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IMPROVED MK42 MELTING MODEL

The existing melting model that was developed for the Mark 16B assembly gives unnecessarily restrictive confinement protection limits (CPL's) when it is applied to the Mark 42 assembly. With this model the CPL analysis for the P-2 cycle indicates a reactor power penalty of 10-20%. An improved Mark 42 melting model has been defined for establishing CPL's. The new model is expected to give satisfactory Mark 42 CPL's in the P-2 cycle without restricting reactor power. This memorandum describes the new melting model and its application in computing CPL's.

Summary

The Mark 42 melting model assumes that either PuO_2-Al tubes melt and leave the inner Li-Al tube intact, or that melted PuO_2-Al tubes collapse against the inner Li-Al tube which is then heated to the melting temperature. The first course gives a smaller but more quickly realized reactivity increase than the second course. Both courses should be considered in Mark 42 CPL analysis. In P-2, the reactivity transient caused by the melt Δk will be analysed explicity for the first course, and specific limits will be published in separate documents. THE ABS-S/C DROP test would initiate reactor shutdown before the Li-Al tube begins to melt, so analysis of transients induced by melt of the Li-Al target will not be necessary. The second course does not apply if the Mark 42 contains no inner Li-Al tube.

Discussion

Background

Mark 42 assemblies have been in P reactor since August 1980, and recently (P-1) became targets, requiring confinement protection analysis for loss-of-target. In this context, targets are defined as net importers of neutrons.

Mark 42 has the same geometrical design as Mark 16B (reference 1). Analysis to establish Mark 42 confinement protection limits (CPL's) for P-1 used the Mark 16B melt model and a GRASS calculated melt function of melt ΔK vs melt fraction. (The melt function is described in a later section). In the P-1 design, Mark 42 has a low reactivity worth. The PuO_2-Al tubes are marginally targets, and Mark 42 assemblies contain weak (0.15 g ^6Li/ft) or no inner Li-Al tubes. Mark 42 CPL's for P-1 should not restrict reactor power (reference 2,3). In the P-2 design, Mark 42 PuO_2-Al tubes will be stronger absorbers than in P-1, and Mark 42 assemblies will contain 2.2 g ^6Li/ft Li-Al inner tubes. Mark 42 CPL's calculated using the Mark 16B melt model would restrict reactor power 10% to 20% in P-2. The Mark 16B melt model does not consider the inner Li-Al target because it is not always present. The model assumes the fuel and inner Li-Al target (if present) melt simultaneously, and the assembly Δk (fuel tubes and target) is realized during melt of the fuel tubes. An improved melt model for Mark 42 has been defined to treat melting of the inner Li-Al tube more explicitly. Preliminary calculations using the new melt model indicate Mark 42 CPL's will not restrict reactor power in P-2.

Mark 42 Melt Model

Model Description. The melt model includes two possible courses. One assumes that the PuO_2-Al tubes melt and disappear, and that the inner Li-Al tube remains intact. Data reported in reference 4 seem to imply that the inner Li-Al tube would not melt during the accident. GLASS calculations show that adiabatic heating of the Li-Al tube from absorbed alpha and gamma would produce melting temperatures about 70 seconds after the PuO_2-Al tubes melt. GLASS calculations that assumed the Li-Al tube was intact and particles from the melted PuO_2-Al tube were washed into the moderator region of the Mark 42 cluster gave a negative k at the present stage of the irradiation. Particle distribution in the moderator was discarded as non-conservative. Results of SLUMP calculations for melting of PuO_2-Al tubes only are shown by the solid line in figure 1. The calculations were made for a Mark 42 power of 3.0 MW and a coolant flow rate of 465 gpm. Mark 42 power is not expected to exceed 3.0 MW in P-2.

The second course assumes that melted PuO_2-Al tubes slump against the inner Li-Al tube. As the Li-Al tube temperature reaches the melt point, PuO_2-Al and Li-Al tubes disappear together. This model is described in detail in a later section. The dashed curve in figure 1 shows the additional time required for the Li-Al tube to heat as successive axial regions of PuO_2-Al tube begin to melt. The total time required for the hottest axial region of the PuO_2-Al tube to reach its melt point and the corresponding region of the Li-Al tube to rise to melt temperature is 8.2 sec. The heatup energy is 24.6 MW-sec.

