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EFFECT OF CORE COOLING ON REMELTING OF TMI-2 DEBRIS BED

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Possible remelt of the TMI-2 debris bed was examined by using the simple assumptions of heat conduction in the debris bed. Physical properties, heat generation rate and surface heat flux were selected as parameters for the analysis. The following conclusions were drawn from the results.

i) The center region of the TMI-2 debris bed would have remelted at 20 min after the debris bed lost its coolable geometry due to possible flow blockage by the molten core.

ii) Among the physical properties, reductions of density, specific heat and depth of the debris bed would reduce the time to remelt the debris bed.

iii) Due to the simple assumptions made in the present analysis, there exists some uncertainty in the time to remelt the TMI-2 debris bed since the effect of remaining coolant in the debris bed and its steam cooling effect were neglected in the analysis.

iv) Uncertainty associated with the assumptions made in the present analysis would be approximately -10 min and +20 min.

Further analysis will be necessary to better characterize the remelt of the TMI-2 debris bed. The following considerations will have to be made for future analysis; quench characteristics of the debris bed, coolant distribution in the debris bed, better characterization of the debris bed.

Keywords: TMI-2, Debris Bed, Severe Accident, Degraded Core, Source Term, Heat Conduction.

TMI－2号炉のデブリ層の再溶融に対する冷却性の影響

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TMI－2デブリ層の再溶融の可能性について熱伝導を仮定した解析を行った。あわせてデブリ層の物性値，発熱量，表面除熱量をパラメータとした感度解析を行い，次の結論を得た。

i）TMI－2デブリ層は，溶融炉心による流路閉塞によりデブリ層の冷却性が失われると20分で再溶融が始まる可能性がある。

ii）物性値の中では，デブリ層の密度，比熱，デブリ層深さが減少すると，再溶融開始までの時間が短くなる。

iii）単純化のためデブリ層内部に残存する冷却水と蒸気冷却の効果を省略したため，結果に不確実性が存在する。

iv）本解析の仮定に基づく不確実性はおよそ－10分から＋20分である。

なお，さらに詳細な解析を行うためには，デブリ層のクエンチ特性，デブリ層内部の冷却材分布，デブリ層の物性値を明らかにする必要がある。

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1. INTRODUCTION

The accident at the Three Mile Island Unit 2 (TMI-2) reactor in 1979 has drawn considerable attentions due to its impact on nuclear industry. One of important issues generated from the TMI-2 accident is safety evaluation of a severe accident which requires better understanding of the accident sequences and consequences. The TMI-2 accident provided us a unique opportunity to grasp how the accident took place and how it proceeded.

With recognition of the significance of the TMI-2 accident, the Department of Energy (DOE) of U.S.A. initiated the TMI-2 Research and Development (TMI-2 R&D) program to obtain as much informations as possible from the TMI-2 accident and its cleanup process.[1] The Japanese group, consisting of 10 utilities, 3 manufacturers, 2 plant construction companies, the Nuclear Power Engineering Center (NUPEC) and the Japan Atomic Energy Research Institute (JAERI), is the only foreign participant in the program.

In the past years, several important findings in relation to the degree of core damage were made through visual observations by using a CCTV camera, examination of core void by the sonar detector, sampling and metallurgical investigation of the debris bed.[2)-5)] One of the important findings from the debris examination was that the TMI-2 core was believed to have remelted after it was solidified in the core. The scenario was first presented by J. Broughton[6] of Idaho National Engineering Laboratory (INEL) in which fuel rods first melted due to loss of core cooling and moved down to the bottom half of the core where the molten core blocked a flow path at the bottom of the core. Then the core became hot due to the loss of coolant flow blocked by the molten material and the core remelted. The remelted core flowed down to the lower plenum where it became solid again and eventually the core was quenched.

The scenario described above has no quantitative evidence yet, however as core drilling becomes available, it will be better explained. It is however worth while to examine the core remelting process and its impact on severe accident analysis.

The present report describes the method to estimate core remelting and effect of core cooling on the remelting process.

2. ANALYTICAL MODEL

2.1 Assumptions

During the TMI-2 accident, the core lost its integrity almost immediately after the recirculation pump was turned on at 180 min after the accident initiation. It was believed at this time that debris bed was formed in the lower part of the core as shown in Figure 2.1.[6] The debris bed still generated heat due to its decay energy and cooling would have continued if adequate core cooling was maintained.

However there was a possibility that core cooling was not maintained due to flow blockage at the bottom of the core by molten material. Thus the debris bed must have remelted due to heat generated in the core by the decay heat as the estimated end state core conditions shown in Figure 2.2.[6]

In order to estimate a possible existence and its criteria of remelting process, the following assumptions were made.

(1) Debris was uniformly distributed in the core.
(2) Heat transfer mechanism in the debris bed was heat conduction only and no convective heat transfer was assumed inside the debris bed.
(3) No heat transfer through core barrel and adiabatic condition was assumed at the vessel wall.
(4) Rate of heat removal at the top and bottom of the debris bed was assumed constant.
(5) Heat generation was due to decay heat of debris bed only and uniform throughout debris bed.

With the assumptions from (1) to (5), the problem becomes one dimensional heat conduction with heat source in it.

2.2 Governing Equation

Governing equation for the remelting problem was given by a simple one dimensional heat conduction equation. Figure 2.3 shows a simplified geometry of the core region. With the coordinate system shown in Figure 2.3, the governing equation becomes

$$dC_p\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + Q(x,t) \qquad (2.1)$$

where T: Temperature of the debris bed,
x: Axial coordinate in the debris bed,
t: Time,
d: Equivalent density of the debris bed,
C_p: Specific heat of the debris bed,
k: Thermal conductivity of the debris bed,
Q: Heat generation.

The governing equation given in equation (2.1) must be solved with initial condition and boundary conditions described in the following.

It was assumed that the core debris was at the uniform temperature at the beginning. Thus the initial condition is given by

$$T = T_o \qquad \text{at } t = 0 \qquad (2.2)$$

where T_o: Initial temperature.

From the assumptions described in 2.1 heat flux at the boundary representing the top and the bottom of the debris bed was assumed to be maintained at constant. Then boundary conditions become

$$\frac{\partial T}{\partial x} = 0 \qquad \text{at } x = 0 \qquad (2.3)$$

$$-k\frac{\partial T}{\partial x} = q_o \qquad \text{at } x = H \qquad (2.4)$$

where q_o: Heat flux at the debris surface,
H: Half depth of the debris bed.

The governing equation (2.1) must be solved to satisfy the initial condition (2.2) and the boundary conditions (2.3) and (2.4).

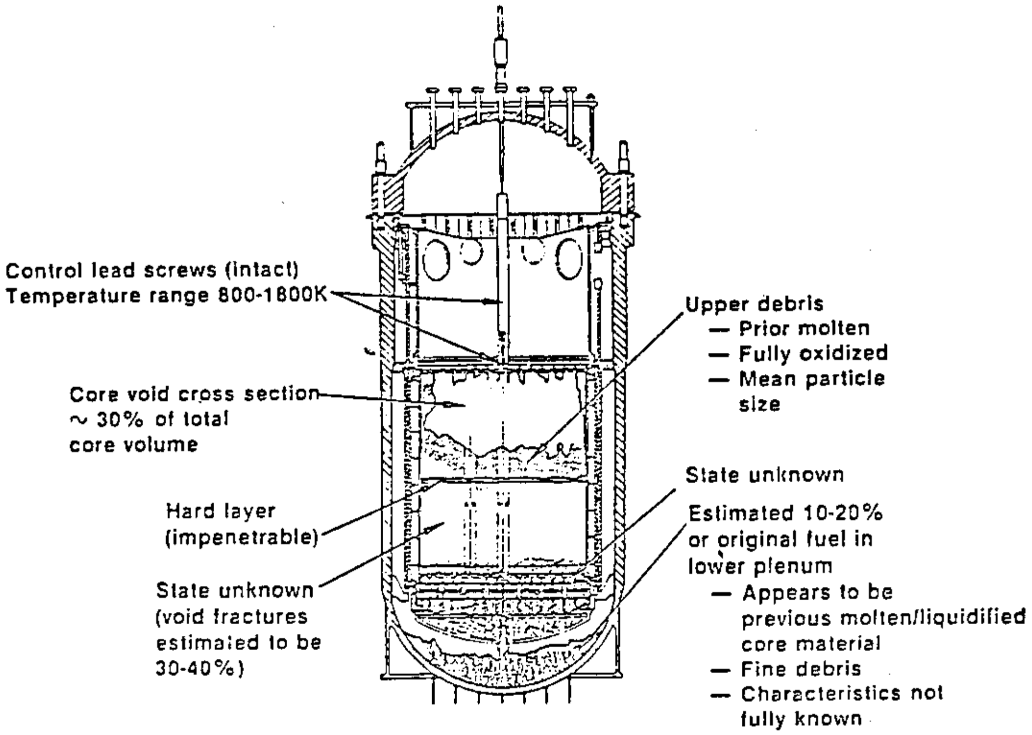

Fig. 2.1 Known core and reactor vessel conditions. (Reference (6))

