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Emergency Cooling and Afterheating Effects of a CTR Blanket

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Abstract

The thermal effects of loss of flow accident and afterheat to a UWMAK-I type blanket are investigated. The temperature response of the first wall, as well as the whole blanket are calculated with a finite difference method. For a loss of flow accident, the plasma has to be quenched between 10 to 60 seconds, beyond which we may lose the first wall. The temperature of the first wall does not present a serious problem due to afterheat. No freezing will occur in the blanket within two days of reactor shutdown so that the blanket does not have to be evacuated.

Introduction

The Wisconsin Fusion Design Study Group is working on a low-β D-T fusion reactor based on the Tokamak confinement concept, the UWMAK-I.(1) The thermal power output of the plant is 5000 MW. The basic structural material is 316 stainless steel. Natural lithium is used both as the coolant and the breeding material(2) A stainless steel layer is used as the moderator-reflector. Materials compatibility between 316 stainless steel and dynamic lithium limits the lithium-stainless steel interface temperature to below 500°C to avoid excessive corrosion of steel by lithium(3).

A cross section of UWMAK-I is shown in Fig. 1. The major parameters related to heat transfer problems are listed on Table 1. Lithium coolant for a magnetic confined reactor requires careful considerations regarding magneto-hydrodynamic effects to both heat transfer and pumping pressure drop(4). However, our recent study (2) shows that lithium can be an effective coolant for such a reactor in a steady state operation if the coolant channels are properly designed. Further study shows lithium coolant can be used in a system with stronger magnetic field and larger wall loading(5).

Very little work has been done on the thermal effects for the loss of flow accident and afterheating effect of a CTR blanket. An ideal CTR blanket should have a larger thermal inertia near the first wall to prevent a thermal shock in a losing flow accident. It also should have a good thermal conductance to prevent first wall overheating due to the afterheat and to minimize the possibilities of localized freezing near the sink after the reactor shut down. It is the author's belief the lithium blanket has an edge over flibe blanket in this regard. Exact comparisons can be made only after similar calculations are made for other blankets.

The thermal effect of loss of coolant accident is yet to be calculated. The spatial heating rate distribution in the blanket is completely different from the normal one and is not available at this time.

System Description

A section view of the blanket is shown in Fig. 2. The first wall is 2.5

mm thick for minimum stress(2). The next 20 cm are called the radial flow cells which direct coolant to the first wall to cool it. The next 30 cm is polodial headers which distribute coolant along the poloidal direction. 15 cm stainless steel 316 reflector follows, which is divided into two layers to provide adequate cooling. After which is the shield region which is separated from the blanket by a vacuum gap acting as a thermal barrier. This keeps the blanket as a hot zone and the shield as a cold zone. A schematic of the composition and dimensions of the blanket and shield for heat transfer calculation is shown on Fig. 3. The first wall thickness is 4 mm to account that a curved wall is represented by a smooth one. It is followed by a 95% Li-5 % 316 stainless steel zone. After which there are reflector zone, coolant zone, structure, vacuum and shield.

The surface and volumetric heat input rates were taken from neutronic calculations(6) and shown on Fig. 4. Based on this the temperature distribution in the blanket and shield is calculated with an implicit finite difference method with a two dimensional point mesh conforming to the streamlines of the coolant flow.(2) This result is shown in Fig. 5, which constitutes the initial condition for the following calculations.

Afterheating Effect

During reactor shutdown, it is essential to prevent either overheating of the first wall or localized freezing in the blanket. If the first wall is overheated for an extended period of time, it will be damaged and may have to be replaced. If freeze occurs in the blanket, the volumetric change will cause large stresses in the structure and may damage the structure. It is, therefore, necessary to evaluate the blanket before freezing occurs.

It is assumed no additional cooling is provided for the blanket during the reactor shutdown. The afterheat is calculated for the UWMAK-I(7) blanket as a function of length of operation time, time after shut down and distance from the first wall, part of which is shown in Fig. 6. The shield is assumed to be an isothermal sink. The energy generated in the blanket is transferred across the vacuum gap to the sink by thermal radiation. Therefore, the emissivity of the surfaces facing the vacuum gap will be an important parameter.

The calculation is carried out with an implicit finite difference method with a one dimensional point mesh representing the system shown in Fig. 3. The heat input is fed into the calculation by 10 points picked from Fig. 6 and linearly interpolated for the values in between. Thermal emissivity of both surfaces facing the vacuum gap are assumed to be the same and its effects have been determined.

Fig. 7 shows the first wall temperature as a function of time after reactor shutdown with a 2 year operating time. Two values of thermal emissivity are shown in the figure. For either case, the first wall temperatures do not exceed 570°C, which is well within the stress limit of 316 stainless steel. The maximum first wall temperature occurs after 2 or 3 hours after the reactor shutdown. Just for comparison, if the breeding material is changed to flibe while keeping the initial temperature and the afterheat input the same, the first wall temperature will exceed 620°C even with a back wall emissivity 1.0. The first wall will stay beyond 600°C for about 40 hours, where it will probably lose its cold work.(8)

Figure 8 shows the back wall temperature as a function of time after reactor shut down after 2 years of operation with thermal emissivity equal to 1.0. It takes about 50 hours for the temperature to reach 300°C. Therefore, it can be assumed that if the reactor is to be shutdown for less than two days, the blanket will not freeze. If the reactor is to be shut down for more than two days, evacuation of the blanket may be necessary.

