 20 assemblies did not oxidize significantly (peripheral "corner" assemblies), none of the assemblies were oxidized significantly below 6 feet except for the center assembly and then only to 6 3/4 feet, and that significant contributions to the total amount of Zircaloy converted to oxide occurred only between the depths reached for embrittlement and eutectic formation. Thus, only 4 feet of fuel rods in 40 assemblies, 5 1/4 feet in 56 assemblies, 6 feet in 60 assemblies, and 6 1/2 feet in one assembly were oxidized more than 1/6 of the wall thickness to contribute to hydrogen generation. This then leads to the estimate that a maximum of 31% of the Zircaloy in the core assemblies could have been converted to oxide. A similar calculation for the minimum damage estimate leads to the conclusion that at least 10% of the Zircaloy had been converted to oxide. Since it is probable that the "best estimate" of the level of damage is much closer to the maximum estimate, it is concluded that between 25 and 30% of the Zircaloy cladding was converted to oxide in the first three hours of the accident. This compares favorably to the 35-40% conversion estimated by others from the total amount of hydrogen present and burned immediately after the deflagration in the containment vessel at 9.9 hours into the accident. This latter estimate included any oxidation of cladding occurring <u>after</u> three hours.

The time of the initial bursts was estimated to be at 18 to 20 minutes after the top of the core was first uncovered. If core uncovery started at 100 minutes into the accident event, then rod bursting started at 118-120 minutes. If the first two feet of the core were uncovered in three minutes, then rod bursting would have occurred at 115 minutes. The first indication of fission product release at the fuel handling bridge just above the reactor vessel was found on the air sample monitor chart at 115 minutes into the accident.

Estimates made by others(11-14) from the fission product concentration measurements indicate that the fuel pellet temperatures of at least 30% of the fuel had to be greater than 4700°F or greater than 4000°F for significant times (several hours) if the release of fission products as to types and amounts were to be accounted for. The reaction between the αZr + ZrO_2 eutectic liquid and the UO_2 in the outer surface of the fuel pellets to produce another liquid phase containing equal or larger portions of UO_2 could lead to release of a major portion or all of the volatile fission products present in the UO_2 reacted. The Zr-O-UO_2 phase diagram reported by the PNS core melt project at KfK, Karlsruhe, Germany(15) indicates that at 3630°F a liquid phase consisting of approximately equal molar amounts of Zr and UO_2 exists in equilibrium with a solid phase given as $(U, Zr)O_{2=x}$. If the densities of UO_2 and Zr at 2000°C can be assumed to be within 10% or so of their densities at room temperature, then each volume of molten Zr will "melt" or dissolve approximately twice its volume of UO_2. The BUILD-5 calculations referred to earlier(10) indicates that approximately 0.013 inches of the wall remains as metallic Zircaloy when the fuel rod is oxidized in steam from one side and is ramped from 1500 to 3500°F in about 25 minutes. If this is assumed to be the case, then approximately 0.052 inches of the diameter of the fuel pellet may be dissolved from the outer surface to form a liquid phase. This is about 26% of the volume of a fuel pellet. The maximum damage estimate indicates that about 30% of the core reached temperatures allowing the liquid phase formation. This would then allow a rapid release of about 8% of the core inventory of volatile fission products. This would be in addition to the fission products in the gap and released by diffusional and cracking processes. If it can be assumed that the fuel pellets continued to heat up by decay heat only after the eutectic liquid formation occurred (locally), then additional release of fission product inventory could occur by two mechanisms: the increased temperature of the solid part of the pellet, and additional liquid phase formation as the temperature continued to rise. It is not possible from these calculations to estimate a maximum temperature for any of the fuel pellets.

Since much of the oxidized cladding was susceptible to cracking from thermal shock, it would be expected that these parts of the fuel rods would crack and fragment when the primary pump was turned on, or when the core was being slowly reflooded from injected water.

The discussion above indicates that many of the observations of the system and accident can be explained, predicted, or analyzed by the simple scenario used and the calculations made. These include most of the hydrogen generated, the first release of fission products at 115 minutes into the accident, part of the large fraction of core inventory fission products released, the flow blockage observed, and the high temperature readings of the assembly thermocouples after the core was quenched. It fails, however, to explain how and why the fuel assembly thermocouples survived, when they pass through the length of the instrumentation tube from the top of the core structure through the fuel assemblies to the bottom core structure, and then out of the reactor. It does not seem possible for the instrumentation tube and its contents to have survived when the temperatures of surrounding fuel rods must have been between 3000 and 4000°F. A more detailed analysis and scenario is being developed to consider fuel rod behavior in different areas of each of the assemblies. Such an analysis has been examined cursorily and the resulting calculations indicate a possible mode for survival of the in-core thermocouples. The analysis will be published in an updating "Memo to File" when completed.

M L Picklesimer

M. L. Picklesimer
Fuel Behavior Research Branch
Division of Reactor Safety Research

REFERENCES

1. R. E. Pawel, R. A. Perkins, R. A. McKee, J. V. Cathcart, G. J. Yurek, and R. E. Bruschel, "Diffusion of Oxygen in Beta-Zircaloy and the High Temperature Zircaloy-Steam Reaction," in Zirconium in the Nuclear Industry, ASTM STP 633 (1977), pp 119-149.

2. Cathcart, J. V., et.al., "Zirconium Metal-Water Oxidation Kinetics IV. Reaction Rate Studies," ORNL-NUREG-17, August, 1977.

3. S. Hagan, et.al., Projekt 4241, "Experimentalle Undersuchung der Abschmelzphise van UO_2-Zircaloy - Brennelemeuten bei versagender Not Kuhlung," Projekt Nucleare Sicherheit Halbjahresbericht, 1977/2 KfK 2600, P. 416-428.

4. T. F. Kassner, H. M. Chung, A. M. Garde, and S. Majumdear, "Zircaloy Caldding Embrittlement, Recommended Criteria," presented at the Sixth Water Reactor Safety Research Information Meeting, NBS, Gaithersburg, MD, November 6-9, 1978, and published in "Memo to File" Comments on the Symposium on Embrittlement of Zircaloy by Oxidation, 6th WRSR Information Meeting, NBS, Gaithersburg, MD, November 6, 1978, By M. L. Picklesimer, NRC, dated December 4, 1978. Available at the NRC Public Document Room.

5. T. F. Kassner, et.al., LWR Safety Research Program Quarterly Progress Reports, Part III. Argonne National Laboratory. ANL-78-25, NUREG/CR-0089 October-December, 1977, pp 31-44 (Published May, 1978). ANL-78-77, NUREG/CR-0423, April-June, 1978, pp 19-42 (Published December, 1978).

6. R. E. Pawel, Oak Ridge National Laboratory. Build-5, per se, is not reported in a formal document, but the basis is laid in two papers, R. E. Pawel, "Diffusion in a Finite Systen with a Moving Boundary," Jnl. Nuc. Matls., 49, pp 281-290 (1974) and R. E. Pawel, "Oxygen Diffusion in Beta-Zircaloy During Steam Oxidation," Jnl. Nuc. Matls., 50, pp. 247-258 (1974).

7. G. P. Marino, personal communication to M. L. Picklesimer, BUILD-5 Calculations for Several Temperature Ramps, April 16, 1979.

8. R. H. Chapman, et.al., "Preliminary Multirod Burst Test Program Results and Implication of Interest to Reactor Safety Evalutions," Workshop on Multirod Burst Tests, Sixth WRSR Information Meeting, Gaithersburg, MD, November 6, 1978, published in "Memo to File, Minutes of the Workshop on Multirod Burst Testing, 6th WRSR Information Meeting, Gaithersburg, MD, November 6, 1978," by M. L. Picklesimer, dated January 10, 1979, available at the NRC Public Document Room.

9. L. S. Tong and J. Weisman, "Monograph on Thermal Analysis of Pressurized Water Reactors," ANS, July, 1970, p. 25, eq. 1.5.

10. Letter from R. E. Pawel, ORNL, to M. L. Picklesimer, RSR/NRC, dated April 24, 1979, transmitting computer printouts for oxidation data calculated by modified version of BUILD-5 for several temperature ramps.

11. "Core Damage Assessment for TMI-2," Memorandum for R. J. Mattson, DSS/NRR from R. O. Meyer, CPB/DSS/NRR, dated April 13, 1979.

12. Letter dated April 16, 1979, from J. Rest, Argonne National Laboratory to G. P. Marino, FBRB/RES/NRC, concerning fission product release calculations using GRASS-SST.

13. Telephone conversation between A. P. Malinauskas, ORNL, and R. R. Sherry, FBRB/RES/NRC, confirming estimates of temperatures required to release amounts and types of fission products observed.

14. Telex, dated April 11, 1979 from R. A. Lorenz, ORNL to R. O. Meyer, CPB/DSS/NRC, reporting calculations by Malinauskas of temperatures required toreleas the amounts of fission products observed at TMI-2.

15. P. Hofmann, et.al., Projekt 4244, "Konstitution und Reaktionsverbalten vou LWR-Materialieubeim Corechmelzen," Projekt Nukleare Sicherheit Halbjahresbericht, 1974-2, KfK 2130, pp. 261-275, Kernforschungszentrum, Germany.