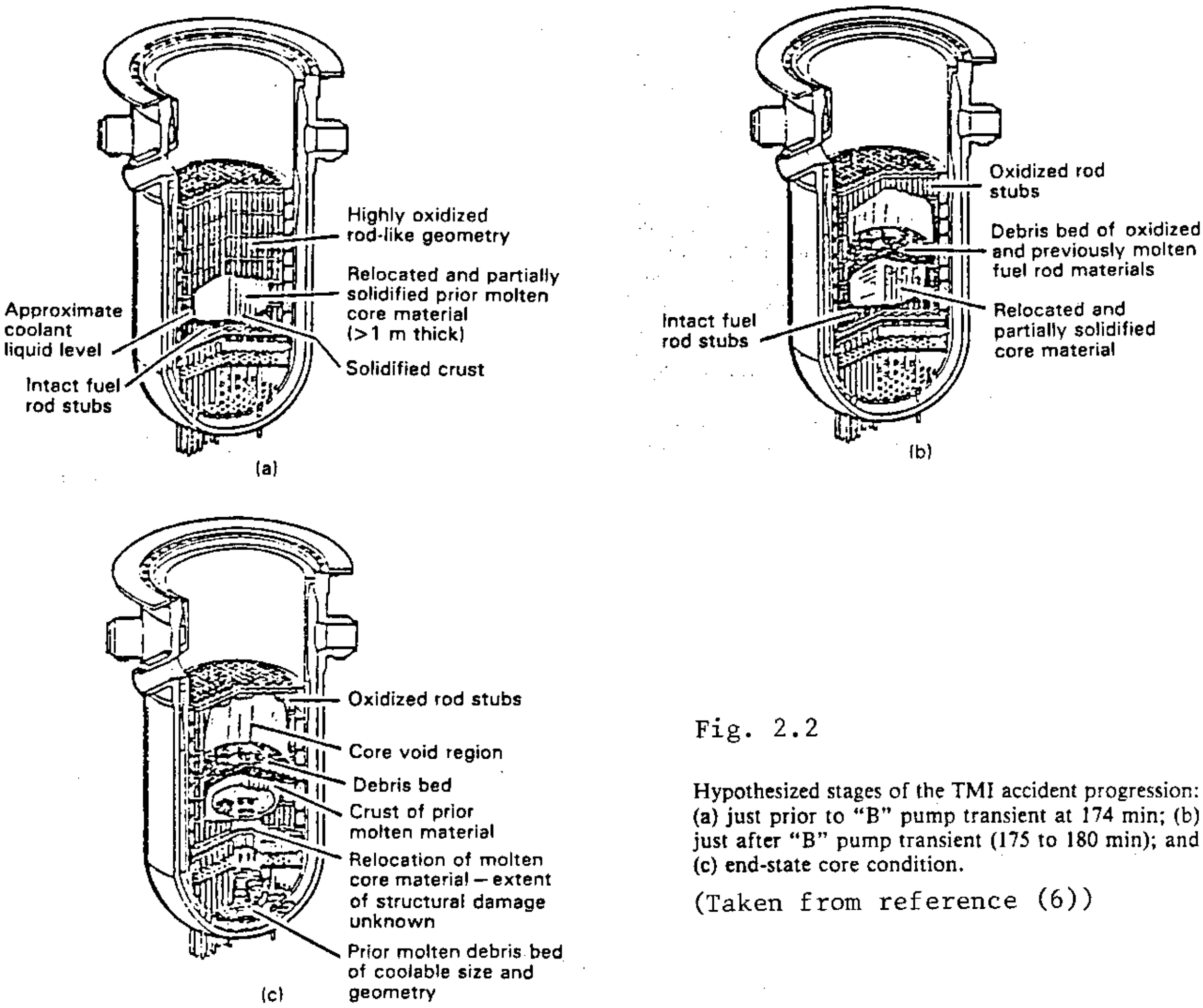

Fig. 2.2

Hypothesized stages of the TMI accident progression: (a) just prior to "B" pump transient at 174 min; (b) just after "B" pump transient (175 to 180 min); and (c) end-state core condition.

(Taken from reference (6))

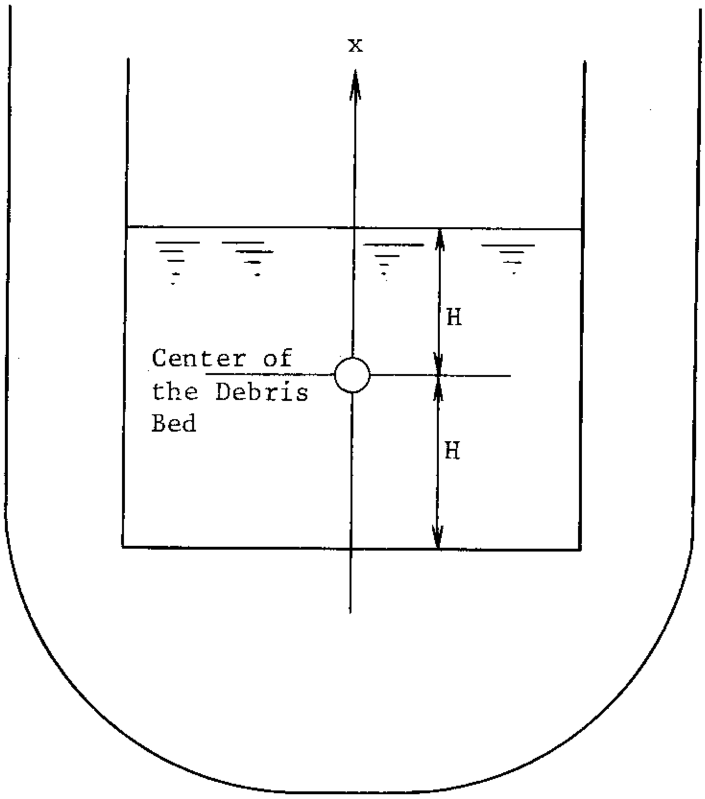

Fig. 2.3 Simplified Geometry of the Debris Bed

3. METHOD OF SOLUTION

3.1 Nondimensionalization

Governing equation (2.1), the initial condition (2.2) and the boundary conditions (2.3) and (2.4) can be nondimensionalized by defining the following set of variables.

$$\bar{T} = \frac{T-T_o}{T_M-T_o},\quad \bar{t} = \left(\frac{k}{dC_pH^2}\right)t,\quad \bar{x} = \frac{x}{H}$$

$$\bar{Q} = \frac{H^2}{k(T_M-T_o)}\,Q,\quad \bar{q}_o = \frac{q_o}{k}\left(\frac{H}{T_M-T_o}\right) \tag{3.1}$$

where T_M: Melting point of the debris bed,

Then the governing equation in nondimensional form is given by

$$\frac{\partial \bar{T}}{\partial \bar{t}} = \frac{\partial^2 \bar{T}}{\partial \bar{x}^2} + \bar{Q}(\bar{x},\bar{t}) \tag{3.2}$$

The initial condition and the boundary conditions become, respectively,

$$\bar{T} = 0 \qquad \text{at } \bar{t} = 0 \tag{3.3}$$

$$\frac{\partial \bar{T}}{\partial \bar{x}} = 0 \qquad \text{at } \bar{x} = 0 \tag{3.4}$$

$$\frac{\partial \bar{T}}{\partial \bar{x}} = -\bar{q}_o \qquad \text{at } \bar{x} = 1 \tag{3.5}$$

The governing equation (3.2) subject to the initial and boundary conditions given in equations (3.3) through (3.5) must be solved.