Loss of Flow Accidents

During reactor operation, failure of the pump constitutes one of the possible causes of loss of flow accident. The plasma is still in full power, but the coolant becomes stationary. It is essential to calculate the temperature response of the first wall to estimate how soon the plasma has to be quenched. one has to keep in mind there is 3 x 10^9 Joules of thermal energy in the plasma which probably has to be dumped to the first wall during the quenching of the plasma. Therefore, enough time must be allowed for the quenching process to avoid a thermal shock of the first wall.

The temperature distribution shown on Fig. 5 is used as the initial condition for the calculation. The heat input is the same as shown in Fig. 4. It assumes that during the steady state operation, the coolant suddenly becomes stationery with the full plasma power on. Fig. 9 shows the temperature reaction of the first wall after the accident occurs.

Two temperatures are of most interest. The first is 600°C below which no damage will be done to the first wall. The reactor can be back in operation after repair work is done. The other temperature is 800°C beyond which we may lose the first wall. Large quantities of lithium may be dumped to the torus. The temperature in between will not cause major damage to the first wall, but may cause repair work. Therefore, the plasma is preferred to be shut down within 10 seconds after the accident occurs. It has to be quenched within 1 minute after the accident occurs. The energy in the plasma amounts to .1 MW/m^2 if the energy is distributed uniformly over 10 second period. This is no reason to doubt the accident cannot be detected and plasma quenched between the time 10 to 60 seconds.

Conclusions

The thermal effect of afterheat and loss of flow-accident for the UWMAK-I lithium cooled blanket have been studied. No major hazard can be visualized at this stage. The following conclusions can be made:

1. The first wall temperature will never exceed 550°C after reactor shut down. No damage to the first wall material can be forseen at that temperature.
2. No freezing will occur within 48 hours after reactor shut down so that the blanket does not have to be evacuated.
3. In a lose of flow accident, the plasma should be quenched within 10 seconds after the accident occurs.
4. If the plasma is not quenched within 60 seconds after lose of flow accident occurs, major disaster may occur.
5. Li has advantages over flibe or helium in an emergency cooling situation.

Acknowledgement

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Table I

Summary of Important Parameters for Heat Transfer

Total Thermal Load	5000 MW
Major Radius	13 m
Minor Radius	5.5 m
Total Thermal Wall Loading	1.77 MW/m^2
Magnetic Field on Plasma Axis	3.86 Tesla
Structural Material	316 SS
Blanket Coolant	Lithium
Maximum Lithium Temperature	500°C
Lithium Temperature Rise	200°C
Lithium Flow Rate	5.64×10^3 kg/sec
Maximum Lithium Pressure Drop	410 psi
Maximum First Wall Pressure	300 psia
Lithium Pumping Required	22 MW

