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TMI-2

WEEKLY UPDATE OF TMI-2 CALCULATIONS, April 23-26,1979

M.L.Picklesimer, FBRB MLP 5/4/79

Bounding estimates of the damage to the Zircaloy fuel rod cladding in the TMI-2 core at three hours after the initiation of the accident were made using simplified calculations, simplifying assumptions, and a simplified scenario of core uncovery. Time-temperature plots were developed for cladding heatup by decay heat only and by decay heat plus oxidation heat for several typical assemblies in the core as functions of axial and radial power during operation and of time of uncovery during boil-off. These plots were then used to estimate maximum and minimum damage as functions of radial and axial core profiles xxxxxxxxxxxx to develop maximum and minimum core damage maps for both transverse and axial core sections..The resulting plots were assembled into a handout prepared for and distributed at the NRC/EPRI TMI Core Damage meeting on April 27,1979.A copy is attached.It was concluded that all fuel rods burst for either maximum or minimum damage estimate, that the maximum extent of damage resulted in cladding embrittlement to the 6 to 7 foot level from the top of the core,that significant amounts of oxidation did not occur any place in the core below the 7 foot level from the top of the core, and that molten Zr + ZrO_2 eutectic was formed in sufficient quantity to produce a significant volume of liquid phase in reaction with the outer parts of the UO_2 fuel pellet to a depth of 5 to 6 feet over most of the core, but not in low-power corner bundles on the periphery of the core. The minimum damage likely was cladding embrittlement to a depth of 5 feet from the top over most of the core, with the liquid phase reaction between fuel and cladding going only to a depth of four feet and only in the central assembly.The most probable damage level lies someplace between the two.Since these calculations were made,new data has been obtained from TMI-2 to develop a better scenario of core uncovery. A "Memo to File" is being written, and new calculations will be ma

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BOUNDING ESTIMATES OF THE DAMAGE TO ZIRCALOY FUEL ROD CLADDING IN THE TMI-2 CORE AT THREE HOURS AFTER THE START OF THE ACCIDENT

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Purpose: attempt to establish bounding limits for the extent and locations of damage caused to the Zircaloy fuel element cladding in the first "uncovery" of the core during the first three hours after the accident sequence started.

Method : use simplifying assumptions and approximations to develop graphical solutions which can be "adjusted" to approximate the time-temperature history of the cladding at selected locations in the core for various "scenarios" of the sequence of events.

Assumptions:

1. The voiding of the water in the immediate volume of the reactor 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 and refill-reflood began.
3. Assume the level of the water in the core decreased linearly with time after the top was first uncovered at a rate of 12 ft/hr.
4. Assume that the heat capacity of UO_2 and the Zircaloy of the fuel rod are approximately constant with temperature (they change by 10-15%, increasing with increasing temperature and phase changes are ignored).
5. Since 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, approximate the losses by setting them equal to 25% of the heat developed in by the fuel rod after the water level has fallen below the specific position/elevation.
6. Assume the power peaking factor map of the core is the same as that measured for Rancho Seco.
7. Assume that the heat generated by steam oxidation of the Zircaloy cladding can be calculated with the Cathcart-Pawel rate equations, that the oxidation is one-sided only, and that the oxidation can be calculated by linear ramps over 100°F increments, using linear ramp calculations developed with BUILD-5 code.
8. Assume the decay heat in the middle of the period of calculations is 1% of the power developed at the start of the accident.
9. Assume oxidation of Zircaloy by steam stops when the molten α-Zr + ZrO_2 reacts with the UO_2 fuel to produce a liquid phase at about 3480°F.

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Calculational Results:

1. The heat capacity of UO_2 fuel pellets per inch of fuel rod is

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

2. The heat capacity of Zircaloy cladding per inch of fuel rod is

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

3. The heat capacity of the fuel rod per inch of rod is

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

4. The power profile of the fuel rod is calculated by the equation

$$P_{max} = \frac{B+1}{B+2/\pi} == \text{axial peaking factor}$$

$$P(z) = \frac{0.5746 + \text{cosine}\left(\frac{\pi z}{2 \ell}\right)}{0.5746 + 2/\pi}$$

$$= 0.4744 + 0.8256 \cos\left(\frac{\pi z}{2 \ell}\right)$$

5. $T(x) = T_{sat}$ (at time of uncovery) $+ \Delta T$(time= t - time of uncovering)

for decay heat heat-up only, $\Delta T = \frac{\text{decay heat} \times \text{time increment} \times 0.75}{\text{heat cap fuel rod}}$

for both decay and oxidation heating,

$$\Delta T = 0.75\left(\frac{\text{decay heat} \times \text{time increment}}{\text{heat cap fuel rod}} + \frac{\text{oxidation heat}}{\text{heat cap rod}}\right)$$

with time increment calculated for 100°F temperature rise for temperatures above 1600°F.

6. Axial power profiles are shown in Figure 2 for Radial peaking factors of 1.9,1.6,1.3,1.19, and 0.66,representative values in the core.
7. Time-temperature curves for the fuel rod cladding are shown in Figures 3-7 for radial peaking factors from 1.9 to 0.66 and as functions of distance in the core from the top as the core was uncovered.The straight lines are for heating by decay heat only, and the urves lines include heating by steam oxidation of the cladding.
8. Radial and axial core maps of damage to the fuel rod cladding are shown in Figures 8-11 for maximum and minimum estimated limits.