3.2 Analytical Solution

The solution to equation (3.2) subjected to the initial and boundary conditions can be solved analytically provided that the heat source in the debris bed is given as a simple function. It was assumed in the present analysis that the decay heat generated in the debris bed was given by the following function of time as [7)]

$$Q = bQ_o(t+t_s)^a \tag{3.6}$$

where t_s: Time after scram in s,
Q_o: Initial core power,
a,b: Constants, a = -0.26 and b = 0.095.

In terms of nondimensional parameters, equation (3.6) becomes

$$\bar{Q} = A(\bar{t}+\bar{t}_s)^a \quad (3.7)$$

where

$$\bar{t}_s = \left(\frac{k}{dC_pH^2}\right)t_s,$$

$$A = \left(\frac{H^2Q_ob}{k(T_M-T_o)}\right)\left(\frac{dC_pH^2}{k}\right)^a \quad (3.8)$$

Then the solution to equation (3.2) can be given as a summation of two functions, one being function of time only and the other being function of time and position. The solution is then given by

$$\bar{T} = \bar{T}_1(\bar{t}) + \bar{T}_2(\bar{x},\bar{t}) \quad (3.9)$$

Substitution of the definition (3.9) into the governing equation gives two sets of the governing equation and the conditions. The first set of equations is for the time dependent variables as follows.

Governing equation

$$\frac{d\bar{T}_1}{d\bar{t}} = A(\bar{t} + \bar{t}_s)^a \quad (3.10)$$

Initial condition

$$\bar{T}_1 = o \qquad \text{at } \bar{t} = o \quad (3.11)$$

Solution

Solution to the governing equation is given by

$$\bar{T}_1 = \frac{A}{a+1}\{(\bar{t}+\bar{t}_s)^{a+1} - \bar{t}_s^{\,a+1}\} \quad (3.12)$$

The second set of equations is for time and position dependent function and it is given as follows.

Governing equation

$$\frac{\partial\bar{T}_2}{\partial\bar{t}} = \frac{\partial^2\bar{T}_2}{\partial\bar{x}^2} \quad (3.13)$$

Initial condition

$$\bar{T}_2 = 0 \qquad \text{at } \bar{t} = 0 \qquad (3.14)$$

Boundary conditions

$$\frac{\partial \bar{T}_2}{\partial \bar{x}} = 0 \qquad \text{at } \bar{x} = 0 \qquad (3.15)$$

$$\frac{\partial \bar{T}_2}{\partial \bar{x}} = -\bar{q}_0 \qquad \text{at } \bar{x} = 1 \qquad (3.16)$$

Solution

Solution to equation (3.13) satisfying the initial condition (3.14) and the boundary conditions (3.15) and (3.16) becomes

$$\bar{T}_2 = \bar{q}_0 \left\{ -(\bar{t} + \frac{\bar{x}^2}{2}) + \frac{1}{6} + \sum_{n=1}^{\infty} \frac{2(-1)^n}{(n\pi)^2} e^{-(n\pi)^2 \bar{t}} \cos(n\pi\bar{x}) \right\} \qquad (3.17)$$

Finally solution to the governing equation becomes by substituting the two solutions given by equations (3.12) and (3.17) into equation (3.8) as

$$\bar{T} = \bar{T}_1 + \bar{T}_2$$

$$= A\,(F(\bar{t}) + B\,G(\bar{x},\bar{t})) \qquad (3.18)$$

where

$$F(\bar{t}) = \frac{(\bar{t}+\bar{t}_s)^{a+1} - \bar{t}_s^{\,a+1}}{a+1} \qquad (3.19)$$

$$G(\bar{x},\bar{t}) = -(\bar{t} + \frac{\bar{x}^2}{2}) + \frac{1}{6} + \sum_{n=1}^{\infty} \frac{2(-1)^n}{(n\pi)^2} e^{-(n\pi)^2 \bar{t}} \cos(n\pi\bar{x}) \qquad (3.20)$$

$$A = \left\{ \frac{H^2 Q_0 b}{k(T_M - T_0)} \right\} \left(\frac{d C_p H^2}{k} \right)^a, \quad B = \frac{q_0}{b Q_0 H} \left(\frac{k}{d C_p H^2} \right)^a$$

$$\bar{T} = \frac{T - T_0}{T_M - T_0}, \quad \bar{t} = \frac{k}{d C_p H^2} t, \quad \bar{x} = \frac{x}{H} \qquad (3.21)$$

Solution (3.18) gives temperature transient in the debris bed subjected to the assumptions made in section 2.1. The generalized functions $F(\bar{t})$ and $G(\bar{t},\bar{x})$ are shown in Figures 3.1 and 3.2, respectively. The parameters A and B defined in equation (3.18) must be determined from property values of a debris bed under consideration. Non-dimensional parameter $\bar{T}/A$ is shown in Figures 3.3 through 3.7 by varying numerical value of the parameter B. Once the parameters A and B are determined, non-dimensional temperature $\bar{T}$ can be easily determined.