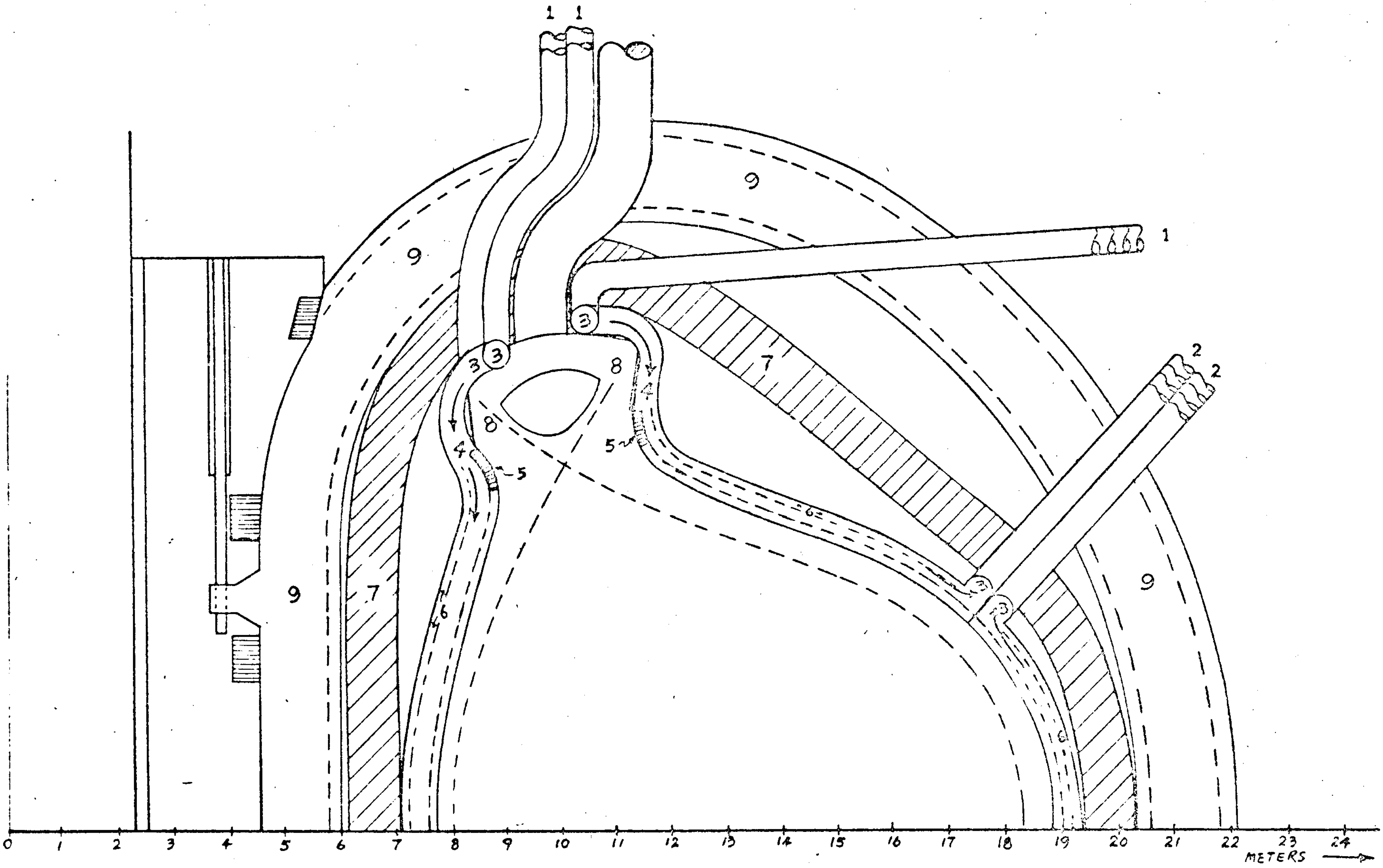

FIGURE 1 SECTION VIEW OF A TOROIDAL MODULE

1. Feed Pipes
2. Discharge Pipes
3. Toroidal Headers
4. Poloidal Headers and Connectors
5. Radial Flow Cells
6. S. S. Reflector
7. Shield
8. Divertor Slots
9. Superconducting Magnets