Conclusions:

1. All fuel rods burst, with the elevations of bursting being from about 1 foot from the top of the core in the center assembly to about three feet down for those on low=power corners.
2. Preliminary "guesstimates" of total Zircaloy oxidized is more than 25% but probably less than 33%.
3. Some of the periphereal bundles only burst, and never reached temperatures high enough to oxidize to any significant degree.
4. The minimum amount of damage that could have been sustained with the scenario used would be that the great majority of fuel assemblies were emrbittled to at least four feet fx down from the top of the core,some down to five feet, and twenty assemblies were burst but not embrittled.

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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 0.66		
P								
R								

X.XX X.XX	Calculated Results Measured Results

Fig 1

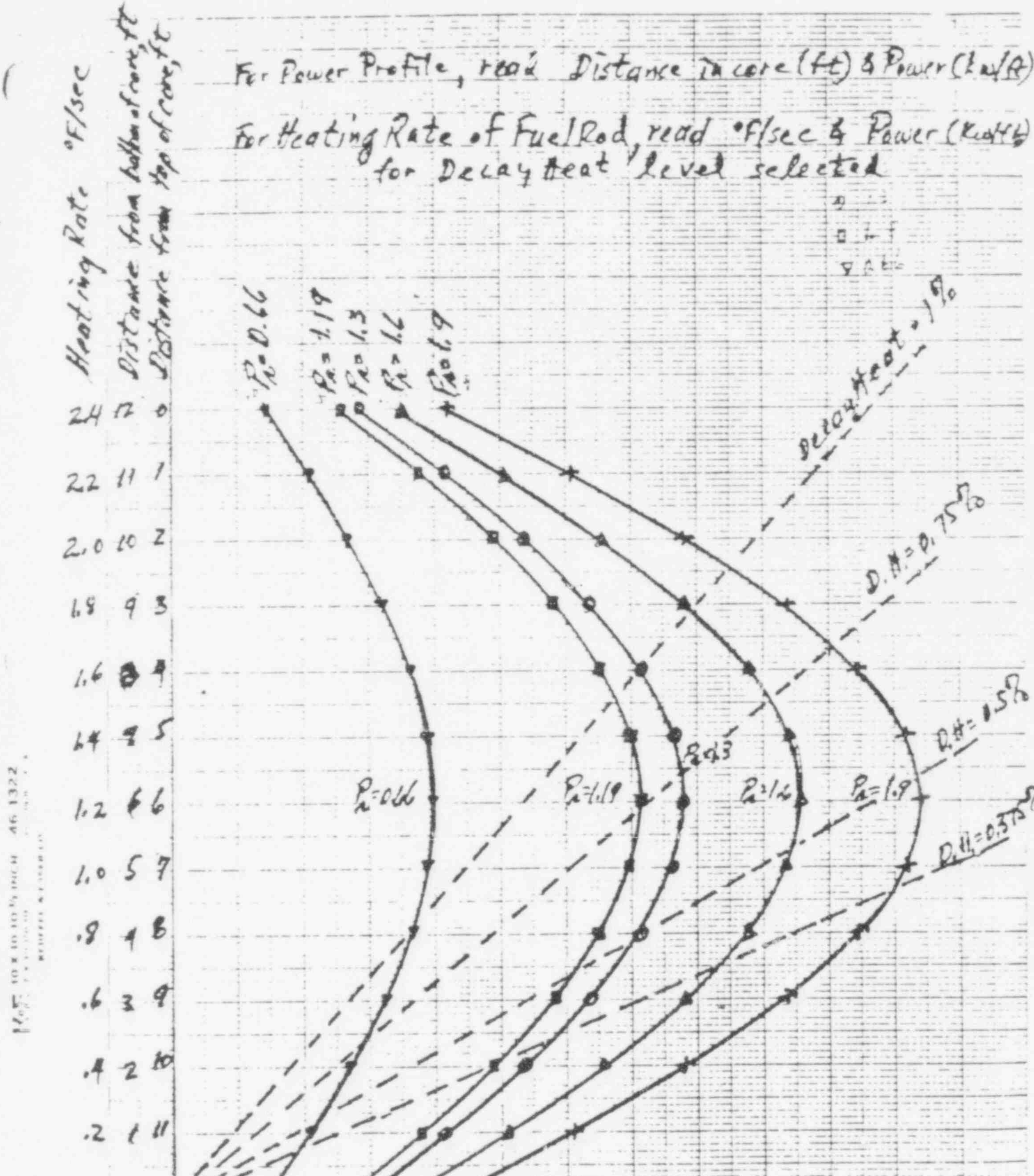
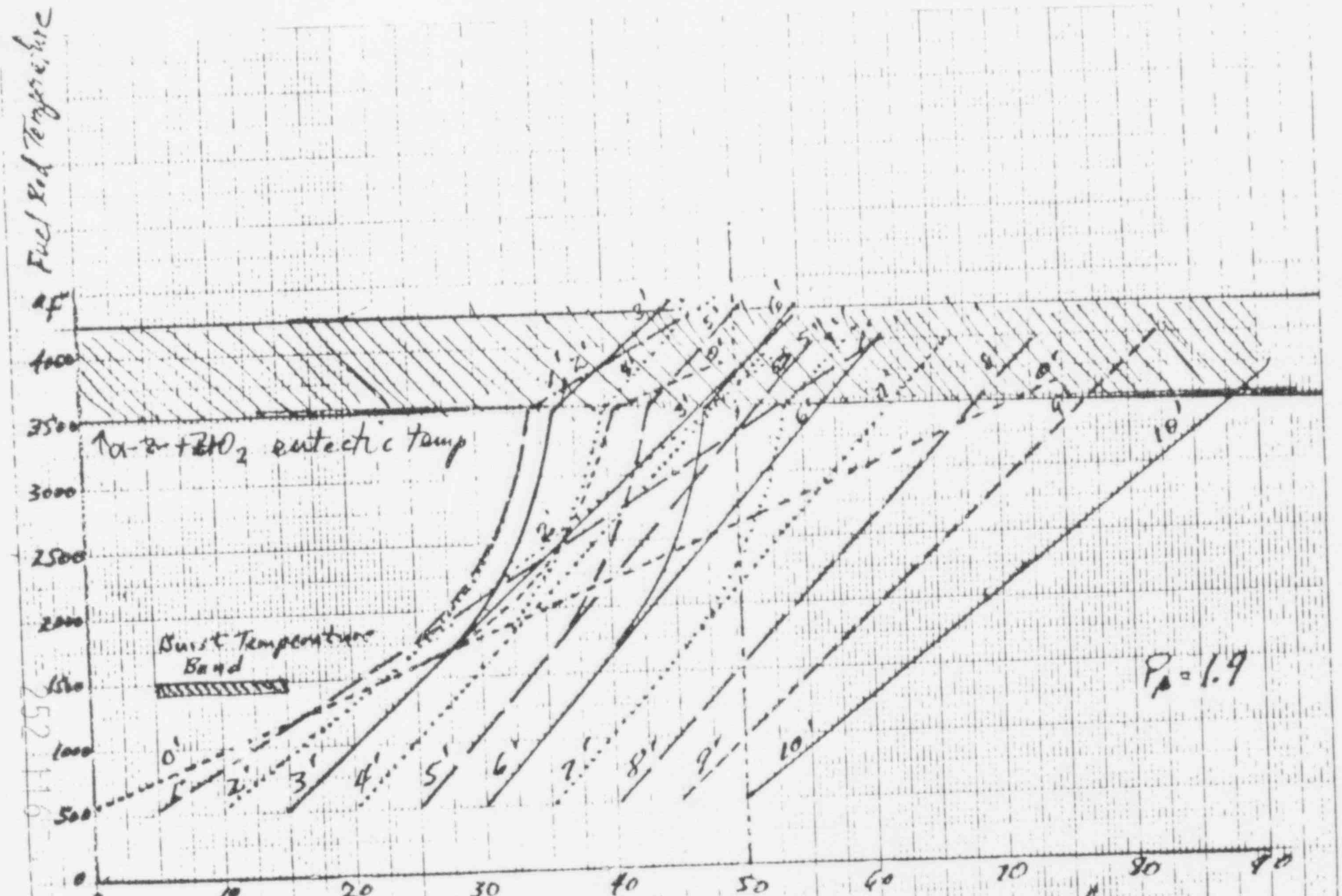