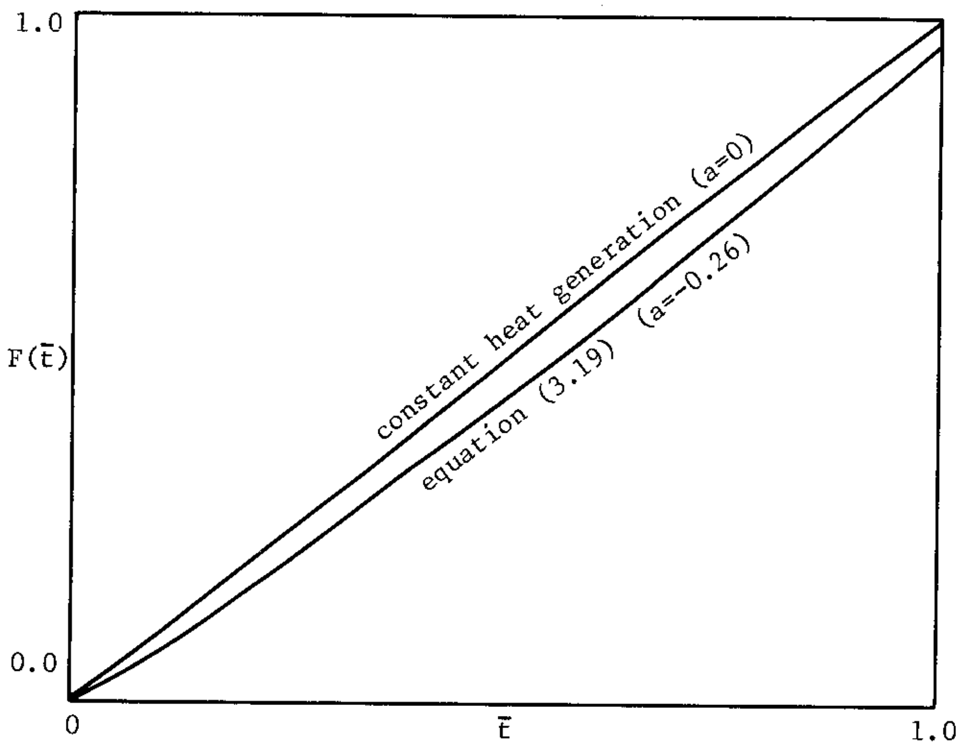

Fig. 3.1 Nondimensional Function $F(\bar{t})$

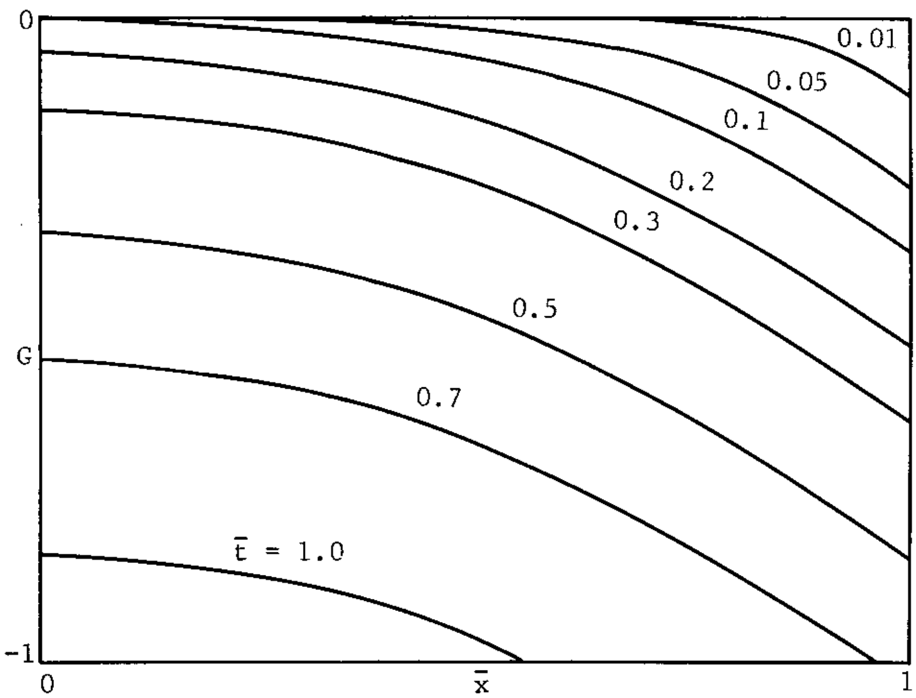

Fig. 3.2 Nondimensional Function $G(\bar{x}, \bar{t})$

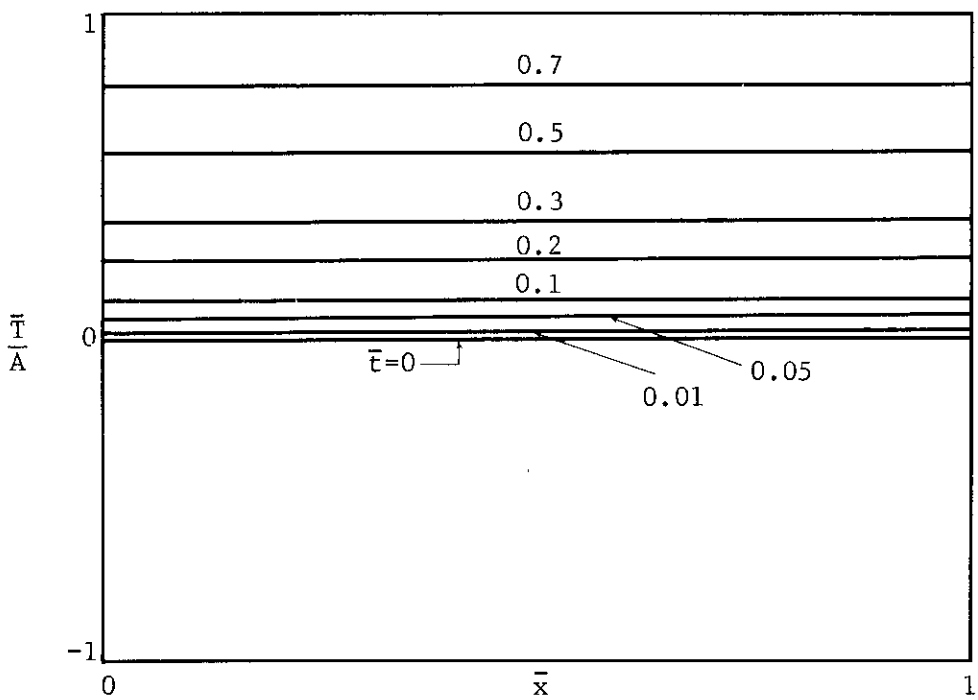

Fig. 3.3 Nondimensional Temperature $\bar{T}/A$
for B=0 (Adiabatic case)