Model Application

In loss-of-target accidents, the flow monitoring safety computer is assumed to be bypassed. A scram, which initiates the ABS-S/C logic tests, is ordered when the temperature signal reaches the scram set point.

Separate analyses (reference 5) have shown that the ABS-S/C DROP test will initiate reactor shutdown no later than 6.9 sec after blockage of an assembly flow. Reactor shutdown before onset of Li-Al tube melt is assured if Mark 42 power does not exceed 3.5 MW (= 24.6 MW-sec/6.9 sec). As mentioned earlier, the maximum Mark 42 power expected in P-2 is 3.0 MW. P-2 analysis will be made for the first melt course for reactivity transients induced by the k derived from melting of PuO_2-Al tubes only. (The ABS-S/C DROP test will not prevent onset of PuO_2-Al tube melt for power greater than 1.8 MW.) The maximum reactivity from

loss of Mark 42 PuO_2-Al tubes with the Li-Al tubes intact is about 0.06% k in P-2.1, compared to about 0.28% k for loss of PuO_2-Al and Li-Al tubes. Preliminary calculations indicate that a Mark 42 CPL of 3.0 MW, which should not restrict reactor power, can be established for a reactivity up to 0.12%k. While sufficient Mark 42 data to evaluate explicity the reactivity worth of the PuO_2-Al tubes in subsequent P-2 subcycles are not yet available in the accident analysis codes, results of P-2 GLASS calculations indicate the worth will not exceed this value.

Melt Function

The melt k vs fraction of assembly melt was calculated with GRASS for a Mark 42 located at X37-Y57 in 360° symmetry. Mark 42 fewgroup parameters were calculated with GLASS. It was assumed that melt began at the axial center and progressed evenly towards both ends of the assembly. The results are shown in figure 2. For comparision, the slump model function used for slug assemblies such as Mark 31 is also shown. The Mark 42 function gives a higher initial k/melt than the slump function, but becomes less after about 25% melt of the assembly. AA3 calculations were made for each melt function. The Mark 42 function gave a faster rate of rise and greater steam pressures prior to shutdown than the slump function.

Inner Target Heatup and Melting

The accidental melting of an inner Li target in the Mk42 assembly is a complex phenomenon that cannot be precisely defined and analyzed mathematically. The analysis is fraught with a number of uncertainties; such as, does the molten fuel* fragment and discharge from the assembly or does it flow against the target? Both types of behavior have been observed in experiments. And if the molten fuel does come in contact with the inner target, how much surface area is contacted, and how well is heat transferred from the hot fuel to the cold target? To some extent, the behavior depends on the conditions that lead to the fuel melting in the first place.

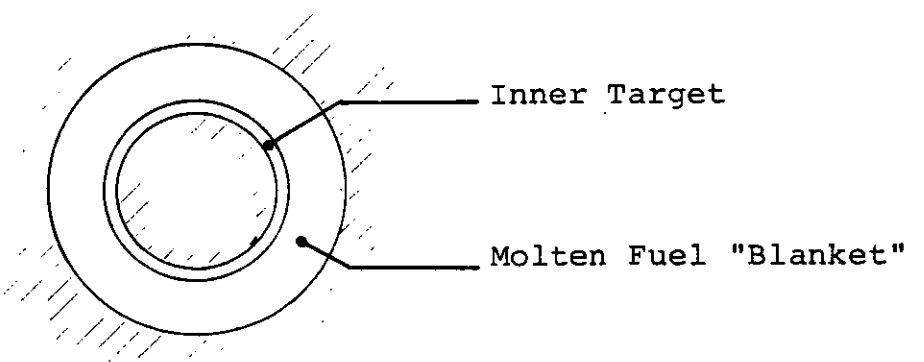
The primary question for the Mk42 accident analysis is, does the inner target melt when fuel is postulated to melt? And given an affirmative reply to this question, how long does it take to melt the inner target? Photgraphs from fuel melting tests with SRP type assemblies in the SPERT facility during the mid 1950's

* In this context, the word "fuel" is used in a general sense to denote material that has a high specific heat generation relative to the "target". In this sense the PuO_2-Al tubes are fuel material, irrespective of their neutronic behavior.

seem to indicate that melting of the inner and outer housings, which were in contact with water, did not occur.[4] However, it cannot be said with absolute certainty that under different conditons melting of the Mk42 inner target housing would not happen.