For Power Profile, read Distance in core (ft) & Power (kw/ft)
For Heating Rate of Fuel Rod, read °F/sec & Power (kw/ft) for Decay Heat level selected
Heating Rate °F/sec
Distance from bottom of core, ft
Distance from top of core, ft
Pr = 0.66
Pr = 1.19
Pr = 1.3
Pr = 1.6
Pr = 1.9
Decay Heat = 1%
D.H. = 0.75%
D.H. = 1.5%
D.H. = 0.375%
100% Power, kw/ft

Fig 2



Fuel Rod Temperature
°F
4000
3500
3000
2500
2000
1500
1000
500
0
↑α-Zr + ZrO2 eutectic temp
Burst Temperature Band
0'
1'
2'
3'
4'
5'
6'
7'
8'
9'
10'
Pp = 1.9
0
10
20
30
40
50
60
70
80
90
minutes after top of core uncovered

Fig 3

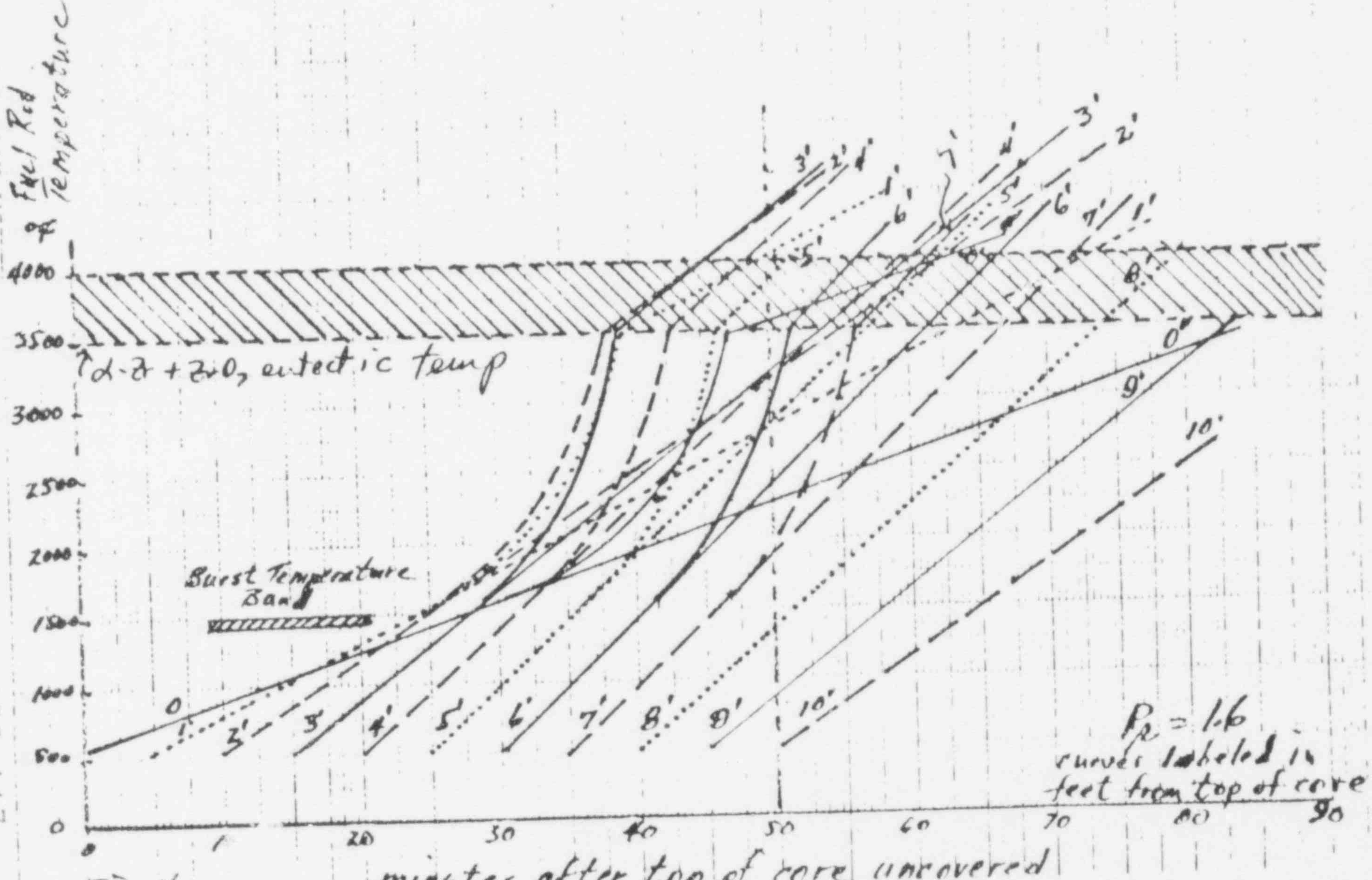