TABLE I

DAMAGE ESTIMATE FOR THE TMI-2 CORE AT THREE HOURS[b]

Penetration Depth from Top of Core (feet)

	MAXIMUM DAMAGE ESTIMATE					MINIMUM DAMAGE ESTIMATE				
Total Peaking Factor, (tpf)	1.9	1.6	1.3	1.19	0.66	1.9	1.6	1.3	1.19	0.66
Damage Type										
Burst	1	1	1	2	3	1	1	1	2	3
Oxidized but not embrittled	7-1/4	7	6-1/4	6	none	7-1/4	6-3/4	6	1/2-5-1/2[a] only	none
Embrittlement	6-3/4	6-1/4	5-1/2	1/2-5-1/4[a] only	none	6-1/4	5-3/4	1-1/2-5[a] only	2-4[a] only	none
Eutectic Formation	6-1/4	5-3/4	5	1-4-1/2[a] only	none	1-1/2-4-1/2[a] only	none	none	none	none

---

a. Occurs only between these levels.

b. Estimates as of 5/1/79

FIGURE 5.1-13

COMPARISON OF MEASURED AND CALCULATED TOTAL CORE POWER DISTRIBUTION RESULTS AT STEADY STATE, EQUILIBRIUM XENON 92.6 % FP CONDITIONS

	Measured	Calculated	
Control Rod Group Positions			
Gps 1-4	100	100	% wd
Gp 5	100	100	% wd
Gp 6	89	87.5	% wd
Gp 7	89	87.5	% wd
Gp 8	16	18.3	% wd
Core Power Level	92.6	92.6	% FP
Boron Concentration	1095	1135	PPM
Core Burnup	32	23.2	EFPD
Axial Imbalance	+ 0.55	+ 0.40	% FP
Max Quadrant Tilt	- 0.10	-	%

Time 1048 Date 1/29/75

	8	9	10	11	12	13	14	15
H	1.88 1.90	1.75 1.74	1.47 1.49	1.66 1.61	1.45 1.27	~~1.68~~ 1.61	1.82 1.64	1.32 1.19
K		1.50 1.53	1.67 1.63	1.44 1.41	1.64 1.47	1.43 1.30	1.53 1.40	1.22 1.13
L			1.44 1.49	1.64 1.51	1.39 1.24	1.55 1.35	1.57 1.49	0.99 0.69
M				1.38 1.36	1.50 1.32	1.22 1.11	1.27 1.14	
N					1.17 1.16	1.16 1.07	0.82 0.65	
O						0.85 0.65		
P								
R								

FIGURE 1. CORE MAP SHOWING TOTAL PEAKING FACTORS MEASURED IN COMPARISON TO THOSE CALCULATED FOR THE RANCHO SECO NUCLEAR POWER PLANT.

X.XX Calculated Results
X.XX Measured Results

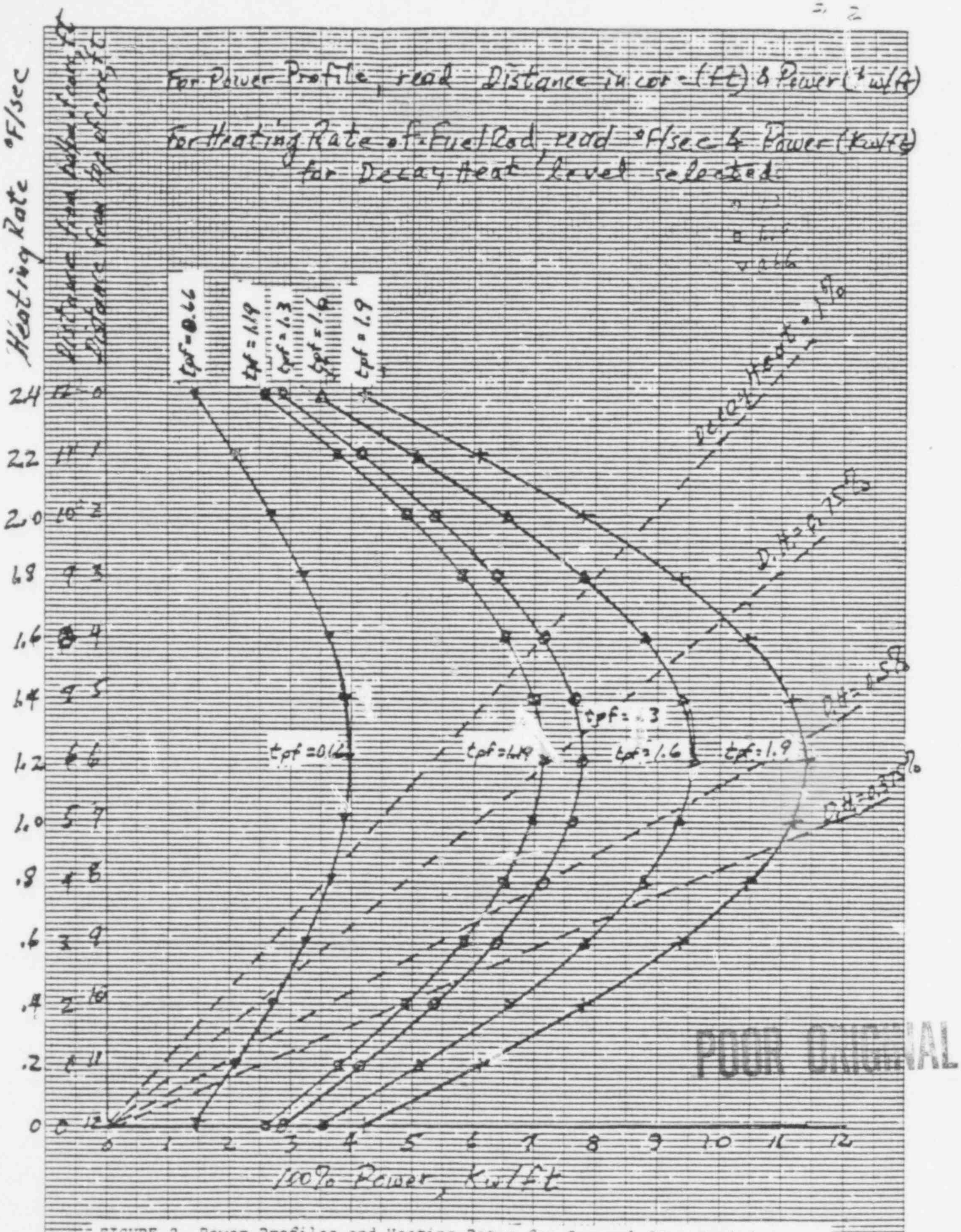

FIGURE 2. Power Profiles and Heating Rates for Several Core Positions

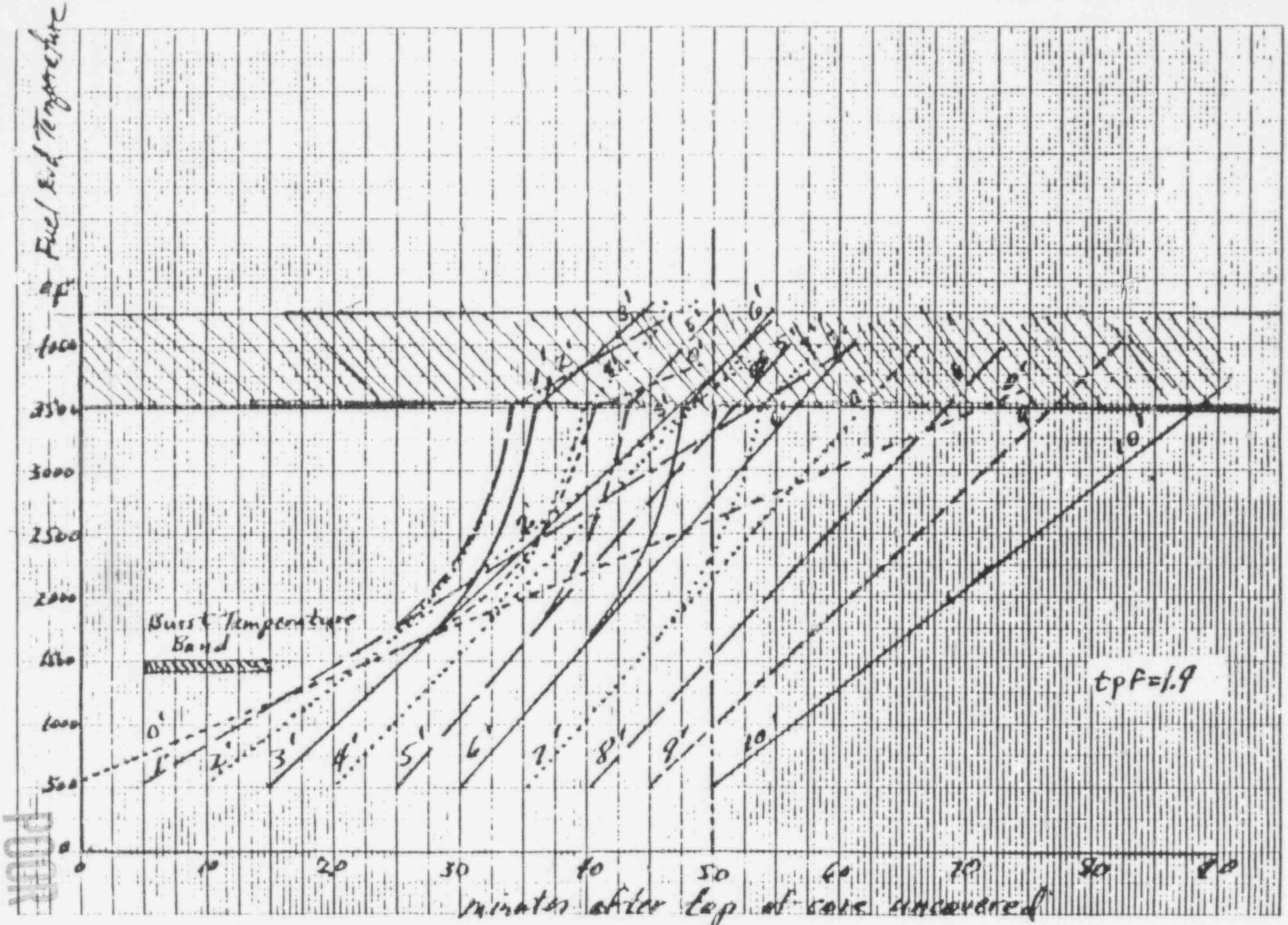

FIGURE 3. Temperature vs Time for Center Bundle Having a Total Peaking Factor of 1.9