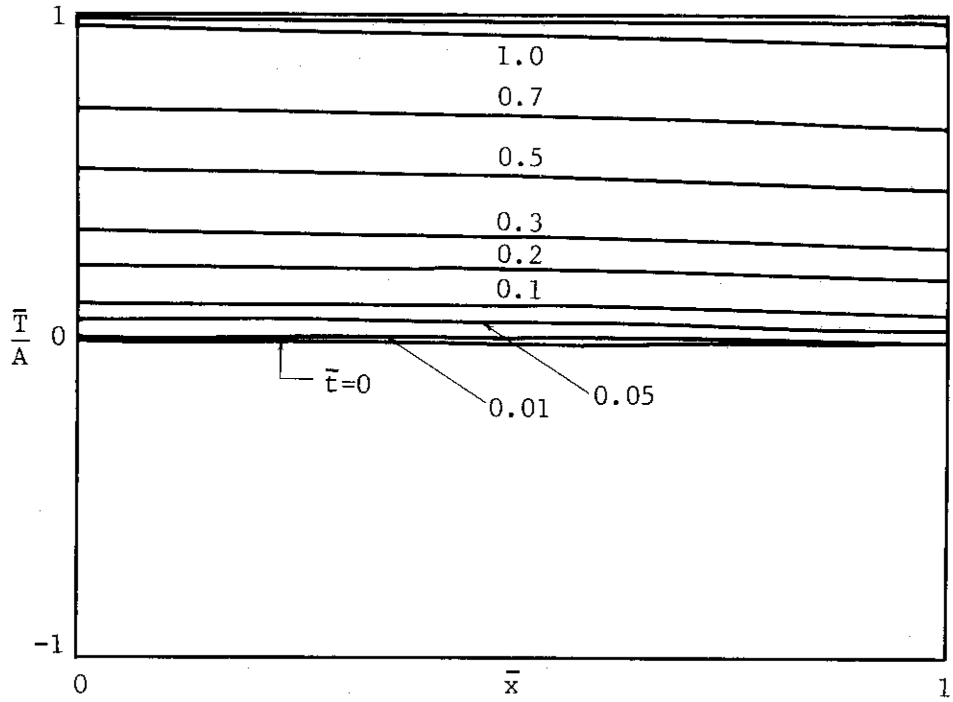

Fig. 3.4 Nondimensional Temperature $\bar{T}/A$ for B=0.1

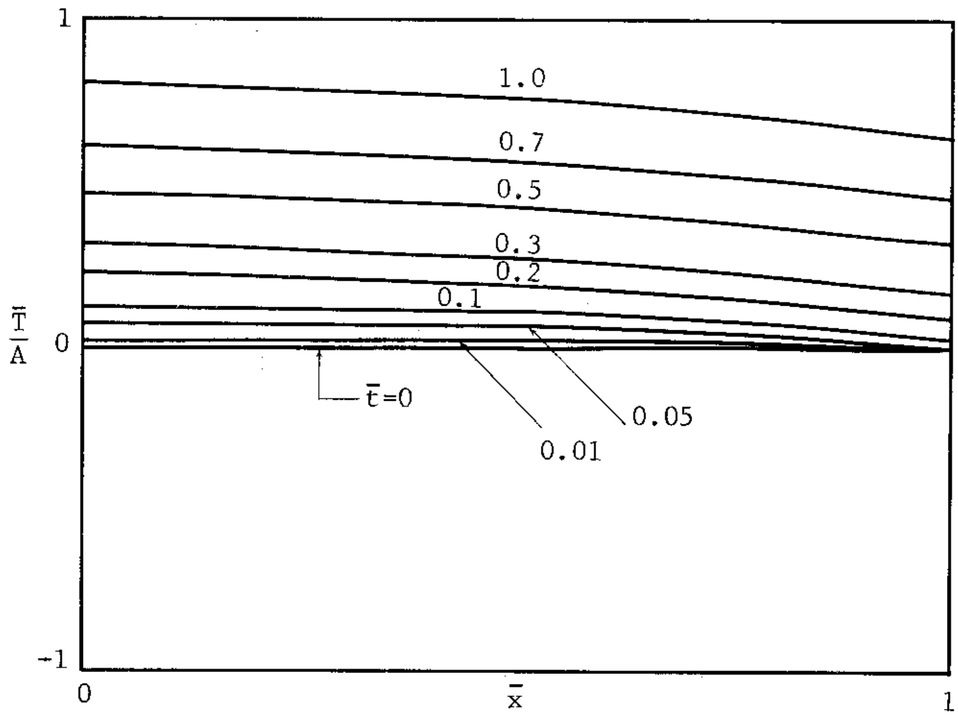

Fig. 3.5 Nondimensional Temperature $\bar{T}/A$ for B=0.3

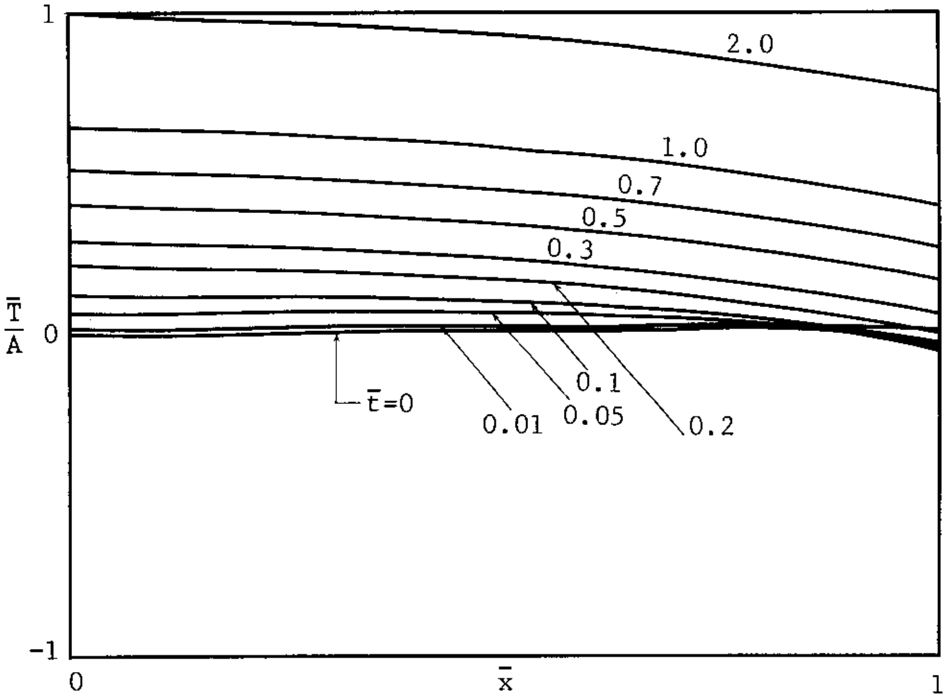

Fig. 3.6 Nondimensional Temperature $\bar{T}$/A for B=0.5

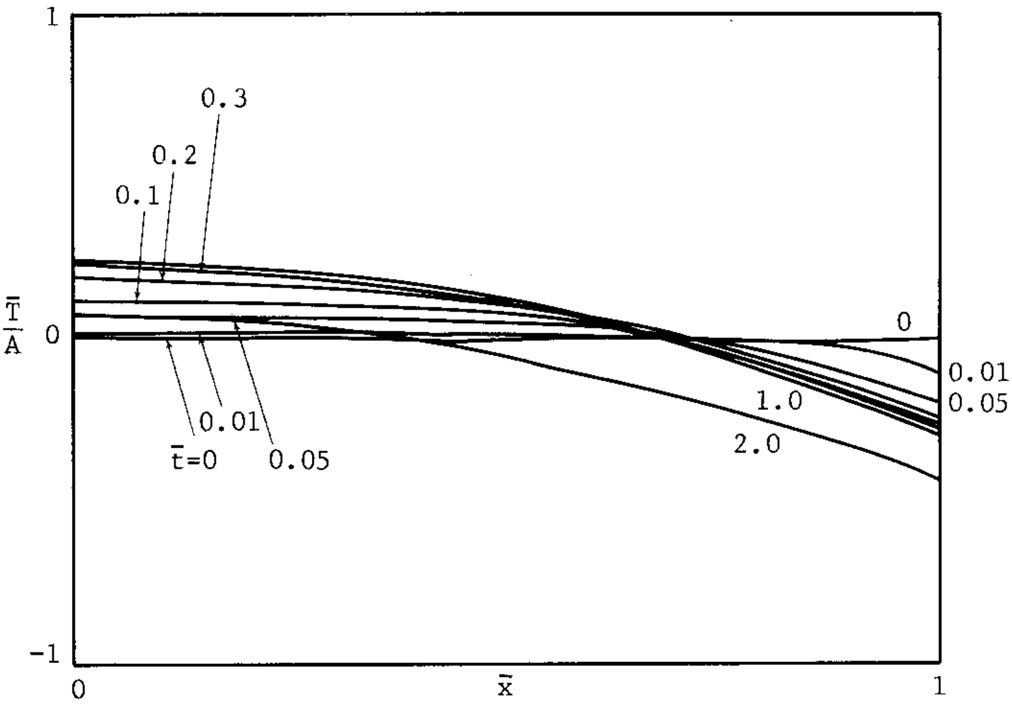

Fig. 3.7 Nondimensional Temperaure $\bar{T}$/A for B=1.0

4. RESULTS AND DISCUSSION

4.1 Time to Remelt the Debris Bed of the TMI-2 Core

According to the scenario presented by J. Broughton[6], the debris bed of the TMI-2 core remelted during the accident due to lack of adequate core cooling about 220 min after the accident initiation. Whether or not the core remelt actually occurred is still subject to debate due to lack of conclusive evidence as of today.

However it is possible to estimate how long the debris bed maintained the coolable geometry under the extreme conditions of the TMI-2 accident. The time to remelt the debris bed was estimated by using the solution given in equation (3.18) in the previous chapter.

4.1.1 Physical Properties of the Debris Bed

In order to estimate the time to remelt the debris bed, physical properties of the debris bed of the TMI-2 core must be evaluated first. In equation (3.18), the parameters A and B include several physical properties. The following estimation was made for the physical properties of the debris bed.

Physical Properties

Recent examination of the samples from the debris bed showed that the debris bed was composed of fuel and structural materials. In order to determine physical properties of the debris bed, i.e. thermal conductivity, density, specific heat, the following assumptions were made.

1) The debris bed consists of solid materials and porous cavities. Composition and physical properties are uniform in the entire debris bed with the assumption that porosity is 0.4.

2) The solid materials consist of UO_2, stainless steel and zirconium with the same volume ratio as that in the TMI-2 reactor core. Table 4.1[8] summarizes compositions of the core materials in the TMI-2 core.

3) Porous cavities of the debris bed are filled with steam at the initial temperature of the debris bed. Steam properties beyond 800°C, which is the highest temperature used in the JSME steam table shown in Table 4.2, are assumed as the same as those at 800°C.

4) System pressure is at 12 MPa throughout the transient.[8]

5) Thermal conductivity and melting point of the debris bed are 13.84 W/mK and 2277°C, respectively.[9]

Physical properties were then determined by the method described in Appendix A. Table 4.3 summarizes the estimated physical properties of the debris bed which was used in the present analysis.

Heat Generation in the Debris Bed

The debris bed generates heat mainly due to decay heat. The decay heat as a ratio to the initial core power can be expressed in terms of time as in equation (3.6). The parameters A and B include the initial core power multiplied by a constant representing heat generation of the debris bed. The heat generation rate in the debris bed was calculated by considering volume fraction of UO_2 in the debris bed, i.e.

Volumetric heat generation rate in the debris bed
= Volumetric heat generation in fuel
x Volume fraction of UO_2 in the debris bed.

Initial volumetric heat generation rate in fuel was calculated by using heat generation rate of a fuel assembly of the TMI-2 core as described in Appendix B. The initial heat generation rate, Q_o, was then estimated to be 1.33×10^8 W/m^3.

Rate of Heat Removal

It is important to estimate how much heat can be removed at the surface of the debris bed. In the present analysis, rate of heat removal was kept at constant value and the effect was included in the parameter B.

In order to estimate an order of magnitude of rate of heat removal, it was assumed at first that heat was removed by film boiling at the debris bed. Following the empirical correlation for film boiling heat transfer by Bromly[10], rate of heat removal was estimated to be 4.57×10^5 W/m^2 as summarized in Appendix C.

Debris Geometry

Since the debris bed in the present analysis was assumed to be one dimensional, only parameter involved in the calculation was half depth of the debris bed, H, which was used in the parameters A and B. The depth, 2H, was estimated to be approximately 1 m.