°F Fuel Rod temperature
4000
3500
3000
2500
2000
1500
1000
500
0
α-Zr + ZrO2 eutectic temp
Burst Temperature Band
0
10
20
30
40
50
60
70
80
90
minutes after top of core uncovered
Pk = 1.6
curves labeled in feet from top of core

Fig 4

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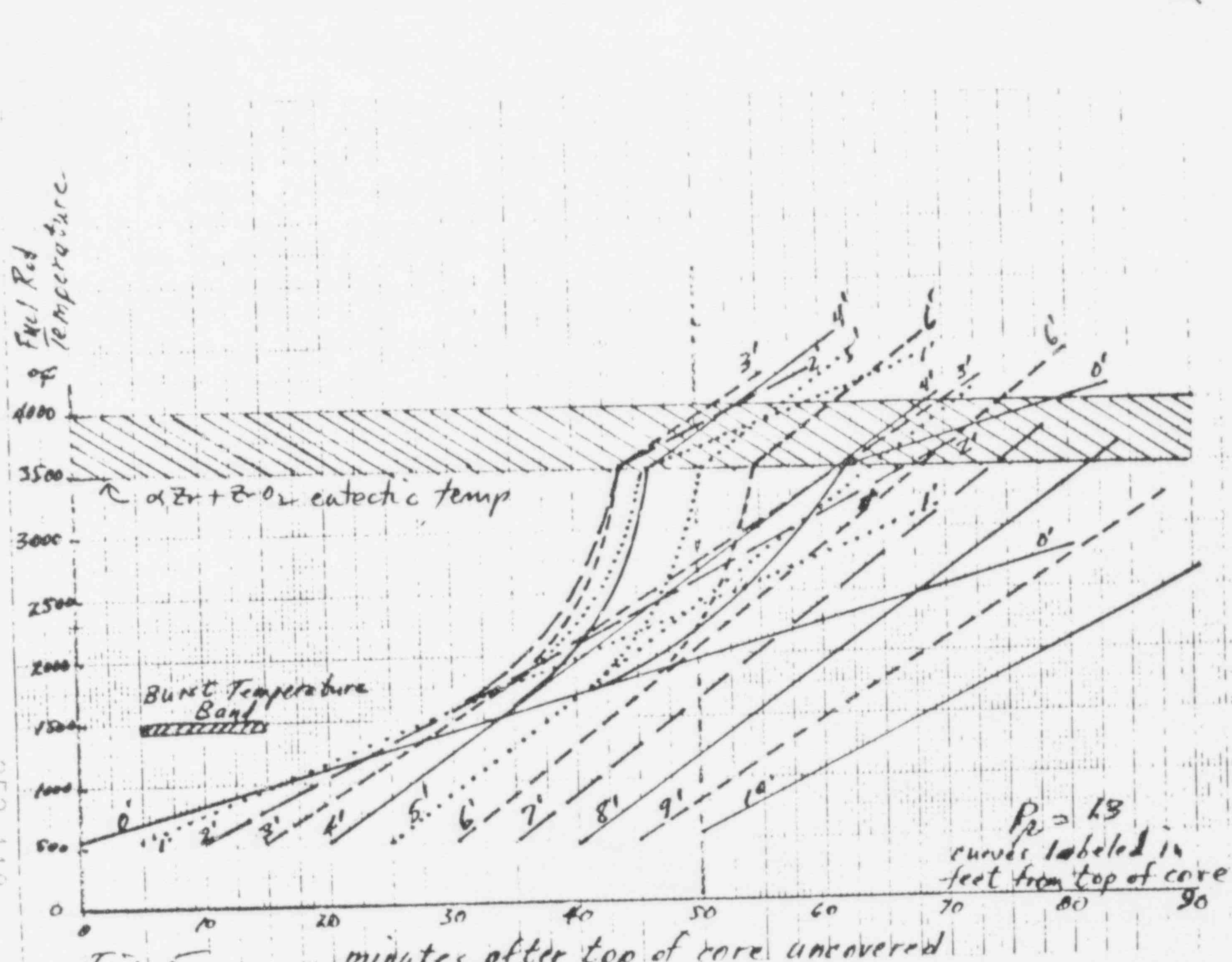
Fuel Rod Temperature °F
4000
3500
3000
2500
2000
1500
1000
500
0
α Zr + ZrO2 eutectic temp
Burst Temperature Band
0' 1' 2' 3' 4' 5' 6' 7' 8' 9' 10'
3' 2' 5' 4' 6' 1' 4' 3' 6' 0' 2' 1' 0'
P_R = 23
curves labeled in feet from top of core
0 10 20 30 40 50 60 70 80 90
minutes after top of core uncovered