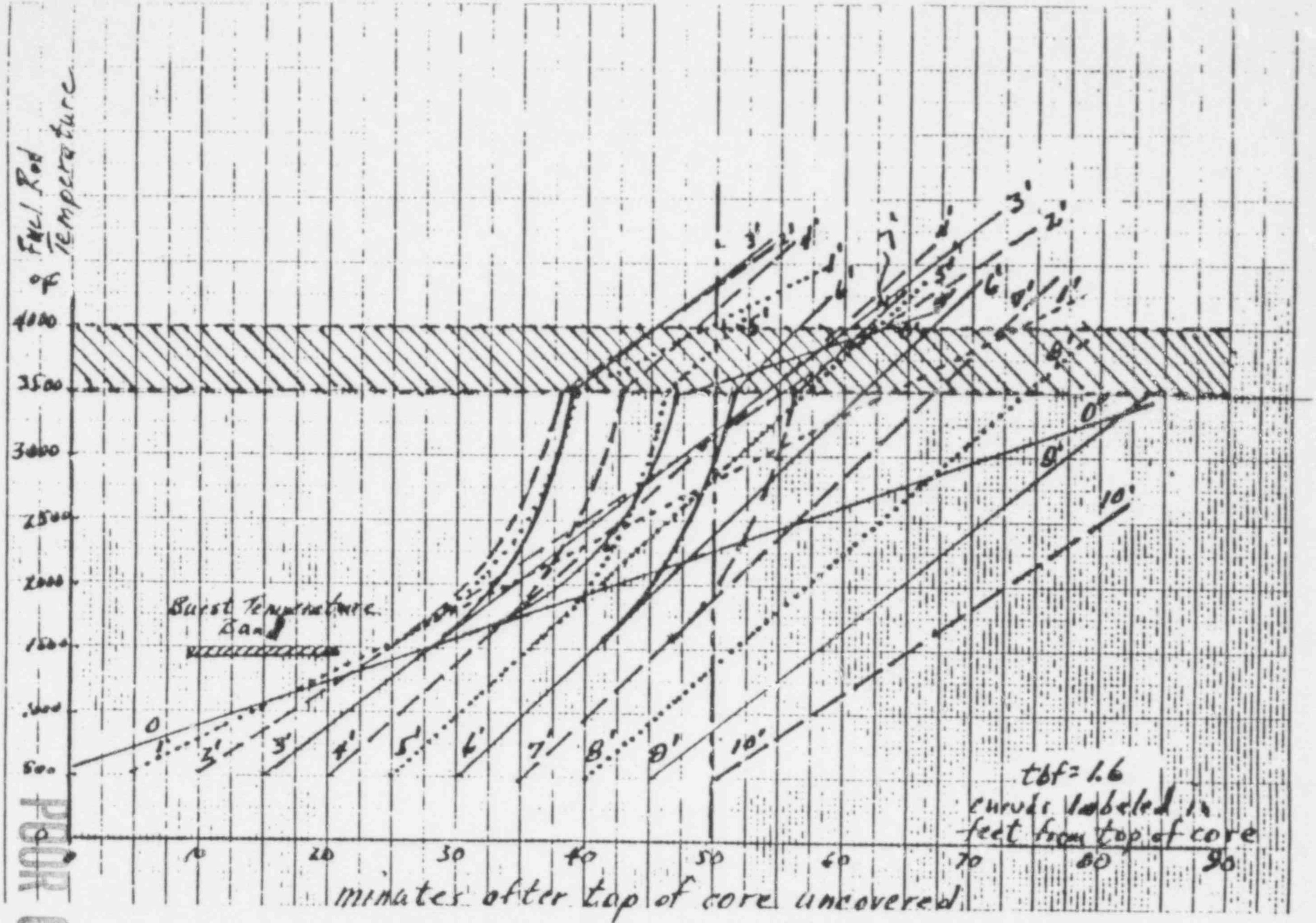

FIGURE 4. Temperature vs Time for Bundle Having a Total Peaking Factor of 1.6

POOR ORIGINAL

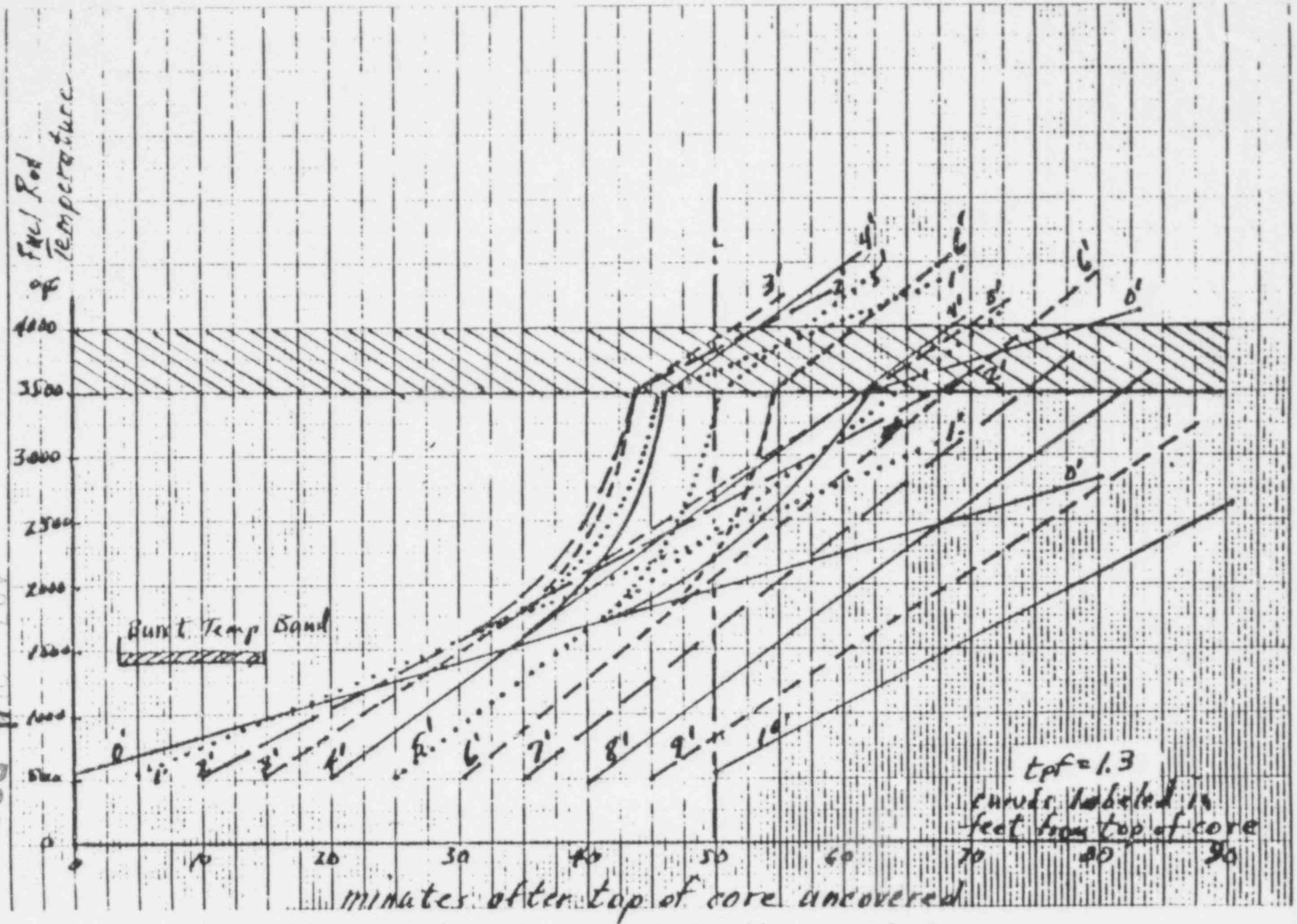

FIGURE 5. Temperature vs Time for Bundle Having a Total Peaking Factor of 1.3

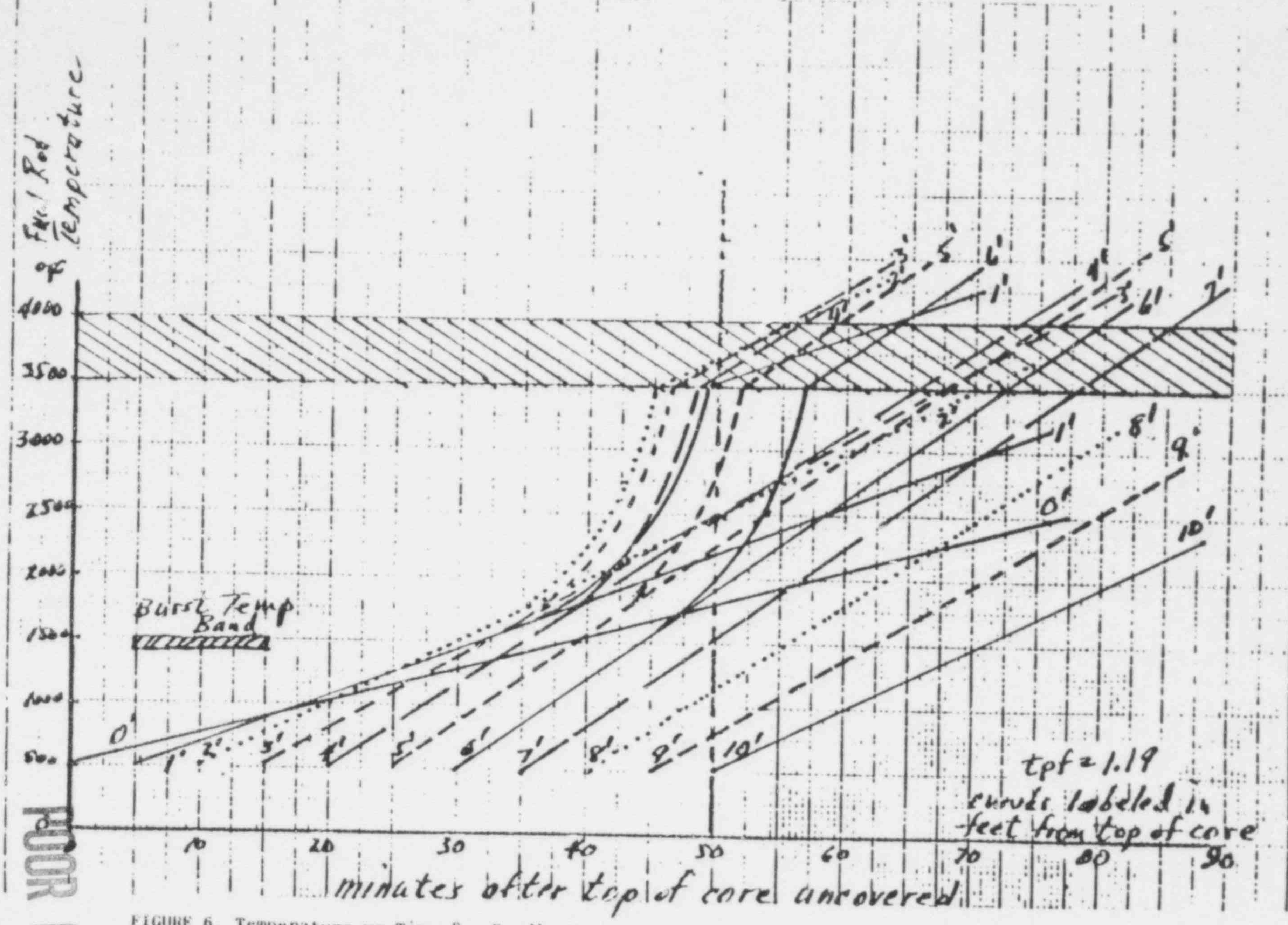

FIGURE 6. Temperature vs.Time for Bundle Having a Total Peaking Factor of 1.19

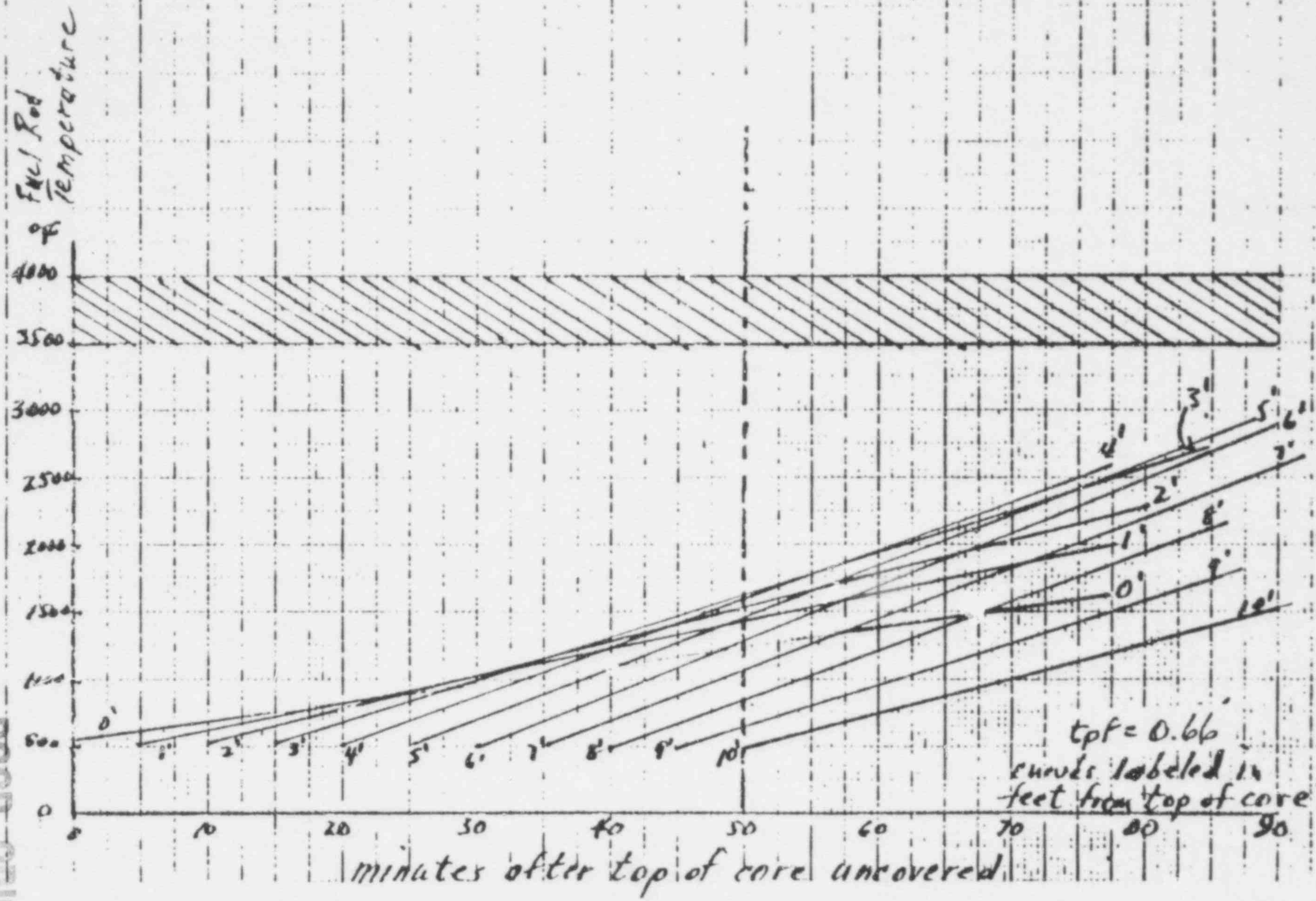

FIGURE 7. Temperature vs Time for Bundle Having a Total Peaking Factor of 0.66

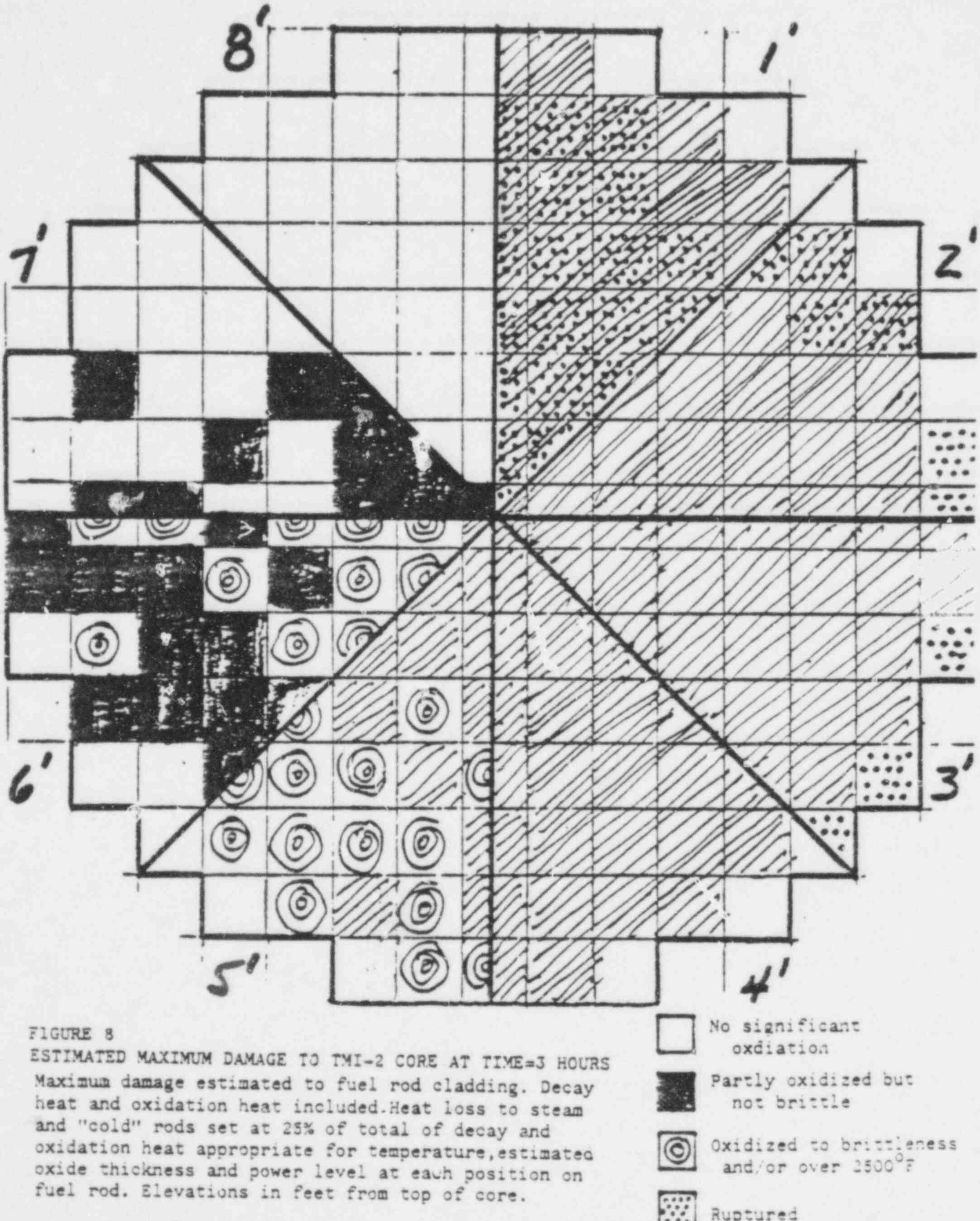

FIGURE 8
ESTIMATED MAXIMUM DAMAGE TO TMI-2 CORE AT TIME=3 HOURS