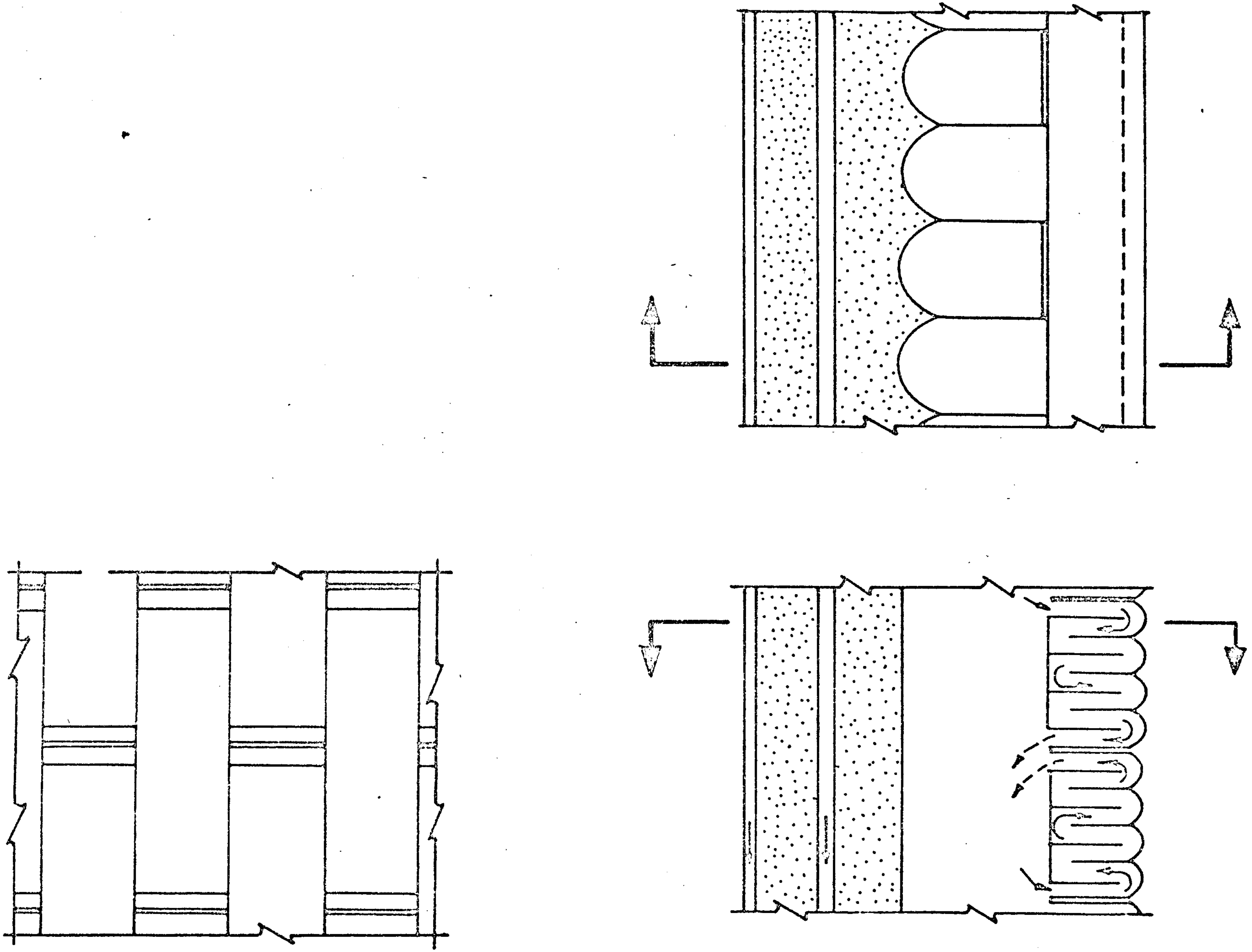

FIG. 2 SECTION VIEWS OF BLANKET

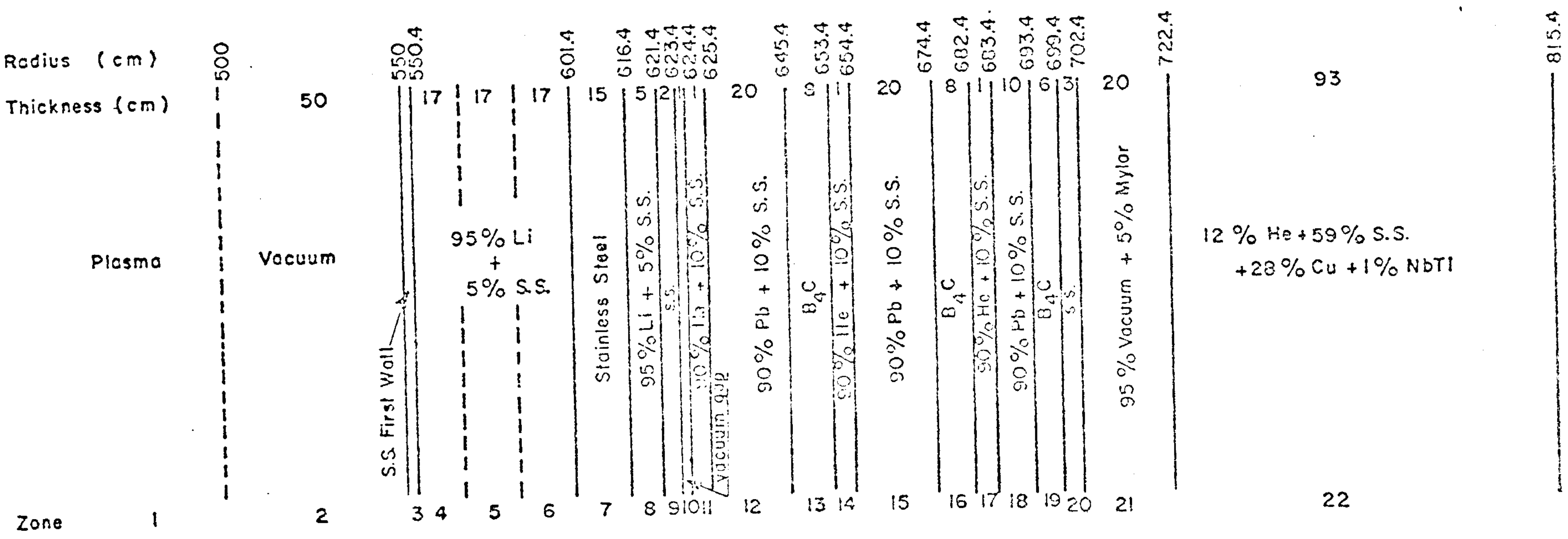

Figure 3 University of Wisconsin CTR Blanket, Shield and Magnet Structure for 5000MW_T System.