Past accident analyses have assumed very conservatively that the target melts and disappears along with the fuel with no time difference between the two events. The requirement of instantaneous melting is unnecessarily restrictive. Given the fuel melts, it must slump over or flow to make contact with the inner tube. The likelihood of perfect contact is low because of the oxidation of the aluminum surface. There would be a contact resistence to heat flow between the fuel and the target that limits how rapidly heat goes from one body to the other. And the temperature of the target depends on the amount of heat transferred to it. So there is a definable lapse of time for the inner target to melt after the fuel melts and contacts the target. And the fuel, although molten, must somehow remain in contact with the target for that length of time. Heat transfer from the fuel by radiation is insufficient to raise the inner target temperature to the melting point in the relatively short time frame (less than 10 seconds) of concern in the accident analysis.

A less restrictive model than instantaneous melting of the target can be defined to calculate conservative limits on Mk42 power. The model assumes that after the fuel melts it somehow comes together and forms a blanket around the inner target tube and stays in contact with it for as long as it takes to melt the inner target. The fuel continues to generate heat internally. Some of this heat is transferred to the target and the rest remains in the fuel raising its internal energy and temperature. For the Mk42 assembly no mechanism is known that would keep the molten fuel from streaming away at these elevated temperatures. The model assumes adiabatic surfaces outside the fuel and inside the inner tube. No credit is taken for heat transfer to the water in the inner most channel. The model strictly looks at the one dimensional, time dependent transfer of heat between two bodies that are adiabatically isolated from all else as shown below.



The initial temperatures of the two bodies at time, $\theta=0$, are assumed to be 1220°F, the melting point for aluminum, for the molten fuel and 190°F for the inner target. The target temperature is the average between the temperature of the fluid in the inner channel (140°F) and the temperature of saturated steam (240°F). Physical properties of aluminum are applicable to both the fuel and the target (see Table I). An average surface contact coefficient of $h = 500$ Btu/hr.ft^2.°F is appropriate for rough aluminum surfaces in contact under light pressure (reference 6, p.18).

The inner target tube was treated as if having negligible internal resistance to heat transfer. According to Kreith (reference 7, p. 128) this simplification is justified when the external thermal resistance between the surface of the system and the surrounding medium is so large compared to the internal thermal resistance of the system that it controls the heat-transfer process, i.e., when $hL/k < 0.1$. For the inner target this dimensionless number is about 0.03.

The temperature of the target as a function of time is given by:

$$\frac{t - T_o}{t_o - T_o} = \exp - (ha/c\rho V)\Delta\theta \qquad \text{(reference 7, p. 129)}$$

See Table I for definition and units.

The molten fuel layer cannot be treated in the same way as the inner target, because the condition $hL/k < 0.1$ is not satisfied. Instead the Dusinberre numerical method can be used to calculate the time dependent temperature distribution within the fuel (reference 6, p. 29). In this method the region of concern is divided into a number of slices, ΔX in thickness. The equations for the iteration method assuming uniform internal heat generation, are given below. The subscripts refer to the layer boundaries and the prime refers to the values at the next time step.

$$T_1' = \frac{T_o + (M-2)T_1 + T_2}{M} + \frac{G_{\Delta x,-\Delta\theta}}{M}$$

$$T_o' = \frac{2Nt + [M-(2N+2)]\ T_o + 2T_1}{M} + \frac{G_{\Delta x,\Delta\theta}}{M}$$

$$G_{\Delta x,\Delta\theta} = q\Delta x/Ak$$

$$N = h\Delta x/k$$

$$M > (2N + 2)$$

$$\Delta\theta = (\Delta x)^2/\alpha M$$

$$\alpha = k/\rho C$$

See Table I for definitions and units.