Maximum damage estimated to fuel rod cladding. Decay heat and oxidation heat included. Heat loss to steam and "cold" rods set at 25% of total of decay and oxidation heat appropriate for temperature, estimated oxide thickness and power level at each position on fuel rod. Elevations in feet from top of core.

- ☐ No significant oxdiation
- ■ Partly oxidized but not brittle
- ◎ Oxidized to brittleness and/or over 2500°F
- ⁘ Ruptured
- ▨ α-Zr - UO$_2$ liquid formed

MLP 4/28/79

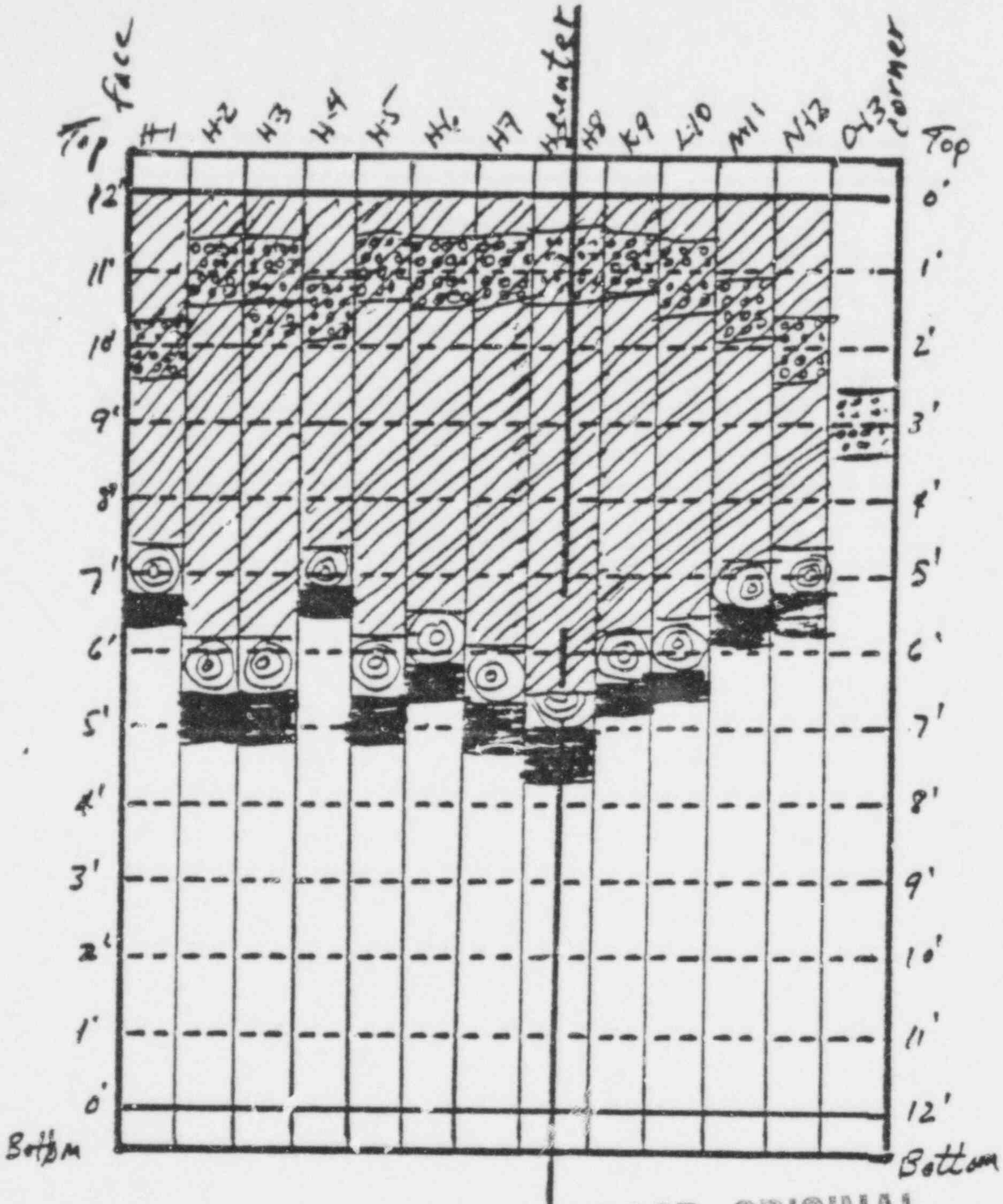

FIGURE 9

ESTIMATED MAXIMUM DAMAGE TO TMI-2 CORE AT TIME=3 HOURS

Maximum damage estimated to fuel rod cladding. Decay heat and oxidation heat included. Heat loss to steam and "cold" rods set at 25% of