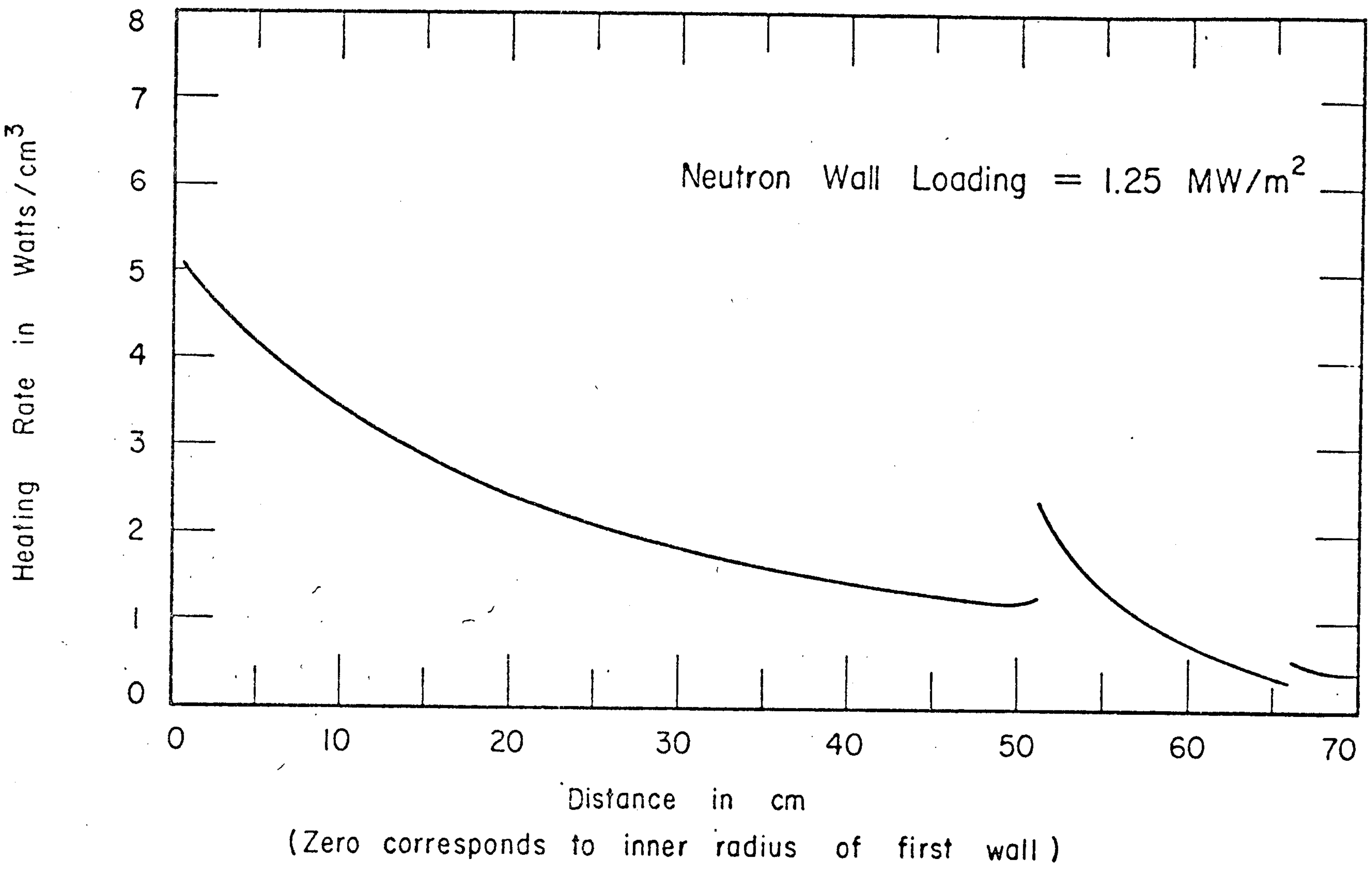

FIGURE 4 Spatial Distribution of Heating Rate in the Blanket and Reflector Regions