4.1.2 Estimated Time to Remelt the TMI-2 Debris Bed

With the use of values estimated for the TMI-2 debris bed as summarized in Tables 4.1 through 4.4, temperature in the debris bed was calculated. Figure 4.1 shows temperature at the center of the debris bed where the temperature was the highest and Figure 4.2 shows temperature profile in the debris bed.

The result shown in Figure 4.1 indicated that nondimensional temperature becomes 1, which corresponds to melting, as nondimensional time approaches 0.045, which corresponds to 20 min after the loss of debris bed cooling, when representative physical properties as given in Table 4.3 were used for the TMI-2 debris bed with the assumption that a loss of coolability in the debris bed was estimated to have occurred at 175 min after reactor scram. i.e.

$$t(\text{melting}) = \bar{t}(dC_pH^2/k)$$
$$= 0.045 \times (5920 \times 0.255 \times 1000 \times (0.5)^2/13.84) \div 60$$
$$= 20 \text{ (min)}.$$

In other words, the debris bed would have melted 20 min after the coolability of the debris bed was assumed to have been lost at 175 min after reactor scram. The cause of the loss of coolability was estimated to be a possible presence of flow blockage at the bottom of the debris bed. It can be seen in Figure 4.2 that the temperature distribution was faily flat except near the debris surface where temperature decreased due to the existence of the constant heat removal. Since the characteristic heat conduction time was approximately 8 hours, the debris bed was heated by the decay heat generation to the melting temperature much faster than by conduction from the surface.

It should be mentioned however that the validity of the present calculation was dependent on the validity of the assumptions made in the analysis. Especially the assumption of heat conduction only for heat removal from the debris bed may result in overestimation of temperature of the debris bed since presence of coolant in the debris bed and its effect on the debris cooling, which contributed to lower the temperature of the debris bed, were not taken into account in the analysis.

4.2 Sensitivity Analysis

4.2.1 Effect of Physical Properties

Among the physical properties summarized in Tables 4.1 through 4.4, thermal properties were used in the parameters A and B in terms of the characteristic conduction time in the debris bed. Therefore effect of physical properties can be evaluated by varying the characteristic conduction time which is defined as

$$\text{Characteristic Conduction Time} = \frac{\text{density x specific heat x (depth of the debris bed)}^2}{\text{thermal conductivity}} = \frac{\text{(depth of the debris bed)}^2}{\text{thermal diffusivity}}$$

It is evident that when the characteristic conduction time becomes small, real time to reach core melt temperature, which is given by nondimensional time multiplied by characteristic conduction time, becomes smaller, in other words, remelting would occur earlier. Hence reduction of density, specific heat and/or depth of the debris bed and increase of thermal conductivity would result in earlier core remelt. This also implies that an increase of thermal diffusivity (k/dC_p) would result in reduction of the estimated time to remelt the TMI-2 debris bed. Uncertainty associated with thermal diffusivity of the TMI-2 debris bed is expected to be in the range of 50% and 200% of the nominal value of 0.033 m^2/h which can be calculated from those given in Table 4.3. It follows that time to remelt the debris bed would be in the range of 10 min and 40 min.

Thermal conductivity is also used in the parameter A which represents the ratio of generation of heat to conduction of heat as in equation (3.18), i.e. $(H^2Q_ob)/k(T_M-T_o)(dC_pH^2/k)^a$. Effect of the parameter A is such that the larger is the parameter A with the same t, the higher becomes nondimensional temperature $\bar{T}$ and the earlier would temperature approach melting point.

Effect of the parameter B is that when the parameter B is large, temperature rise becomes slower since the parameter B gives the ratio of heat removel at the surface of debris bed to heat generation rate in the debris bed. Therefore, for example, increase of heat flux at the debris bed would result in late core melt in general.

4.2.2 Effect of Heat Generation in the Debris Bed

It was assumed in the calculation that heat generation in the debris bed was due to decay heat of the fuel remaining in the debris bed. The decay heat was approximated by equation (3.6). Therefore heat generation is higher when loss of debris bed coolability occurs earlier. Effect of heat generation is self evident such that the larger heat generation results in the faster temperature rise.

Since heat generation due to decay heat does not vary much within the time range of 100 and 250 min after scram, uncertainty associated with timing of loss of debris coolability and the resultant decay heat level did not result in major uncertainty in the remelting time, i.e. at the most 1 to 2 - 5 min.

4.2.3 Effect of Heat Removal at the Debris Bed Surface

The effect of heat removal rate at the debris bed surface can be estimated by varying surface heat flux q_o or equivalently by varying the parameter B. The results indicate that the surface heat flux had little effect on the center temperature while the surface temperature depends on the surface heat flux. It is because the ratio of the characteristic conduction time to the characteristic time to raise temperature of the debris bed to melting temperature given by $QH^2/k(T_M-T_o)$ is about 20 in the range of 100 and 250 min after scram. Therefore conduction time is an order of magnitude larger than the temperature rise time and thus the initiation of remelt of the debris bed would occur at the center of the debris bed regardless of the magnitude of the surface heat flux.

4.3 Uncertainty in the Present Analysis

The present analysis neglected the effect of remaining water in the debris bed and its steam cooling effect for simplicity. It is obvious that the remaining water in the debris bed would lower the debris temperature and prevent early core remelt and the steam cooling also delays core remelt as well. For example, if 10% of void space in the debris bed is assumed to be occupied by water, approximately 2000kg, then 2 min would be needed to vaporize the residual water in the bed.

It was estimated in the TMI-2 accident that bottom portion of the fuel bundle had been covered with coolant throughout the transient and therefore steam had been continuously generated. For the case, the rate of steam generation was estimated to be approximately 0.4 kg/m^2s as described in Appendix D, with the assumptions that bottom 50 cm of the fuel bundle was covered with coolant and heat generation was caused solely by decay heat at 175 min after the scram.

On the other hand, steam flow rate which was effectively used to cool the debris bed was estimated as 0.016 kg/m^2s as described in Appendix E if all of the generated steam was effectively used to cool the debris bed by convective flow of steam in the bed.

Therefore it was concluded that there had been enough steam available at the time when the debris bed had been formed during the accident. However probably due to flow blockage caused by the debris particles, it was likely that the generated steam bypassed the debris bed region and flowed to the upper plenum through the peripheral region of the core. It implies that steam cooling was not effective in the TMI-2 debris bed and the debris was not cooled by steam cooling.

Table 4.1 Basic Data for Calculation of Physical Properties[8]

1. TMI-2 Core Composition

Component	Volume fraction	Volume fraction in solid materials
Fuel	0.303	0.7426
Water	0.580	----
Zirconium	0.102	0.2500
Stainless steel	0.003	0.0074
Void	0.012	----
Total	1.000	1.0000

2. TMI-2 Fuel Characteristics

Design heat output	2772	MW
No. of fuel assemblies in core	177	
Heat generation rate of a fuel assembly	15.661	MW
No. of fuel rods of a fuel assembly	208	
Active length of a fuel rod	365.8	cm
Pellet diameter	0.940	cm

3. Physical Properties of Solid Materials

Material	Density (kg/m^3)	Specific Heat (kJ/kg/°C)
UO_2	1.1×10^4	0.235
Zirconium	6.5×10^3	0.301
Stainless steel	7.8×10^3	0.494

Table 4.2 Physical Properties of Fluid for Debris Bed Properties Calculation

Properties	Values
Saturation temperature at 12 MPa : T_{sat}	324.65 °C
Density of water at T_{sat}	655.0 kg/m^3
Density of steam at 12 MPa & 800°C	24.80 kg/m^3
Specific heat of steam at 12 MPa & 800°C	2.491 kJ/kg/°C

Table 4.3 Estimated Physical Properties of Debris Bed

Properties	Values	
Density	5920	kg/m^3
Specific heat	0.255	kJ/kg/°C
Initial core power density	1.33×10^8	W/m^3
Thermal conductivity	13.84	W/m/°C
Melting point	2277	°C

Table 4.4 Physical Properties of Fluid for Calculation of Heat Transfer Rate at the Top of Debris Bed