total of decay and oxidation heat appropriate for temperature, estimated oxide thickness and power level at each position on fuel rod. Elevations in feet from top of core.

☐ No significant oxdiation

■ Partly oxidized but not brittle

◎ Oxidized to brittleness and or over 2500°F

⁘ Ruptured

▨ α-Zr + UO_2 liquid formed

MLP 4/26/79

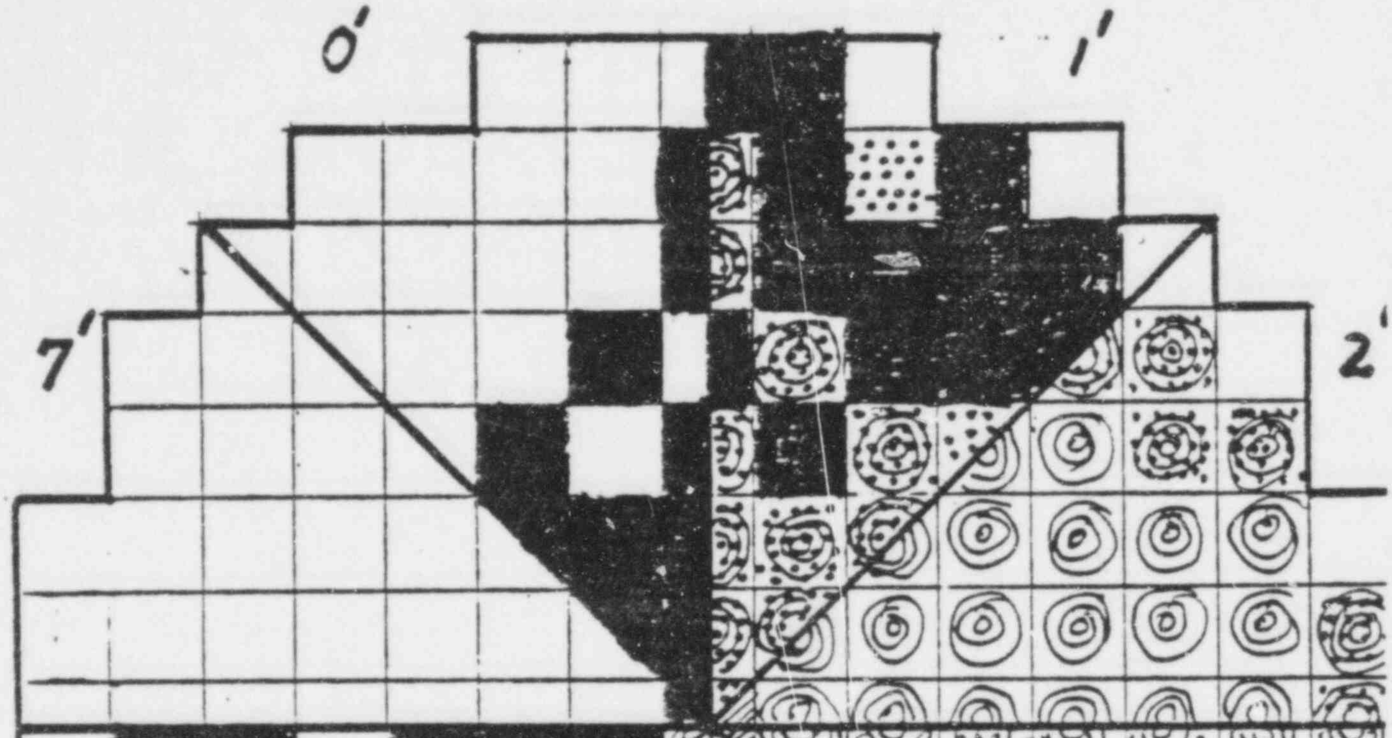

FIGURE 10

ESTIMATED MINIMUM DAMAGE TO TMI-2 CORE AT TIME=3 HOURS
Minimum damage estimated to fuel rod cladding. Decay heat only. Oxidation heat not included. Heat loss to steam and "cold" rods set at 25% of decay heat at each position on fuel rod. Elevations in feet from top of core.