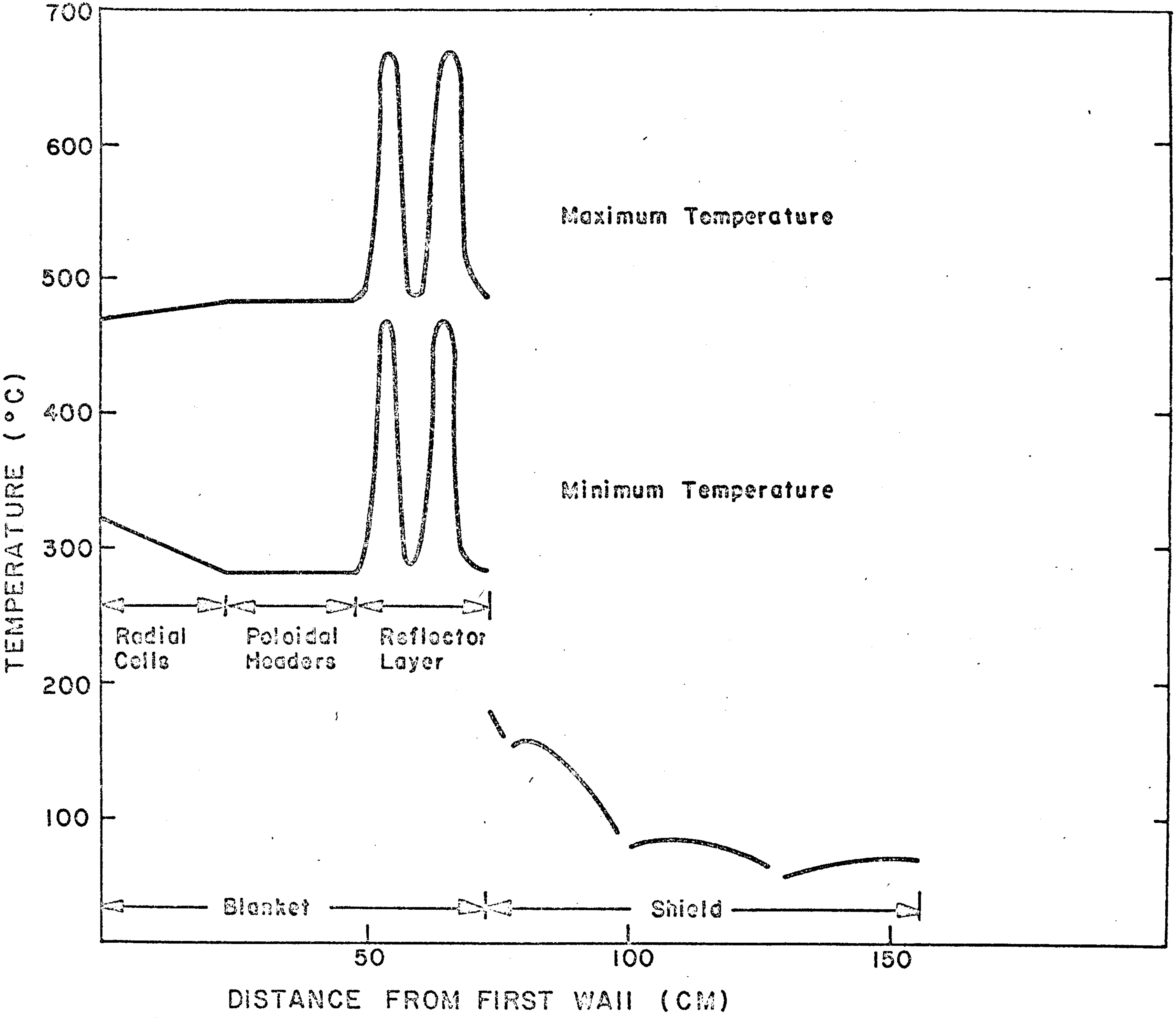

FIG. 5 TEMPERATURE OF BLANKET AND SHIELD

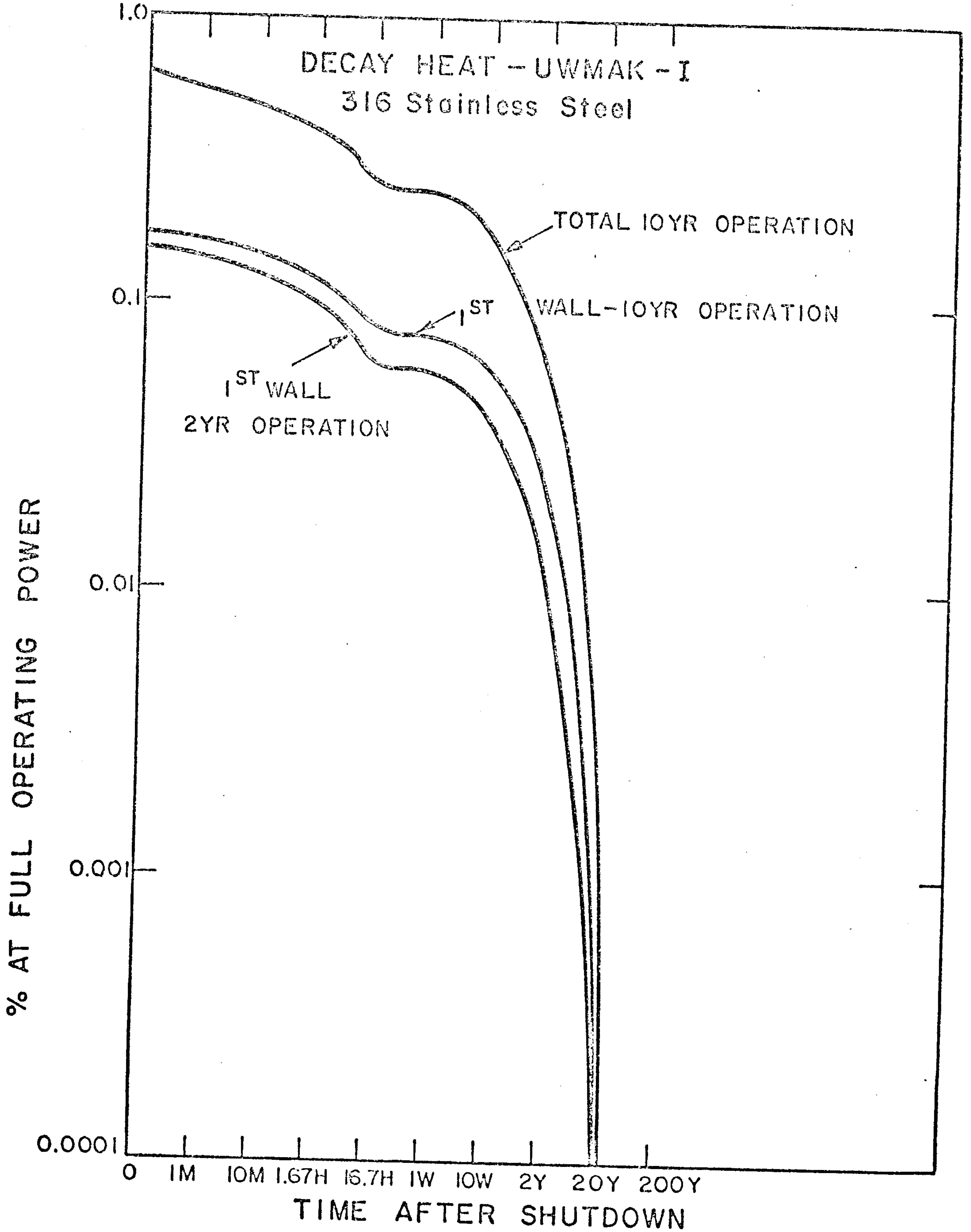
DECAY HEAT - UWMAK - I
316 Stainless Steel
TOTAL 10YR OPERATION
1ST WALL-10YR OPERATION
1ST WALL
2YR OPERATION
% AT FULL OPERATING POWER
1.0
0.1
0.01
0.001
0.0001
0
1M
10M
1.67H
16.7H
1W
10W
2Y
20Y
200Y
TIME AFTER SHUTDOWN