Thermal hydraulic conditions in reactor			
Pressure : P	12		MPa
Saturation temperature at 12 MPa : T_{sat}	324.65		°C
Average film temperature : T_f	660		°C
Properties at P, T_{sat}			
Density of water	655.0		kg/m^3
Properties at P, T_f			
Density of steam	29.15		kg/m^3
Surface tension	8.87	$\times 10^{-3}$	N/m
Thermal conductivity of steam	9.58	$\times 10^{-2}$	W/m/°C
Kinematic viscosity of steam	1.23	$\times 10^{-6}$	m^2/s
Prandtl number	0.925		
Latent heat of vaporization	1.1974	$\times 10^{6}$	J/kg
Isobaric specific heat capacity of stem	2.482	$\times 10^{3}$	J/kg/°C

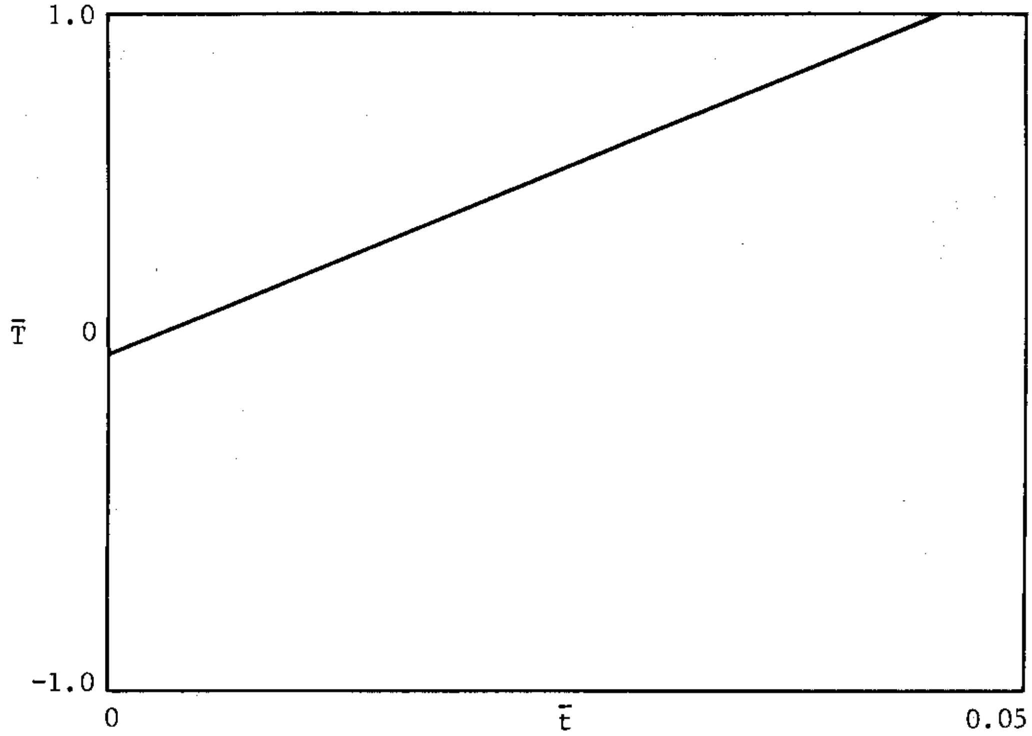

Fig. 4.1 Temperature Increase in the Debis Bed

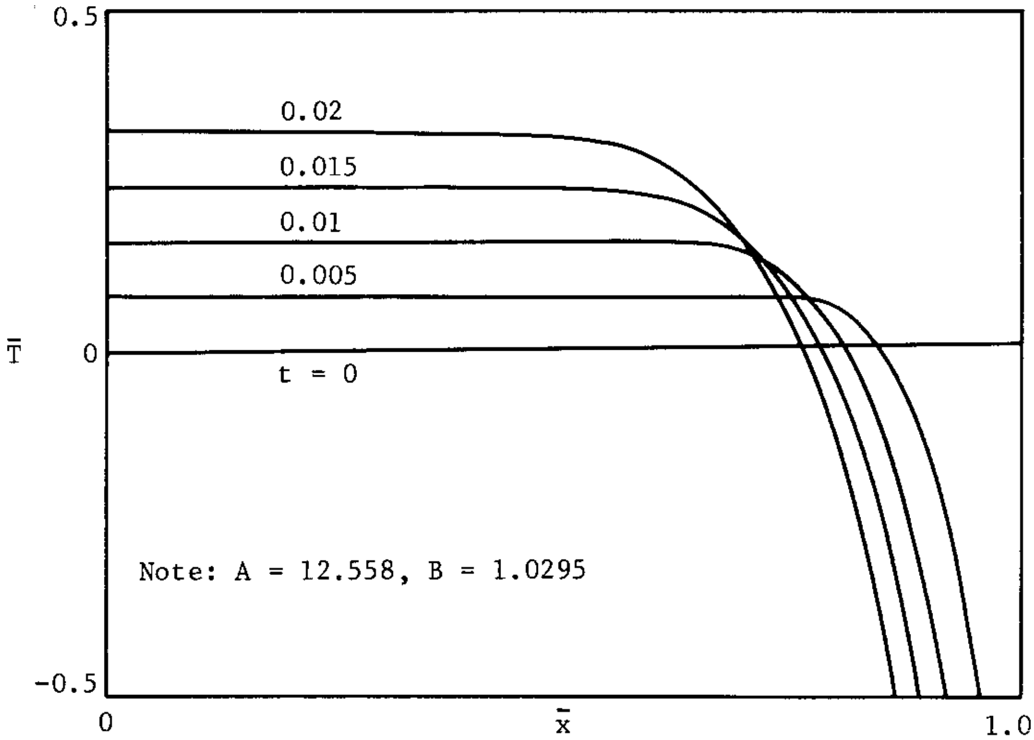

Fig. 4.2 Temperature Profile in the Debris Bed

5. CONCLUSION

Possible remelt of the TMI-2 debris bed was examined by using the simple assumptions of heat conduction in the debris bed. Effect of physical properties, heat generation rate and surface heat flux were examined. The following conclusions were drawn from the present analysis.

i) The center region of the TMI-2 debris bed would have remelted at at 20 min after the debris bed lost its coolable geometry due to possible flow blockage by the molten core.

ii) Among the physical properties, reductions of density, specific heat and depth of the debris bed would reduce the time to remelt the debris bed.

iii) Due to the simple assumptions made in the present analysis, there exists some uncertainty in the time to remelt the TMI-2 debris bed since the effect of remaining coolant in the debris bed and its steam cooling effect were neglected in the analysis.

iv) Uncertainty associated with the assumptions made in the present analysis would be approximately -10 min and + 20 min.

Further analysis will be necessary to better characterize the remelt of the TMI-2 debris bed. The following considerations will have to be made for future analysis; quench characteristics of the debris bed, coolant distribution in the debris bed, better characterization of the debris bed.

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The authors wish to express their appreciation to Mr. H. Tateoka of Nihon Energy Incorporated for his assistance to carry numerical calculations.

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Appendix A Calculation of Physical Properties of Debris Bed

A.1 Density

Solid Materials

Density of solid materials
= (Density of UO_2) x (Volume fraction of UO_2 in solid material)
+ (Density of zirconium)
x (Volume fraction of zirconium in solid materials)
+ (Density of stainless steel)
x (Volume fraction of stainless steel in solid materials)
= $1.10 \times 10^4 \times 0.7426$
+ $6.50 \times 10^3 \times 0.2500$
+ $7.80 \times 10^3 \times 0.0074$
= 9.85×10^3 (kg/m^3)

Debris bed

Density of debris bed
= (Density of solid materials) x (1 - Porosity)
+ (Density of steam) x Porosity
= $9.85 \times 10^3 \times (1 - 0.4) + 24.80 \times 0.4$
= 5.92×10^3 (kg/m^3)

A.2 Specific Heat Capacity

Solid Materials

Heat capacity of unit volume of solid materials
= (Specific heat capacity of UO_2)
x (Volume fraction of UO_2 in solid materials)
x (Density of UO_2)
+ (Specific heat capacity of zirconium)
x (Volume fraction of zirconium in solid materials)
x (Density of zirconium)
+ (Specific heat capacity of stainless steel)
x (Volume fraction of stainless steel in solid materials)
x (Density of stainless steel)