☐ No significant oxdiation

■ Partly oxidized but not brittle

◎ Oxidized to brittleness and/or over 2500°F

⁙ Ruptured

▨ α-Zr - UO_2 liquid formed

MLP 4/26/79

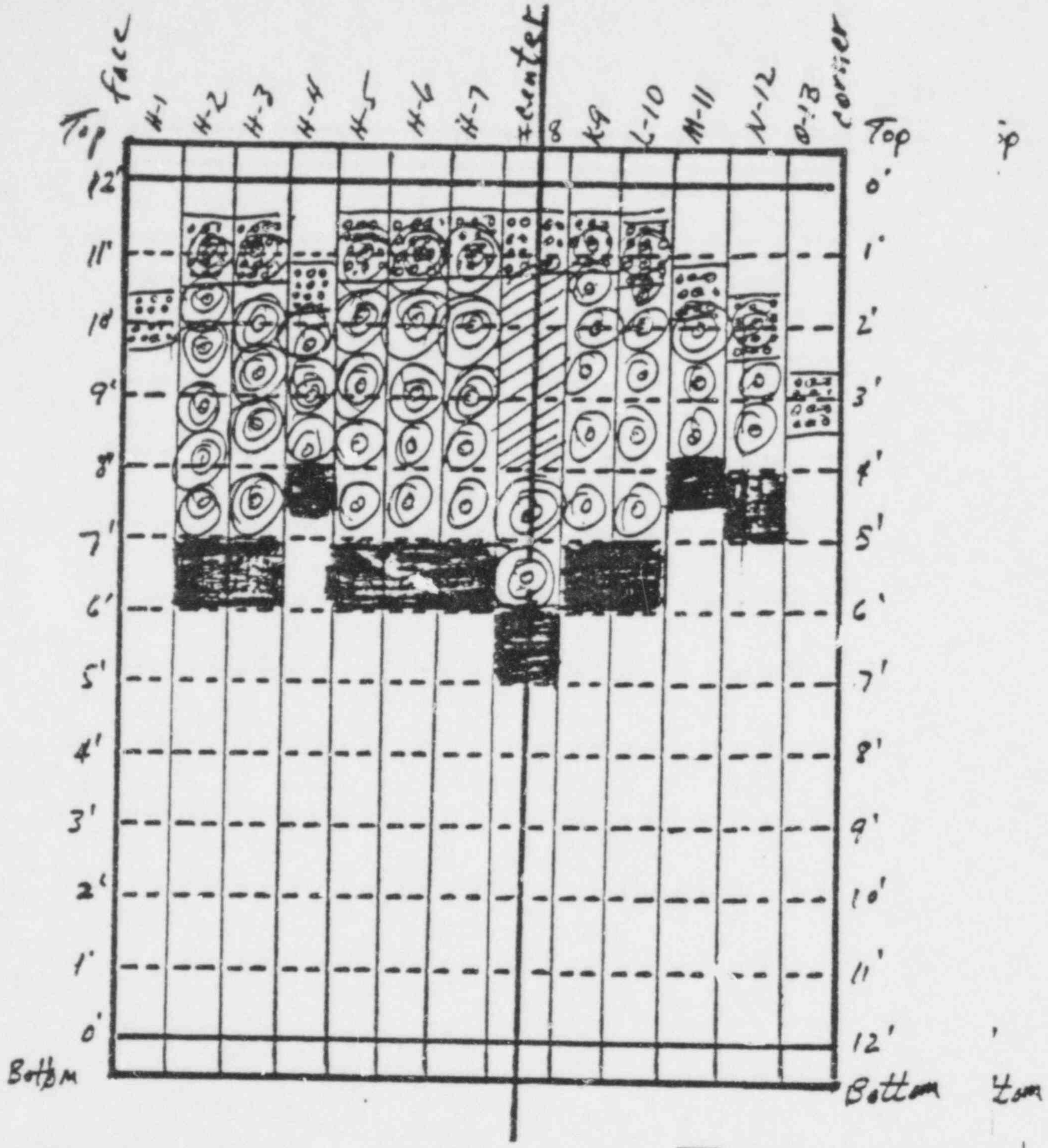

FIGURE 11

ESTIMATED MINIMUM DAMAGE TO TMI-2 CORE AT TIME=3 HOURS
Minimum damage estimated to fuel rod cladding. Decay heat only. Oxidation heat not included. Heat loss to steam and "cold" rods set at 25% of decay heat at each position on fuel rod. Elevations in feet from top of core.

☐ No significant oxdiation

■ Partly oxidized but not brittle

◎ Oxidized to brittleness and/or over 2500°F

░ Ruptured

▨ α-Zr - UO_2 liquid formed

MLP 4/26/79

POOR ORIGINAL

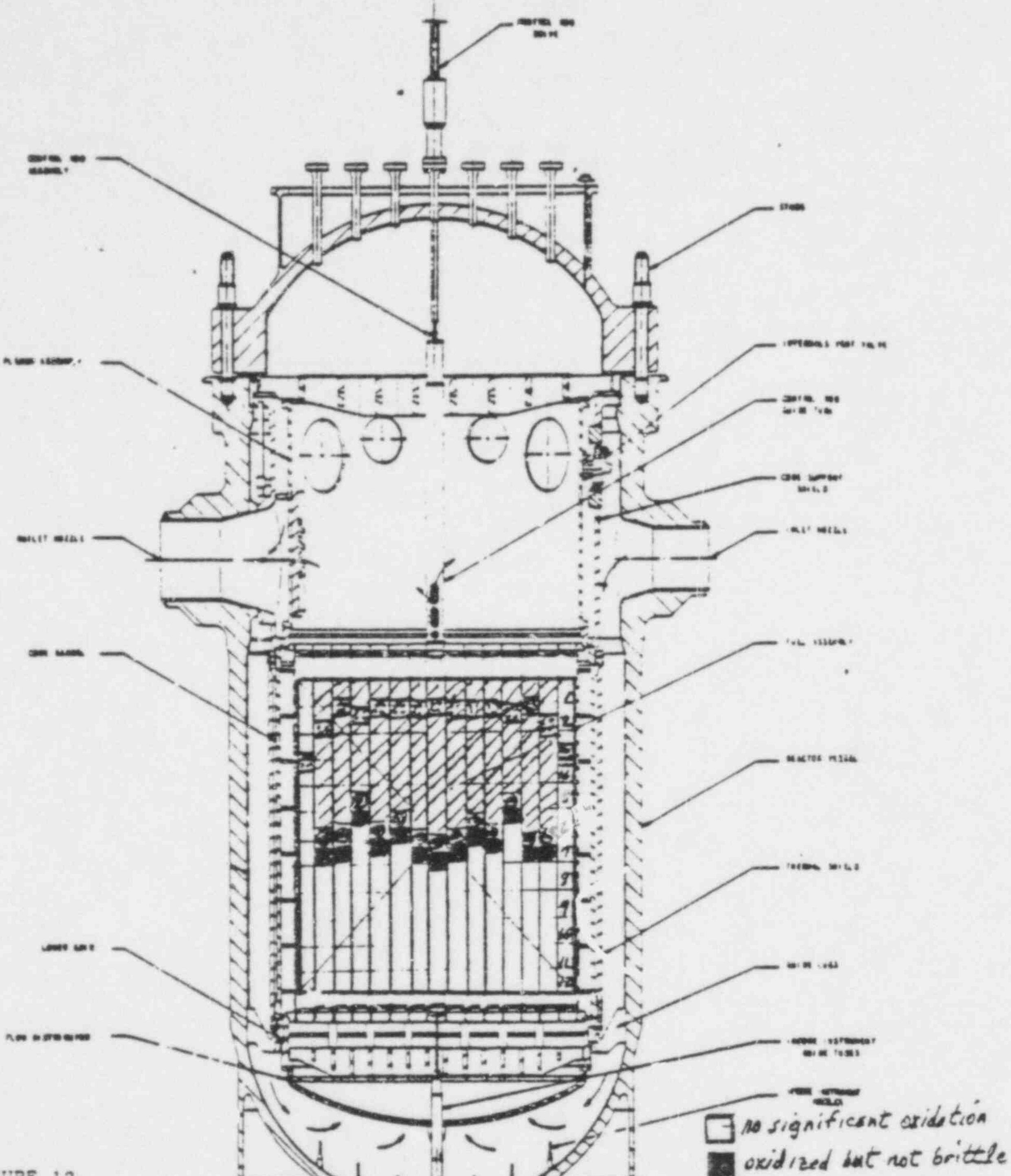

FIGURE 12

ESTIMATED MAXIMUM DAMAGE
TO TMI-2 CORE CLADDING AT 3 HRS.
Decay +oxidation heat.
Heat loss at 25%.Decay
heat at 1% full power
Elevation [illegible] feet from
top of core.