Fig 5

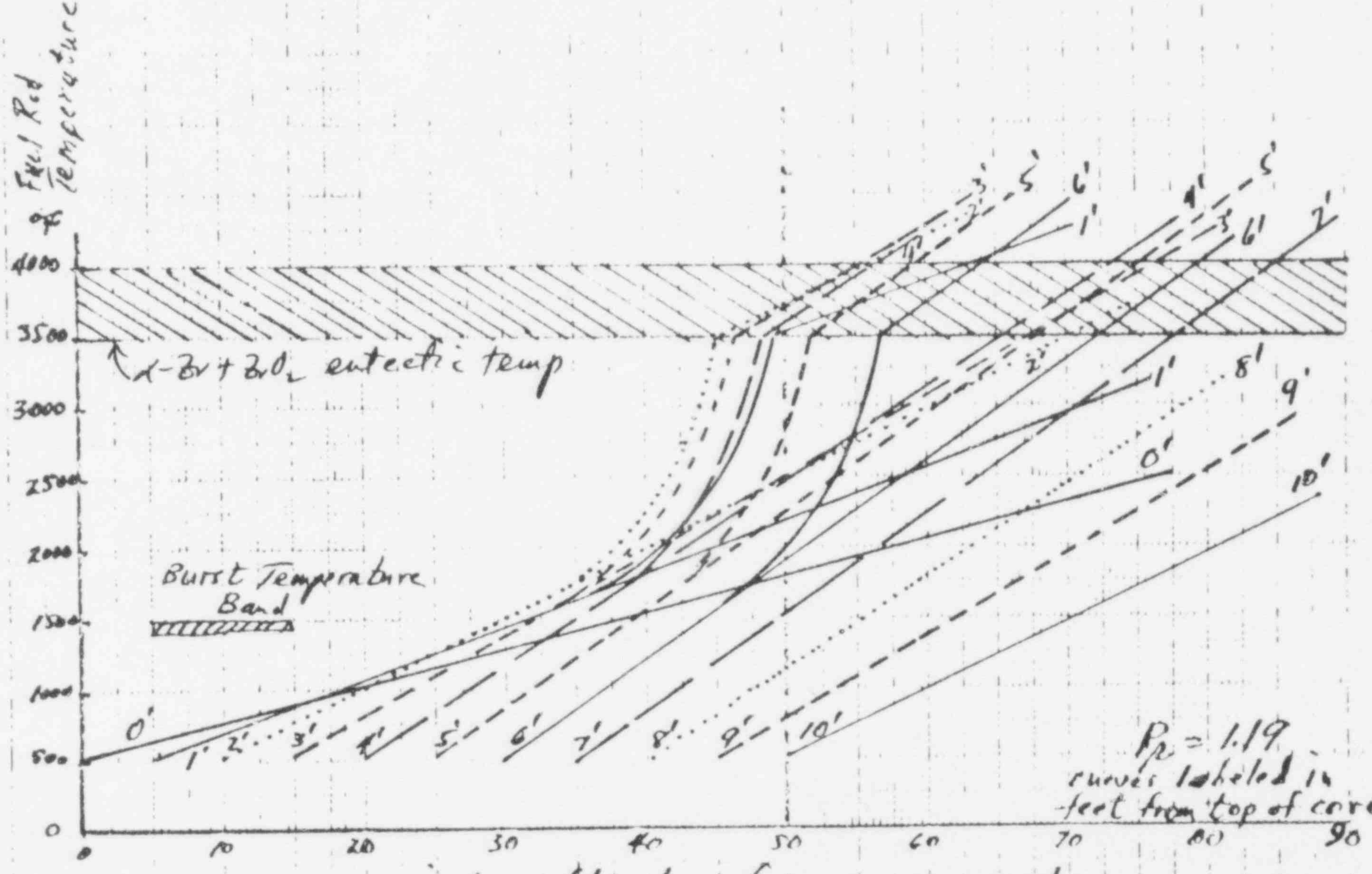

Fig 6

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