FIGURE 6

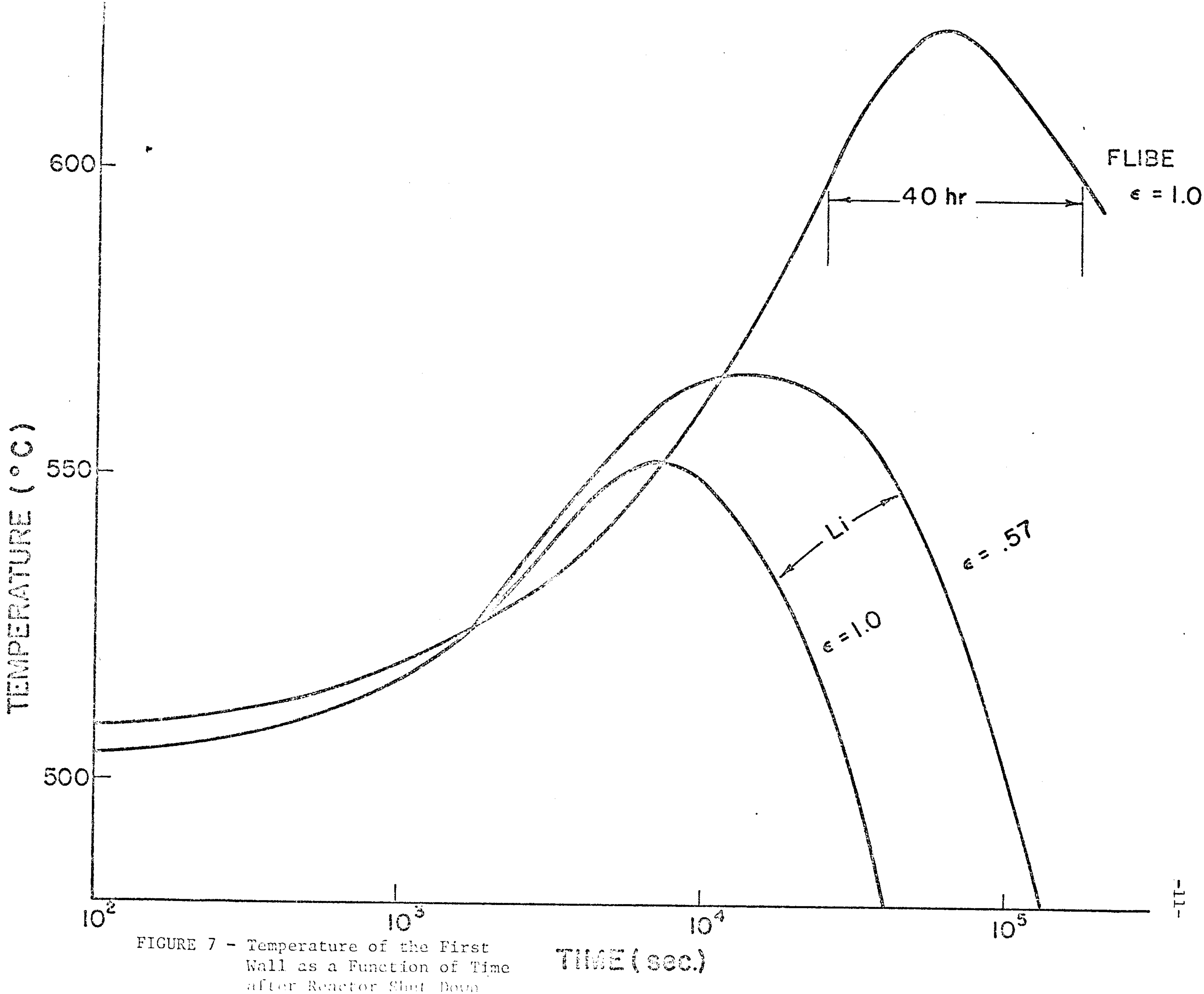

FIGURE 7 - Temperature of the First
Wall as a Function of Time
after Reactor Shut Down