☐ no significant oxidation
■ oxidized but not brittle
▣ oxidized to brittleness
⊡ rupture location
▨ severely oxidized and α-Zr + UO$_2$ liquid phase formed

REACTOR VESSEL & INTERNALS-GENERAL ARRANGEMENT

THREE MILE ISLAND NUCLEAR STATION UNIT 2

Met Ed

FIGURE 4.2-3
AM. 50 (12-8-76)

POOR ORIGINAL

APPENDIX A

CALCULATIONS:

1. Heat Capacity of the Fuel Rod

UO_2: density = 10.08 g/cc (92.5% theoretical density) = 0.3642 lb/in^3

specific heat = 0.077 Btu/lb - F^o

vol/inch of rod = $\frac{\pi}{4}(0.370)^2 \times 1$ inch = 0.1075 in^3/inch of rod

mass UO_2/inch of rod = 0.03915 lbs/inch of rod

ΔH_{UO_2} = mass x specific heat = 0.03915 x 0.0777 = 3.042×10^{-3} Btu/in-^oF

Zircaloy Cladding:

density = 6.54 g/cc = 0.2363 lb/in^3

specific heat = 0.0830 Btu/lb-^oF 600-1100K
0.1315 Btu/lb-^oF 1100-1300K
0.0908 Btu/lb-^oF 1300K
assume = 0.0830 Btu/lb-^oF 600-2300K

vol = $\pi \times \frac{(0.430 + 0.380)}{2} \times 0.026$ = 0.03308 in^3

mass = 7.817×10^{-3} lb/inch of rod

ΔH_{Zr} = mass x specific heat = $7.817 \times 10^{-3} \times 0.0830 = 6.488 \times 10^{-4}$ Btu/inch rod-^oF

Heat Capacity of Fuel Rod/Inch of Road

ΔH_{Zr} = 6.488×10^{-4} Btu/inch of rod-^oF
ΔH_{UO_2} = 30.42×10^{-4} Btu/inch of rod-^oF

ΔH_{rod} = 36.91×10^{-4} Btu/inch of rod-^oF

2. Creep-Rupture of Zurcaloy Clad Fuel Rods:

Minimum internal pressure:

from FSAR:

total internal volume of fuel rod (free) with pellets	$= 1.75\ in^3$
volume of the plena	$= \underline{0.87\ in^3}$
volume of gap + pellet dishes	$= 0.88\ in^3$

cold prepressurization = 445psi He (300K)

$$n = PV/RT = \frac{445 \times 1.75 \times A}{1.987 \times 300} = 1.3064\ A,\ A \approx \text{conversion factor}$$

assume:

1. Top ¼ of rod + upper plenum goes into film boiling.
2. The time is between 1½ and 3 hours after turbine trip.
3. The hot rod peak clad temperature is 1470^0F (800^0C)
4. The total number of moles of gas is constant

   $n = n_1 + n_2 = 1.3064\ A$
5. The fuel rod is separated into two parts, each at a different temperature, and connected by a small pressure capillary, the two parts having volumes of $1.09\ in^3$ at 589K and $0.67 in^3$ at 1073K

   then:

   $$n = n_1 + n_2 = 1.3064\ A = \frac{P \times 1.09\ A}{1.987 \times 589} = \frac{P \times 0.67\ A}{1.987 \times 1073}$$

   $P = 1049psi$ at 1470^0F (800^0C)

Maximum internal pressure:

from B&W estimate, internal pressure = 1200psi at 589K(operating conditions)

$$n = PV/RT = A x 1.75\ in^3 \times 1200psi/1.987 \times 589 = 1.7827\ A$$

$$n = n_1 + n_2 = \frac{A \times P \times 1.09}{1.987 \times 589} + \frac{A \times P \times 0.67}{1.987 \times 1061} = 1.7827\ A$$

$P = 1436.5psi$ at 1450^0F (788^0C)

Circumferential stress in the wall of the cladding:

$\sigma = \frac{\Delta P\ D}{2\ t}$; ΔP = internal pressure - external pressure
D = 0.380 inches
t = 0.0265 inches

$\sigma = 7.1698\ \Delta P$

for $\Delta P = 300$ psi , $\sigma = 2151$ psi , $T_{rupture} \leq 1600\ ^{o}F$
$= 400$ psi , $= 2868$ psi , $\leq 1575\ ^{o}F$
$= 500$ psi , $= 3585$ psi , $\leq 1540\ ^{o}F$
$= 600$ psi , $= 4302$ psi , $\leq 1500\ ^{o}F$

3. Axial Power Profile of Fuel Rods:

Nominal axial peaking factor in Rancho Seco = 1.3

$P(z) = \frac{B + A \cos (\pi\ z/2L)}{B + 2A}\ P_{avg}$; A,B = constants related to the power levels in the core

$P_{max} = A + B,\ P_{avg} = B + 2A/\pi$; $\frac{P_{max}}{P_{avg}}$ = axial peaking factor - 1.3

then at $P_{max} - 1.3\ P_{avg}$, A = 1, and $P_{max} = B + 1 = 1.3\ B + 2.6/\pi$; B = 0.5746

then $P(z) = \left[\frac{0.5746 + \cos (\pi\ z/2L)}{0.5746 + 2/\pi}\right]\ P_{avg}$

$$P(z) = \left[0.4744 + 0.8256 \cos (\pi\ z/2L)\right] P_{avg}$$

Table A-1 Calculation of Axial Power Profiles

Total peaking factor	P_{avg} (core) kw/ft	Axial peaking factor	P_{avg} (rod) kw/ft
0.66	6.0	1.3	3.046
1.19	6.0	1.3	5.49
1.30	6.0	1.3	6.0
1.60	6.0	1.3	7.38
1.90	6.0	1.3	8.77

Lft	z/L	$\frac{\pi Z}{2L}$	0.8256 cos ($\pi z/2L$)	$\frac{P(z) \text{ at } 100\% \text{ Power}}{P_{avg}}$				
				3.046	5.49	6.0	7.38	8.77
6	0/6	90^o	0	1.445	2.604	2.85	3.50	4.16
6	1/6	75^o	0.2137	2.096	3.777	4.13	5.08	6.03
6	2/6	60^o	0.4128	2.702	4.87	5.32	6.55	7.78
6	3/6	45^o	0.584	3.223	5.808	6.35	7.81	9.28
6	4/6	30^o	0.715	3.625	6.53	7.14	8.79	10.44
6	5/6	15^o	0.7975	3.874	6.983	7.631	9.39	11.15
6	6/6	0^o	0.8185	3.956	7.14	7.80	9.60	11.40

4. For graphical solutions of temperature vs. time in rod for decay heat only:

plot $\dot{T}$ (^oF/sec) vs kw/ft inrod;

$\Delta H_{rod} = 3.69 \times 10^{-3}$ Btu/inch-^oF

$\dot{T} = \frac{\text{Power in rod}}{\Delta H_{rod}}$ = kw/ft x ft/inch x 0.9846 Btu/kw-sec x 1/Btu/inch-^oF

$\dot{T} = \frac{0.9845 \times \text{decay geat fraction}}{12 \times 3.68 \times 10^{-3}}$ (kw/ft at power) = 22.4 (decay fraction x power)

for 1% decay heat, and 10 kw/ft power, $\dot{T} = 2.24^oF$/sec

0.75% decay heat and 10 kw/ft power, $\dot{T} = 1.68^oF$/sec

0.5% decay heat, and 10 kw/ft power, $\dot{T} = 1.12^oF$/sec

then:

$T_{z,t} = T_{sat} + \dot{T}\,(\Delta t)$ where T_{sat} = temperature of (z) at time of uncovery

$t = t_o + \Delta t$ where t_o = time of uncovery of (z), and,

Δt_o time increment of calculation

Graphical solution of oxidation heat vs. temperature, use heat generation rate for time increments of 2½ minutes as calculated by BUILD-5 for temperature ramps from 1500 to 3000^oF in 20, 25 and 30 minutes plotted against temperature at the and of the time increment. See Figure A-1

For each $100^{\circ}F$ step above $1500^{\circ}F$, add the oxidation heat at that temperature to the decay heat for that rod, enter Figure A-2 at the power sum, and draw the appropriate slope from the lower temperature of the increment to that temperature plus $100^{\circ}F$, or read incremental time required to heat that $100^{\circ}F$ temperature increment, and extend the rod temperature vs. time plot at elevation z by that amount. Repeat in steps until the temperature for the formation of the alpha-Zr + ZrO_2 eutectic is reached.

Mathematical description:

$$T_{i+1} = T_i + 100^{\circ}F$$

$$t_{i+1} = t_i + \frac{100}{\dot{T}}$$

$$\dot{T}_i = \Delta H \quad + \Delta H_{ox}\Big]_{T_i}^{T_i+1}$$

$\Delta H \Big]_{T_i}^{\;+1}$ is taken from plot of kw/ft vs. temperature for ramp rate concerned and shown in Figure A-1.