$= 0.235 \times 0.7426 \times (1.1 \times 10^4)$
$+ 0.301 \times 0.2500 \times (6.5 \times 10^3)$
$+ 0.494 \times 0.0074 \times (7.8 \times 10^3)$
$= 2440$ (kJ/m^3/°C)

Specific heat capacity of solid materials
= (Heat capacity of unit volume of solid materials)
/(Density of solid materials)
$= 2440 / 9.85 \times 10^3$
$= 0.248$ (kJ/kg/°C)

Debris Bed

Heat capacity of unit volume of debris bed
= (Specific heat capacity of solid materials) x (1-porosity)
x (Density of solid materials)
+ (Specific heat capacity of steam) x (Porosity) x (Density of steam)
$= 0.248 \times (1 - 0.4) \times (9.85 \times 10^3) + 2.491 \times 0.4 \times 24.8$
$= 1490$ (kJ/m^3/°C)

Specific heat capacity of debris bed
= (Heat capacity of unit volume of debris bed)
/(Density of debris bed)
$= 1490 / (5.92 \times 10^3)$
$= 0.255$ (kJ/kg/°C)

Appendix B Calculation of Volumetric Heat Generation Rate in Debris Bed

Total volume of UO_2 in a fuel assembly

= $\pi/4$ x (Pellet diameter)^2 x (Active length of a fuel rod)
  x (No. of fuel rods in a fuel assembly)

= $\pi/4$ x $(0.940)^2$ x 365.8 x 208

= 52800 (cm^3) = 5.28×10^{-2} (m^3)

Volumetric heat generation rate of UO_2

$$= \frac{\text{(Heat generation rate of a fuel assembly)}}{\text{(Total volume of } UO_2 \text{ in a fuel assembly)}}$$

= $(15.661 \times 10^6) / (5.28 \times 10^{-2})$

= 2.97×10^8 (W/m^3)

Volumetric heat generation rate of solid materials

= (Volumetric heat generation rate of UO_2)
  x (Volume fraction of UO_2 in solid materials)

= $2.97 \times 10^8 \times 0.7426$

= 2.21×10^8 (W/m^3)

Volumetric heat generation rate of debris bed

= (Volumetric heat generation rate of solid materials) x (1 - Porosity)

= $2.21 \times 10^8 \times (1 - 0.4)$

= 1.33×10^8 (W/m^3)

APPENDIX C Calculation of Heat Flux at the Top of the Debris Bed

It was assumed in the present analysis that film boiling took place at the surface of the debris bed. Therefore heat flux was calculated based upon the film boiling heat transfer correlations by Bromly, i.e.

$$\frac{hco \cdot D}{\lambda_v} = C\left[\left(\frac{D^3 g}{\nu_v^2}\right)\left(\frac{d_1 - d_v}{d_v}\right)\right]^{1/4} \cdot Pr_v^{1/4} \cdot \left[\frac{L}{Cp_v (T_w - T_s)}\right]^{1/4} \quad (C.1)$$

where
h_{co}: heat transfer coefficient,
g : gravitational constant,
ν_v : kinematic viscosity of vapor,
λ_v : thermal conductivity of vapor,
d_l : density of water,
d_v : density of vapor,
Pr_v: Prandtl number of vapor,
L : latent heat of vaporization,
Cp_v: isobaric specific heat of vapor,
T_w : wall surface temperature,
T_s : saturation temperature.

Berenson extended the Bromly's correlation to film boiling of saturated water on a horizontal flat plate by defining an equivalent diameter D as

$$D = \sqrt{\sigma/g(d_l - d_v)} \quad (C.2)$$

where σ is surface tension, and by assuming that C = 0.425 in the Bromly's correlation.

For the standard case in the present analysis, pressure and initial debris temperature were assumed to be 12 MPa and 1000°C, respectively. Since saturation temperature at 12 MPa is 324.65°C, the average film temperature can be determined by taking an average of the system temperature and the saturation temperature as

$$(324.65+1000)/2 = 662.325°C$$

This temperature was used to determine physical properties of steam and saturation water. Then the equivalent diameter D can be determined as

$$D = \sqrt{\sigma/g(d_l - d_v)} = \sqrt{8.87 \times 10^{-3}/9.8/(655.0-29.15)}$$

$$= 1.203 \times 10^{-3}\ (m) \qquad (C.3)$$

By using the equivalent D determined in equation (C.3), heat transfer coefficient can be determined from the Bromly's correlation as

$$hco = \frac{\lambda_v}{D} C\left[\left(\frac{D^3 \cdot g}{\nu_v^2}\right)\left(\frac{d_l - d_v}{d_v}\right)\right]^{1/4} \cdot Pr_v^{1/4} \cdot \left[\frac{L}{Cp_v(T_w - T_s)}\right]^{1/4}$$

$$= \frac{9.58 \times 10^{-2}}{1.203 \times 10^{-3}} \times 0.425 \times \left[\frac{(1.203 \times 10^{-3})^3 \times 9.8}{(1.23 \times 10^{-6})^2} \times \frac{655.0 - 29.15}{29.15}\right]^{1/4}$$

$$\times 0.925^{1/4} \times \left[\frac{1.1974 \times 10^6}{2.482 \times 10^3 \times (1\,000 - 324.65)}\right]^{1/4}$$

$$= 677.0\ (W/m^2/^\circ C)$$

Finally heat flux at the top of the debris bed was calculated as

$$677.0 \times (1000 - 324.65) = 4.57 \times 10^5\ (W/m^2) \qquad (C.4)$$

It should be noted that heat transfer by radiation in film boiling can not be ignored as the surface temperature increases. The present analysis however neglected the effect of radiative heat transfer in the analysis. It is anticipated that an inclusion of radiation in film boiling heat transfer would increase approximately 20% at the most.

Appendix D Estimation of Steam Generation Rate in the Bottom of the Core

It was assumed that the bottom 50cm of the core was covered with coolant throughout the transient with decay heat corresponding to 175 min after the scram. Following values were used in the estimation;

Initial core power	2772 MW,
Decay heat at 175 min after the scram	23.71 MW,
Fuel active length	3.658 m,
Latent heat of vaporization at 12 Mpa	1.197×10^6 J/kg,
Diameter of the debris bed	3 m.

Then steam generation rate is given as

$$\frac{2.371 \times 10^7 \times 0.5/3.658}{1.197 \times 10^6 \times 3.14 \times 3^2} = 0.383 \text{ kg/m}^2\text{s.}$$

Appendix E Estimation of Steam Cooling Rate in the Debris Bed

For a homogenous debris bed, D. W. Green et al give the following correlation for heat transfer from particles to fluid in a packed bed of particles when Reynolds number is small.

$$Nu = \frac{h_p D_p}{k_f} = 0.013 \times Re^{1.84} \times Pr^2 \quad \text{for } Re = \frac{D_p \times G}{\mu} \leq 10 \qquad (E.1)$$

where

h_p: Average heat transfer rate between particles and fluid per total surface area,

D_p: Diameter of a particle,

k_f: Thermal conductivity of fluid,

G : Fluid mass flux,

μ : Viscosity of fluid.

From equation (E.1), steam cooling rate was calculated with following values,

Depth of the debris bed	1 m,
Paricle size	5 mm,
Porosity	0.4,
Ratio of fuel particles in the debris bed	0.7426.

Therefore total surface area in unit volume of the debris bed becomes

$$4 \times 3.14 (5.0 \times 10^{-3})^2 \times \frac{1.0 \times (1.0-0.4) \times 0.7426}{(4/3) \times 3.14 \times (5.0 \times 10^{-3})^3} = 267 \ m^2/m^3$$

With the assumptions that temperatures of the debris bed and steam were 1000°C and 324.65°C, respectively, then the following values were obtained.

$G = 0.016$ $\mathrm{kg/m^2s}$

$= 2.1\mathrm{x}10^{-5}$ sPa

$Re = 3.81$

$Pr = 1.45$

$Nu = 0.32$

$h_p = 6.27$ $\mathrm{W/m^2{}^\circ C}$

Therefore rate of heat removal by the steam was approximately $1.13\mathrm{x}10^6$ $\mathrm{W/m^3}$, which was almost the same as the decay heat at 175 min after the scram, $1.14\mathrm{x}10^6$ $\mathrm{W/m^3}$.