With the aid of a computer program that combines the target and fuel models, the temperature transients are solved numerically for various power generation rates in the fuel. The heat of fusion is taken into account for both the target and fuel in the computer program.

Figure 3 shows the results of a typical calculation. The assumed power generation rate in the fuel is 0.24 MW/ft, corresponding to 3 MW per assembly. The target temperature rises from 190°F to 1220°F (melting temperature for aluminum) in about 4.5 seconds. After that it takes another 2.5 seconds to transfer enough heat into the target to melt all of it. However, it would not be conservative to assume that the target material remains in place until all of it has become molten. In doing the accident analysis it may be best to take credit for the additional heatup time only, not the melt time. During this transient the average temperature of the molten fuel starts at 1220°F, reaches 1870°F when the target gets to the melting temperature, and exceeds 2200°F when the target has become completely molten. It is likely that some of the fuel would stream away toward the bottom of the assembly until it solidifies against some colder component. This would prolong the time it takes the target to reach 1220°F. And if enough fuel flowed away, it would be likely that the target would not melt at all. But uncertainties in this behavior make it prudent not to rely on it for accident analysis. The target heatup times for various levels of power generation in the fuel are shown in Figure 4.

/mbt

REFERENCES

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4. J. R. Seaboch and J. W. Wade. Fuel Meltdown Experiments, DP-314, October 1958.

5. J. A. Smith and A. A. Tudor. Confinement Protection for Special Target Assemblies, DPST-81-729, September 18, 1981.

6. W. H. McAdams. Heat Transmission, McGraw-Hill, New York, 1954.

7. F. Kreith. Principles of Heat Transfer, International Textbook Co., Scranton, Pa., 1969.

TABLE I

Definitions and Units

t	temperature of target, °F
t_o	temperature of target at time = o, °F
T_i	temperature of fuel at ith boundary, °F (previous time step)
T_i'	temperature of fuel at ith boundary, °F (current time step)
ΔX	slice thickness, ft (i.e., for m slices, $\Delta X = X/m$)
q	internal heat generation rate, Btu/hr
A	effective area for heat transfer through fuel, ft^2 (e.g., log-mean area)
a	surface area of target, ft^2
V	volume of target, ft^3
$\Delta\Theta$	time interval, hr
k	thermal conductivity, Btu/hr ft°F
h	heat-transfer coefficient at interface, Btu/hr ft^2°F
ρ	density, lb/ft^3
c	specific heat, Btu/lb°F