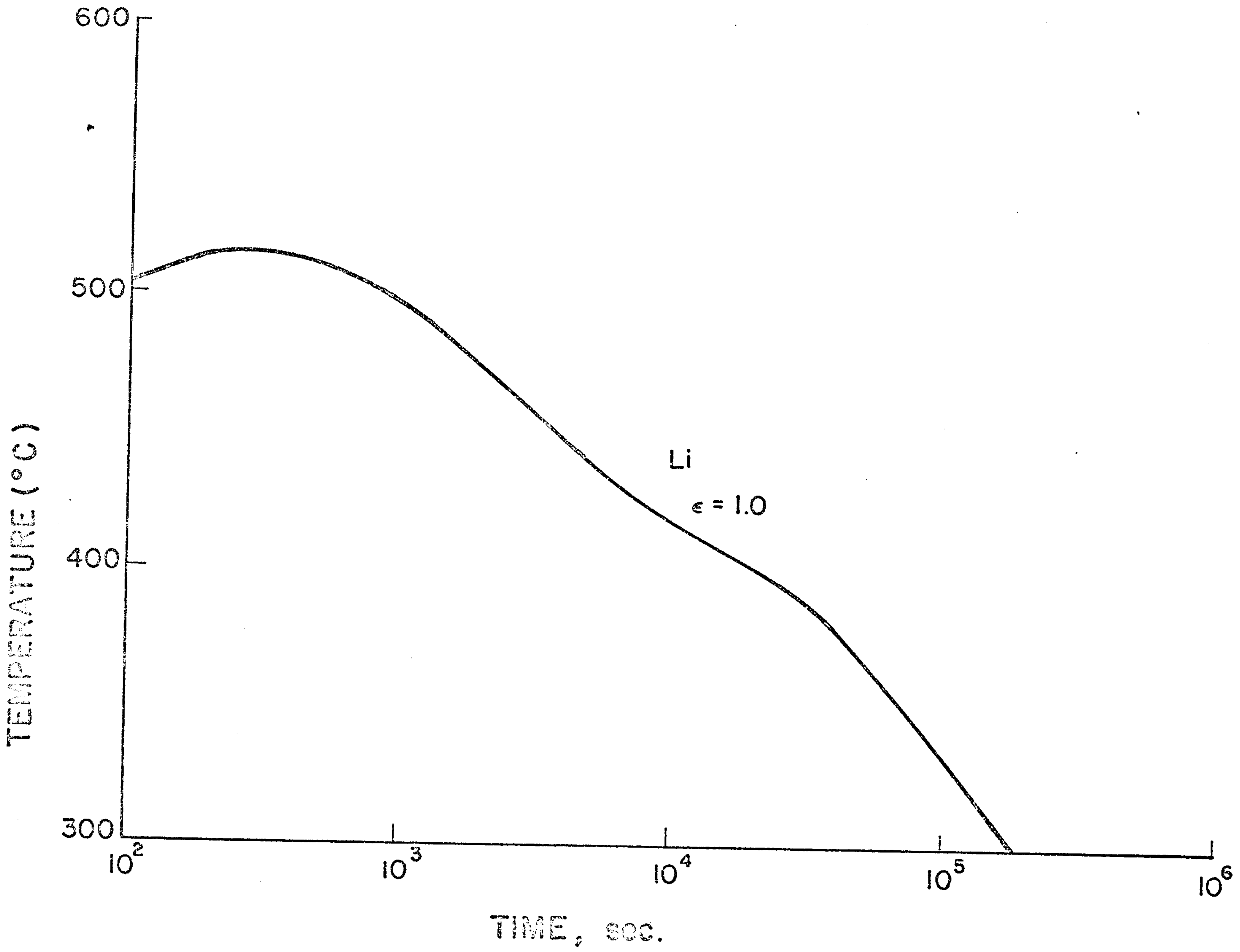

FIGURE 8 - Temperature of the Back Wall as a Function of Time after Reactor Shut Down

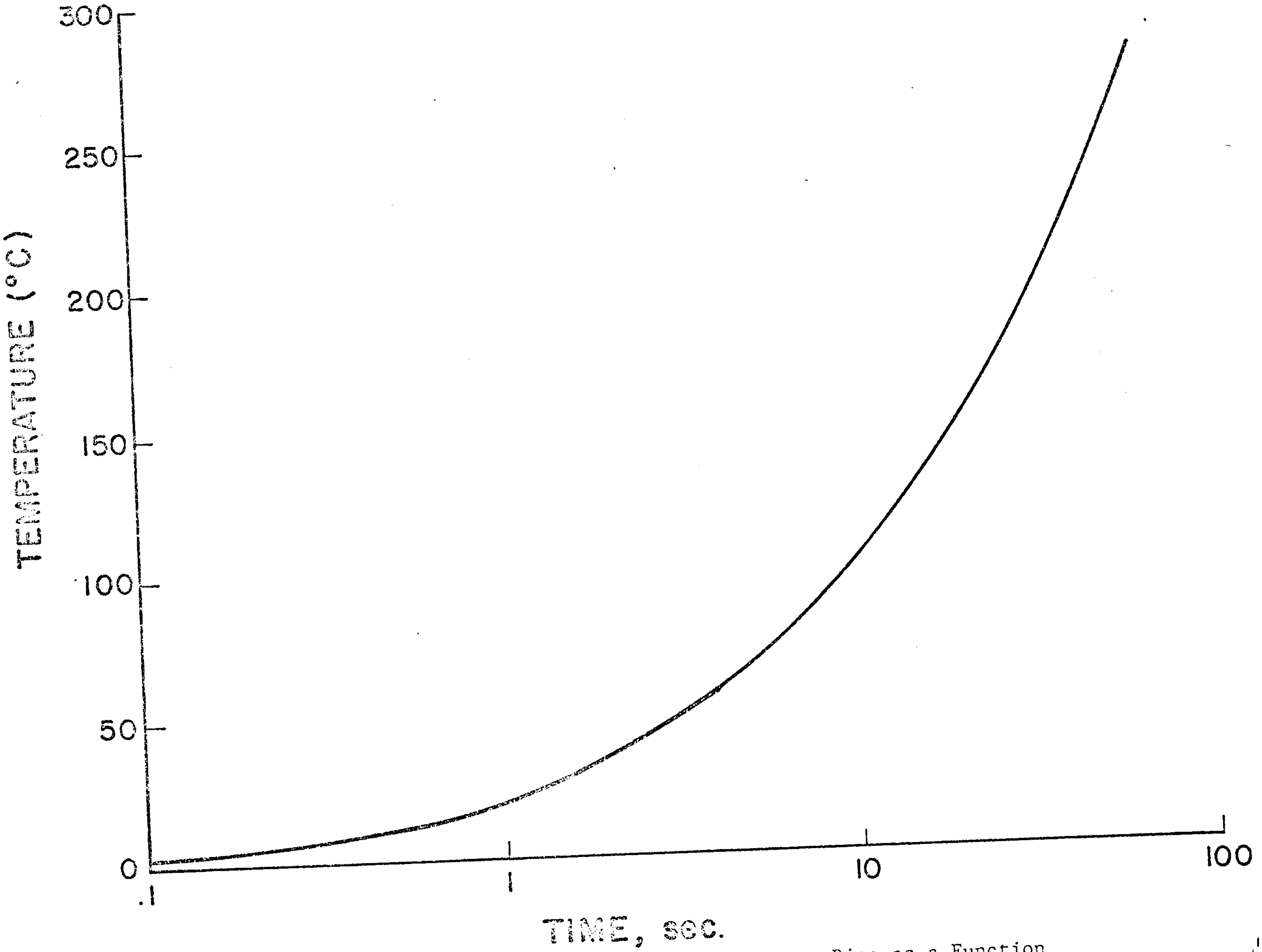

FIGURE 9 - First Wall Temperature Rise as a Function of Time After Loss of Flow Accident Occurs