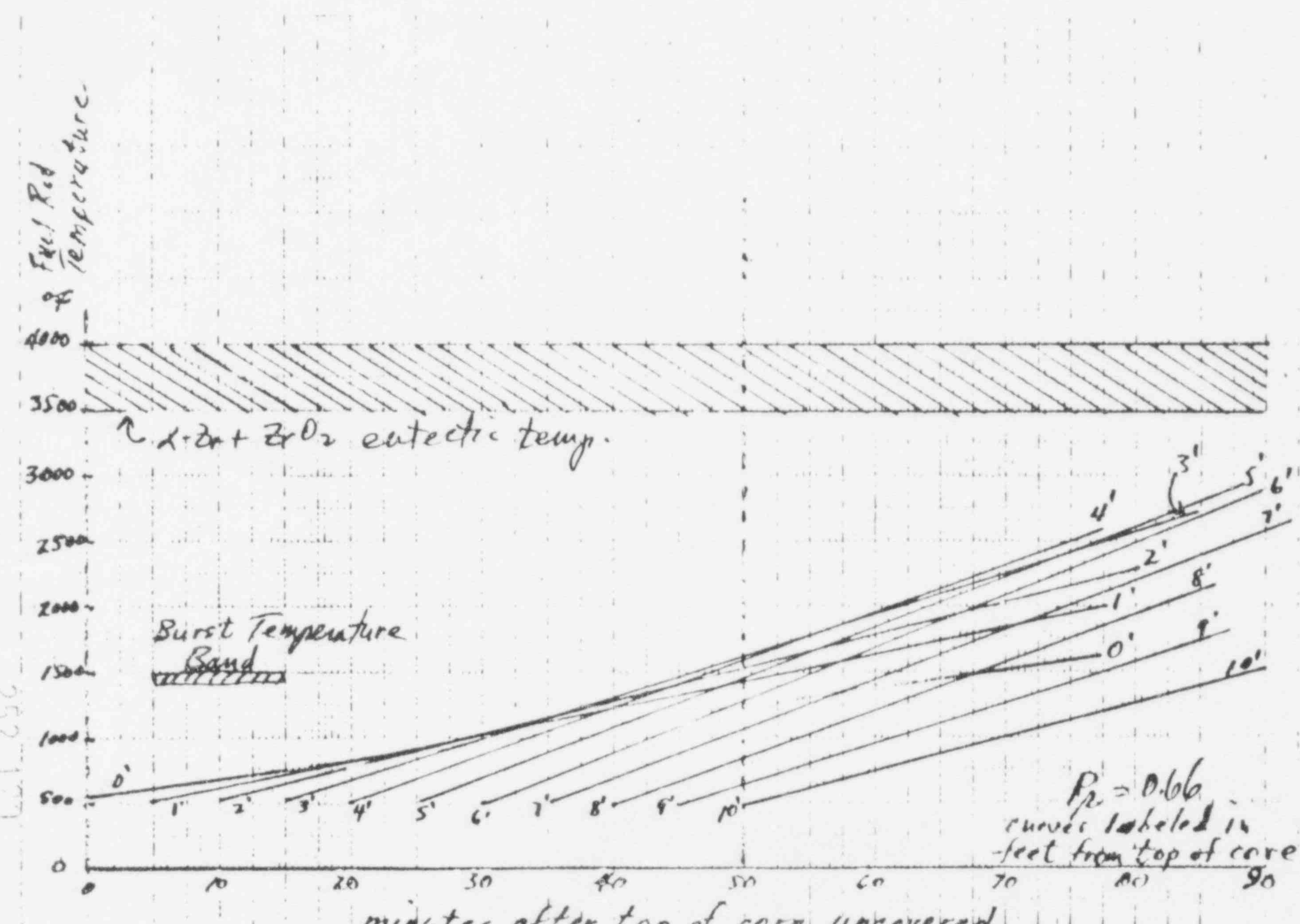
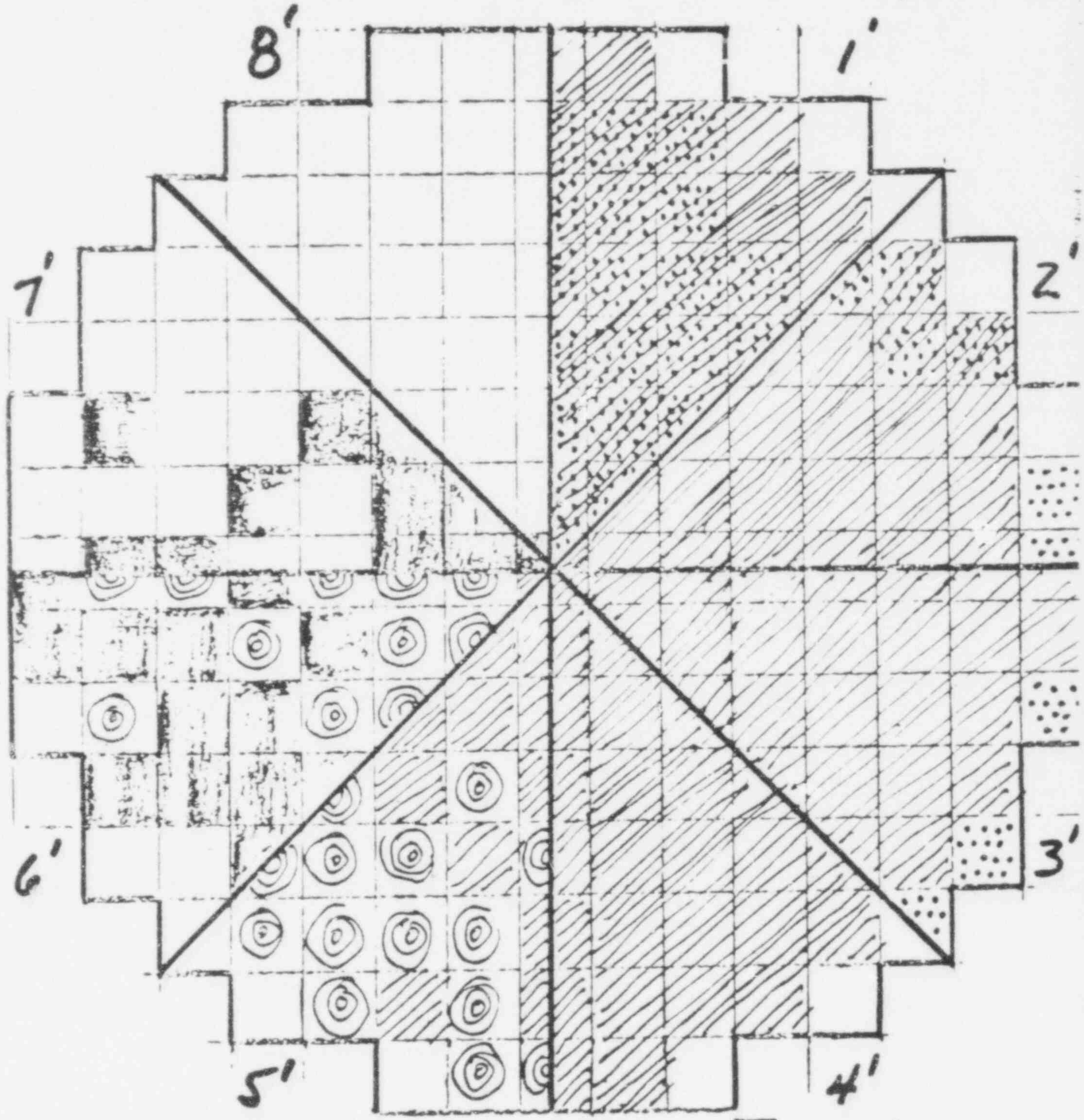