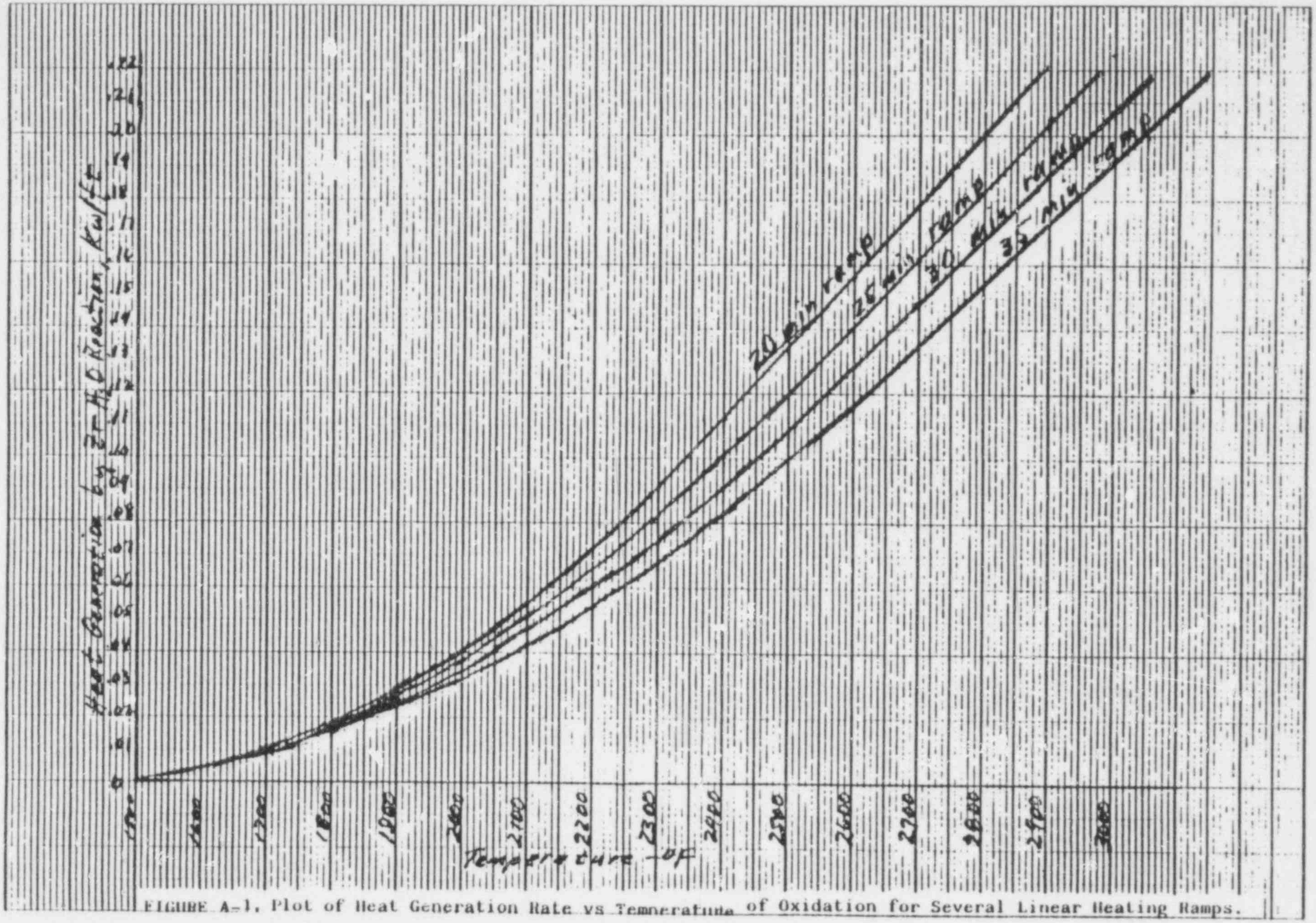

FIGURE A-1. Plot of Heat Generation Rate vs Temperature of Oxidation for Several Linear Heating Ramps.

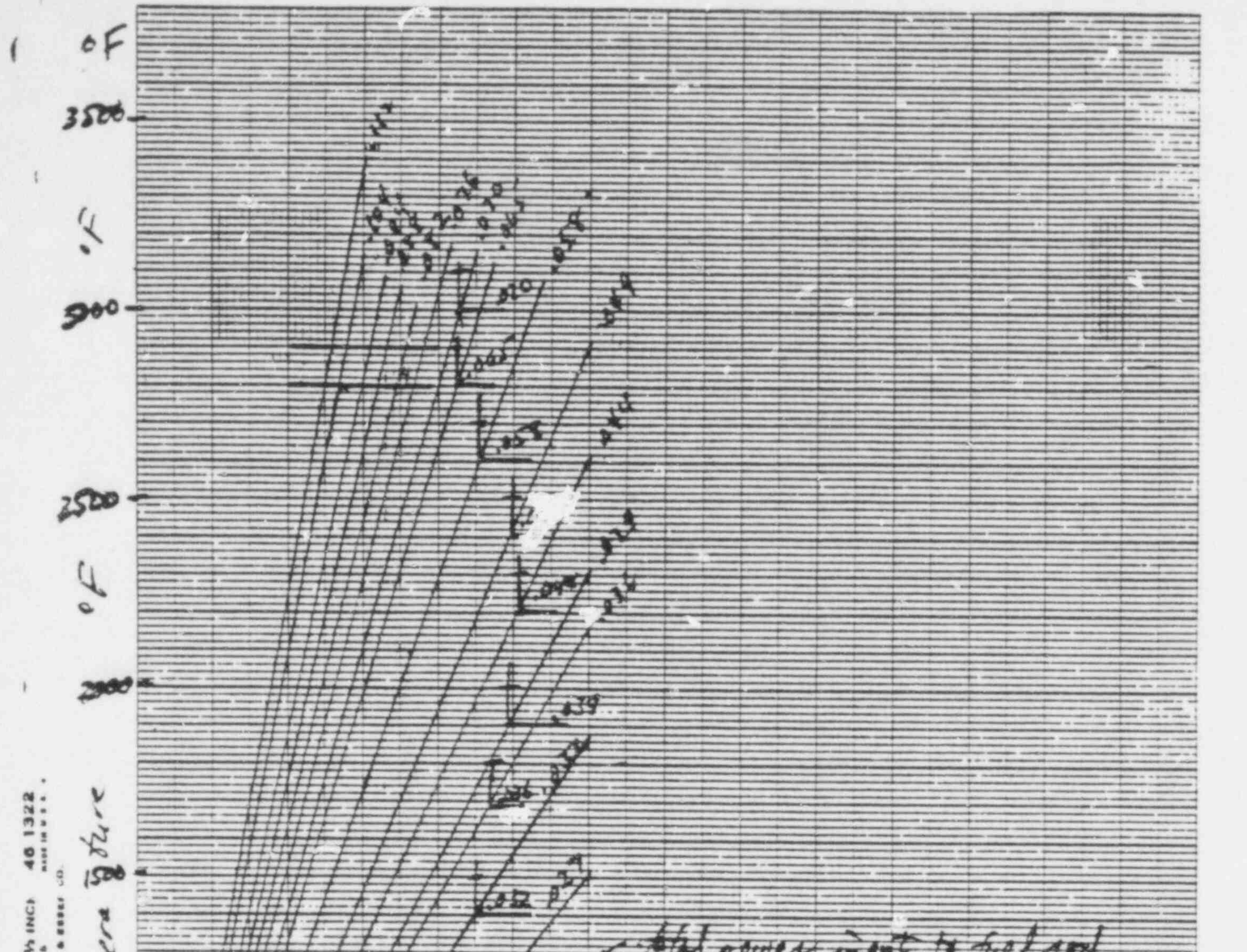

FIGURE A-2 . Time Required to Heat 100°F vs Temperature of Oxidation.Time Increment Includes Effects of Oxide Film Thickness,Heating Rate.

Docket 50-320

ADDRESSEES - LETTER DATED JUL 3 1979.

M. L. Picklesimer, Chairman, NRC/RSR
G. L. Bennett, NRC/RSR
F. D. Coffman, Jr., NRC/DOR
G. P. Marino, NRC/RSR
R. Van Houten, NRC/RSR
D. A. Hoatson, NRC/RSR
R. R. Sherry, NRC/RSR
W. V. Johnston, NRC/RSR
R. J. Budritz, NRC/RES
R. O. Meyer, NRC/DSS
J. A. Norberg, NRC/OSD
J. Voglewede, NRC/DSS
D. Powers, NRC/DSS
L. S. Rubenstein, NRC/NRR
TIDC Accessions Unit/PDR (2)
T. E. Murley, NRC/RES
R. Scroggins, NRC/RES (50-320) ✓
P. O. Strom, NRC/ID
L. S. Tong, NRC/RSR
P. Boehnert, ACRS
D. Bassett, ACRS
R. Fraley, ACRS
P. A. Shewman, ACRS Subcommitte on Fuels
R. N. Oehlberg, EPRI
J. T. A. Roberts, EPRI
R. H. Chapman, ORNL
D. O. Hobson, ORNL
C. S. Hartley, Univ. of Florida
T. . Kassner, ANL
S. Dagbjartsson, EG&G
P. E. MacDonald, EG&G
M. P. Bohn, EG&G
L. G. Ybarrando, EG&G
E. L. Tolman, EG&G
R. R. Hobbins, EG&G
H. M. Zeile, EG&G
C. R. Hann, BNWL
C. Mohr, BNWL
A. Fiege, KfK
M. Fischer, KfK
J. S. Goedkoop, ECN-Petten
S. E. Ritterbusch, CE
P. G. Smerd, CE
C. Crouthamel, Exxon

~~7908090~~

ADDRESSEES - LETTER DATED JUL 3 1979

A. L. Lowe, B&W
M. H. Montgomery, B&W
L. D. Burman, W
R. B. Adamson, GE, Vallecitos
E. D. Hindle, UKAEA
T. Healey, CEGB
S. Kawasaki, JAERI
M. Ishikawa, JAERI
E. Zebroski, EPRI
G. Folwer, NRC/OMPA
A. DiPalo, NRC/OMPA
R. E. English, Presidential Commission
R. Bernero, Task Group #5