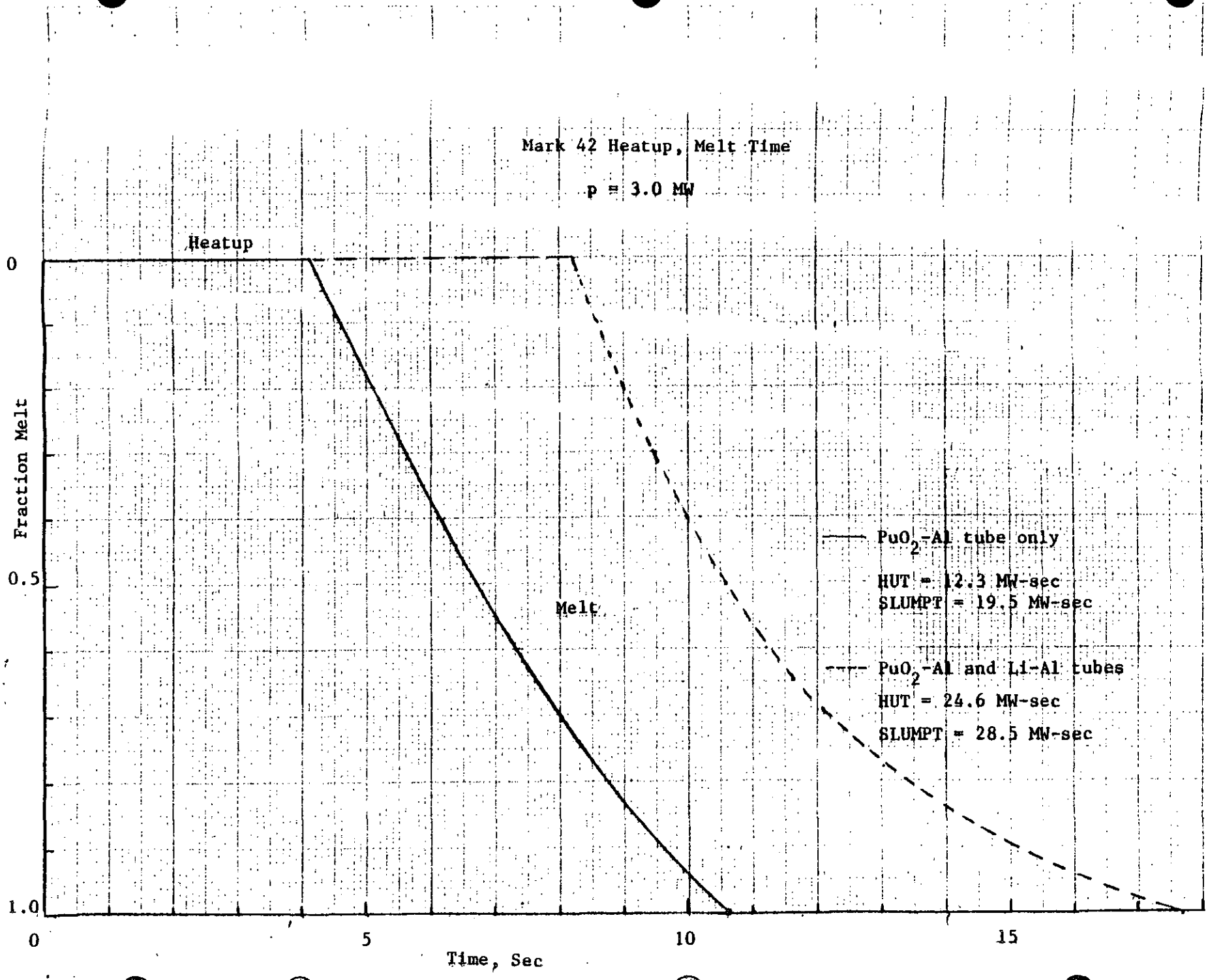
Dimensions

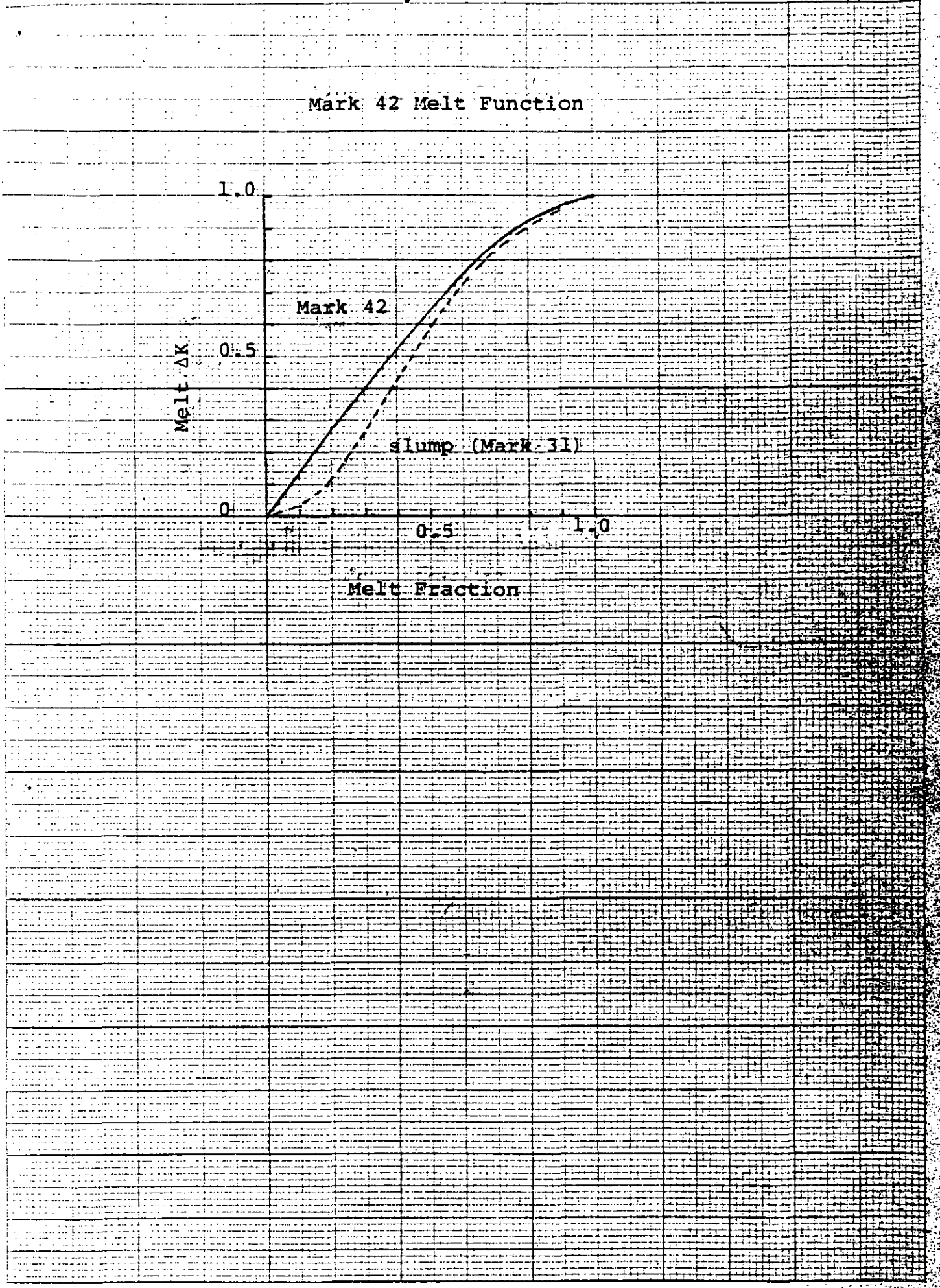
Target volume per foot	.00345 ft^3
Target surface are per foot	.361 ft^2
Molten fuel volume per foot	.0284 ft^3
Fuel log-mean area per foot	.511 ft^2

Physical Properties

Melting temperature, Al	1220°F
Latent heat of fusion, Al	170 Btu/lb
Specific heat for solid Al	.22 Btu/lb°F@212°F
	.28 Btu/lb°F@1100°F
Specific heat for molten Al	.26 Btu/lb°F@1290°F
Density of aluminum	165 lb/ft^3
Thermal conductivity solid Al	119 Btu/hrft°F@212°F
	155 Btu/hrft°F@932°F
Thermal conductivity molten Al	60 Btu/hrft°F@1290°F

Figure 1


Mark 42 Heatup, Melt Time
p = 3.0 MW
Heatup
Melt
0
0.5
1.0
Fraction Melt
0
5
10
15
Time, Sec
PuO2-Al tube only
HUT = 12.3 MW-sec
SLUMPT = 19.5 MW-sec
PuO2-Al and Li-Al tubes
HUT = 24.6 MW-sec
SLUMPT = 28.5 MW-sec


Mark 42 Melt Function
1.0
0.5
0
Melt ΔK
Mark 42
slump (Mark 31)
0.5
1.0
Melt Fraction