°F Fuel Rod Temperature
4000
3500
3000
2500
2000
1500
1000
500
0
α-Zr + ZrO_2 eutectic temp.
Burst Temperature Band
F_R = 0.66
curves labeled in feet from top of core
0 10 20 30 40 50 60 70 80 90
minutes after top of core uncovered

Fig 7

Fig 8 (10)



No significant oxdiation

Partly oxidized but not brittle

Oxidized to brittle [illegible] and or over [illegible]

Ruptured

α-Zr + UO_2 liquid formed

Fig 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.

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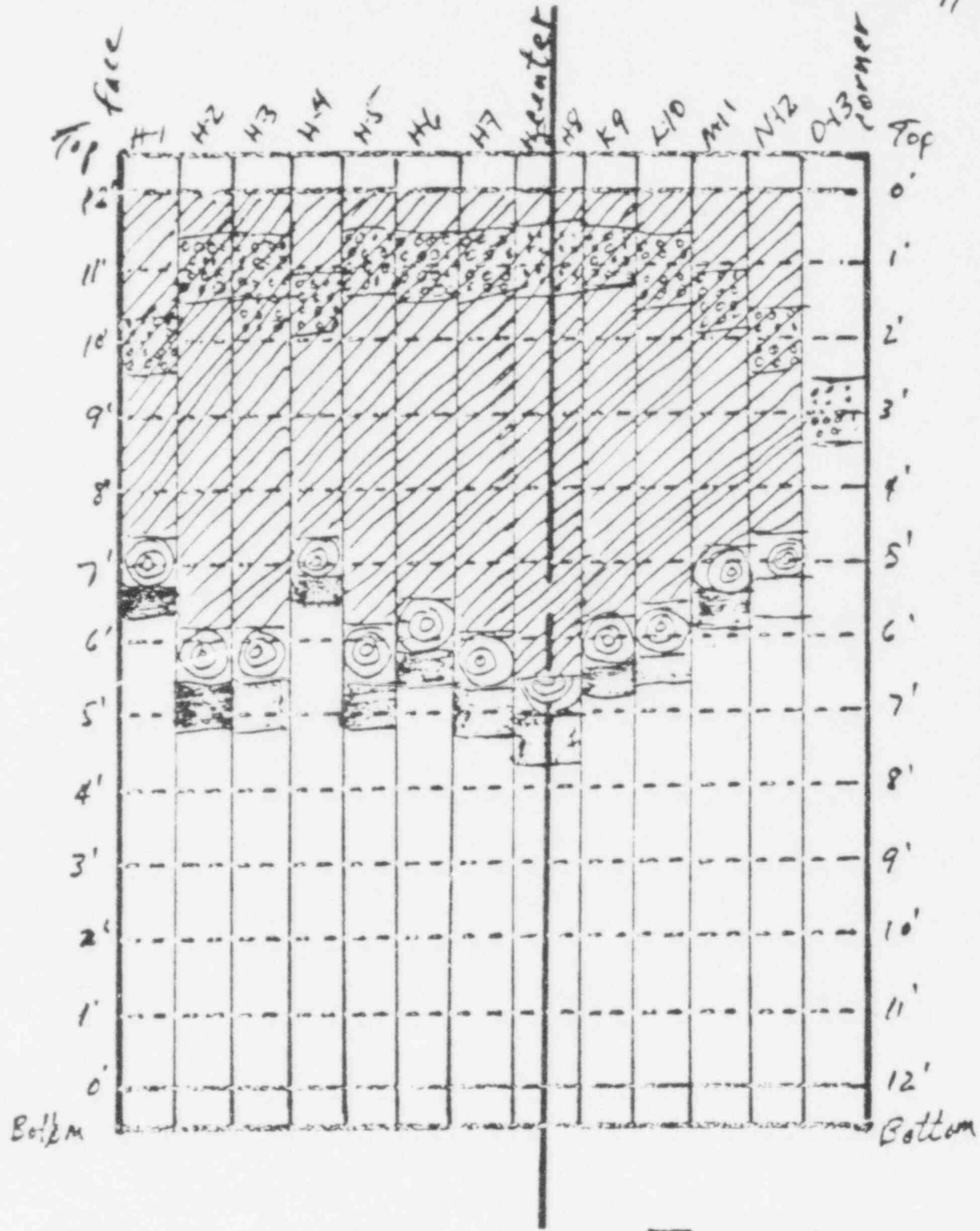
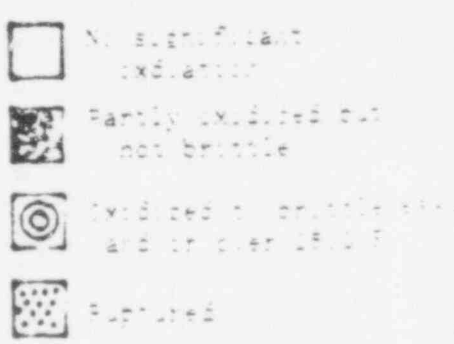


Fig 9

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.



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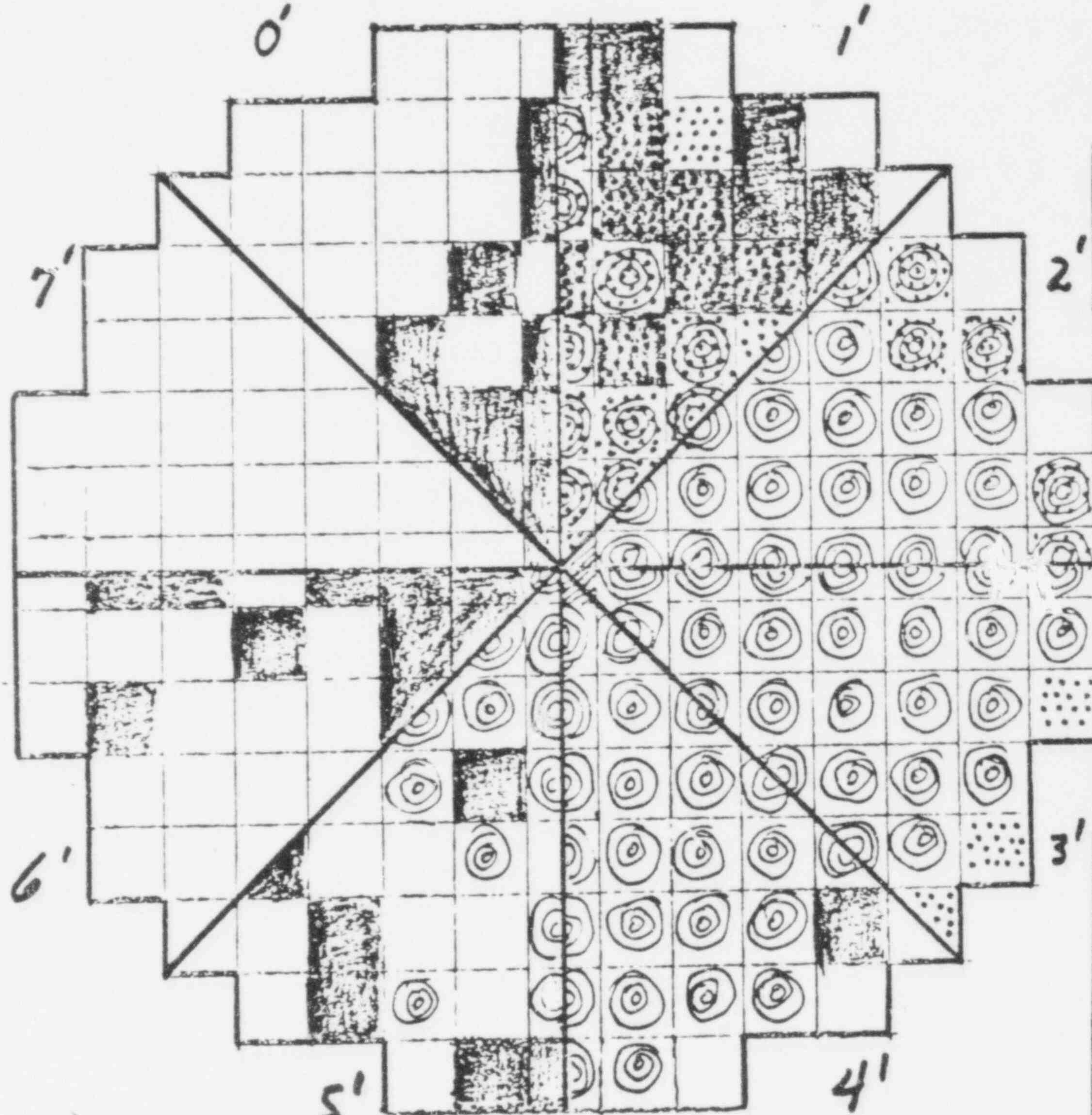
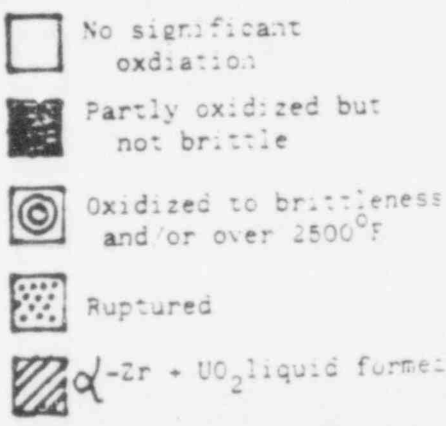


Fig 10

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.



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