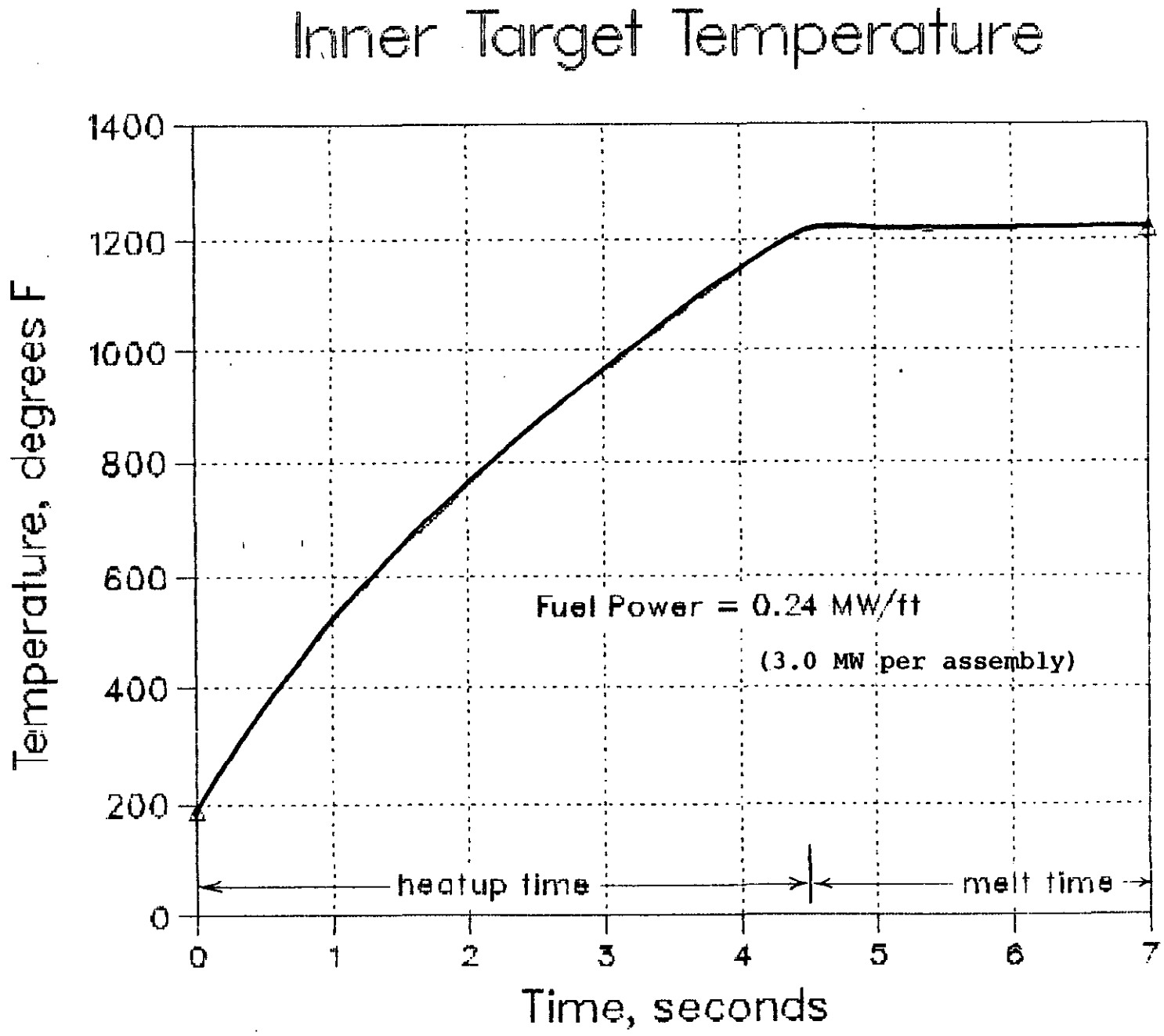
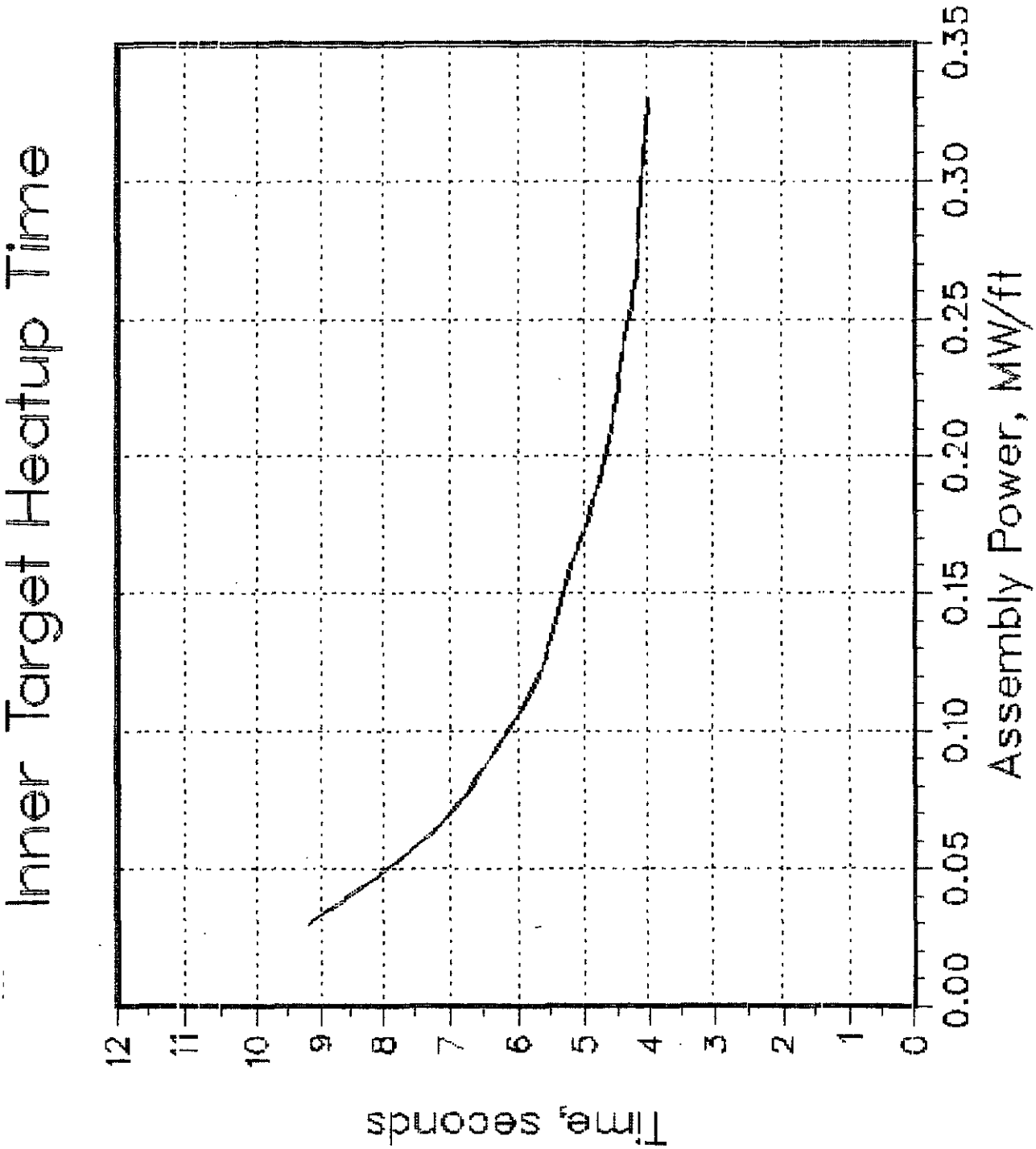

Inner Target Temperature
Temperature, degrees F
1400
1200
1000
800
600
400
200
0
Fuel Power = 0.24 MW/ft
(3.0 MW per assembly)
heatup time
melt time
0
1
2
3
4
5
6
7
Time, seconds

Figure 3

Figure 4


Inner Target Heatup Time
Time, seconds
Assembly Power, MW/ft
0
1
2
3
4
5
6
7
8
9
10
11
12
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35