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ABSTRACT

We consider the growth of the melt pool in natural bed rock or chosen sacrificial material if heat producing core debris penetrates the bottom of the reactor vessel following a hypothetical core meltdown in a fission reactor. We concentrate on the case where the molten pool and material are miscible.

The growth of the pool has been examined in a first approximation by assuming radial growth using a mean heat transfer coefficient. During the early stages the heat delivered to the melting front is mainly used to advance the front, little escaping permanently into the surrounding material. The code BASALT follows the development of the pool in this stage and indicates that after a day the progress of the pool is not very sensitive to initial conditions. At longer times conduction will restrict the growth of the pool and an approximation to the maximum radius is derived. This stage has been examined in more detail using the ISOTHM code in which the heat conduction equation with the moving boundary is solved using the isotherm migration method. These results are used to discuss the constraints on external cooling of the pool to restrict its development.

Computer studies have also been undertaken using more realistic models of the distribution of heat flux at the pool boundary. The PAMPUR codes deal with (I) a cylindrical molten pool, (II) the growth of hemispheroidal pools, in which the vertical cross-section is elliptical, and (III) a model which is similar to II but includes conduction into the bed. In all cases the aspect ratio changes as the melting front advances, depending on the calculated heat transfer rates to the sides and to the bottom. Elongated pools are predicted if cooling of the upper surface of the pool is efficient, particularly when conduction into the bed is included; however agitation of the pool by decomposition gases may result in the pool growth being closer to radial than these calculations imply.

Several candidate sacrificial bed materials have been considered for insertion in a cavity; the most promising configuration consists of a low melting point rock surrounded by a more refractory insulator, provided that cooling of the upper surface of the pool can be relied upon.

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1. INTRODUCTION

If after a hypothetical reactor core meltdown debris penetrates through the bottom of the reactor vessel it will begin to melt into the material beneath. This may be natural bed rock or a bed of 'sacrificial material' placed there against this eventuality [1,2]. In either case it is necessary to estimate how large a molten pool of material will grow. We concentrate here on the case where the molten debris and the sacrificial material are miscible and consider both radially growing and axisymmetric pools.

The amount of heat available for melting the bed consists of the initial heat content of the debris and the integrated fission product decay heat. For a 3 GW(th) reactor the heat content of the debris is around 20 GJ which corresponds to $\sim$ 5 minutes of decay heat. The decay heat generated within the first three years of shutdown ($\sim 7 \times 10^4$ GJ) corresponds to about 6 hours of full reactor power (see [3]), so shortly after the formation of a melt-pool its development is essentially independent of the assumed initial conditions.

2. HEMISPHERICAL POOLS

The primary question concerns the volume of the melt-pool. This can be examined in a first approximation by assuming the pool grows radially using a mean heat transfer coefficient from the turbulently convecting molten pool. In the BASALT model an insulated lid is assumed so all the decay heat is used either to raise the pool temperature or melt new material. In the early stage very little heat escapes permanently into the bed and this is not included in the BASALT model. The growing pool engulfs the melted sacrificial material and forms a well-mixed turbulent pool of uniform temperature save close to the melting front where a boundary layer is present. These considerations lead to the equation obtained by Whipple:

$$\frac{d\theta_1}{dR} = \frac{\gamma}{R^3 - H^3}\left(\frac{Q}{\beta[\theta_1 - \theta_m]} - R^2\right) \tag{1}$$

where γ is a function only of material properties, β depends on the flow of heat to the phase boundary and H is a modified initial radius. This non-linear differential equation with the necessary associated equations is solved in BASALT. Fig. 1 shows a typical evolution of mean pool temperature with time, and equivalently with radius for debris from a 672 MW(th) core with a 1 year irradiation time. In this example the maximum temperature is reached after 15 minutes after which the pool gradually cools.

A characteristic dimension of the pool is $R^* = (3Q_o\tau_o/(2\pi\rho_2 L_2^*))^{1/3}$ where τ_o is a number of equivalent seconds of full power produced by the decay heating: it is taken here to be 1 hour. A typical value of $\tau(\infty)$ for fuel irradiation of one year is 6×10^4 secs, so that the maximum radius a hemisphere could reach when no heat is allowed to escape is $\sim 2.5\ R^*$. Table 2 gives R^* for some sacrificial materials of interest; the ranking of materials by R^* is the same as that given by Gluekler [4].

At early times the pool temperature varies considerably as calculated by the Whipple equation, but as the pool temperature falls towards its solidification temperature so the assumption that all the decay heat generated is used to melt new material or is conducted away becomes increasingly valid.

This latter assumption is used in the ISOTHM code in which conduction into the bed-rock is included. At early times the approximate temperature profile is [5]

$$\theta = \theta_o + (\theta_m - \theta_o)\exp[-u(r-R)/\kappa]\ ;\ r > R \tag{2}$$

where $u = \Phi/\rho L^* = Q(t)/(2\pi R^2 \rho L^*)$. (3)

This is used in ISOTHM until κ/uR reaches 0.05 after which the radial thermal diffusion equation, which may be written in the form $r_t = \kappa[r_{\theta\theta}(r_\theta)^{-2} - 2/r]$, is solved numerically by the particularly appropriate isotherm migration method (IMM) [6]. Typical results are shown in Fig.2.

In table 3 are results for sacrificial beds of basalt, alumina, uranium dioxide and magnesia using the Phillips CFR decay heat data [3] (see table 1 for assumed material properties). At short times the pool radii scale as R^*, so the volumes of pools in Al_2O_3 or UO_2 are similar and about one-third of that for a basalt bed; whereas in magnesia, the pool volume is only one quarter. At later times conductivity becomes an important parameter in restricting the size of the melt-pool; this may be seen by comparing the data for UO_2 and Al_2O_3 where radii are similar at short times but at maximum the pool radius for UO_2 is 15% larger than for Al_2O_3. The maximum volume of a pool of MgO is only 9% of the basalt value so without external cooling considerable savings in volume are possible by using a highly conducting dense oxide.

The calculations reported so far have assumed a semi-infinite bed of material, which in reality will be limited by the size of the reactor cavity. Even for the best material investigated the maximum radius of the melt-pool for a large reactor is over 7m and lower temperature isotherms propogate much greater distances into the material. The ISOTHM code may be used to estimate the demands on a cooling system which may either (a) stop the spread of the pool should it approach the sides or (b) remove heat conducted to the sides when the pool itself does not reach them. As the thermal front is thin until maximum radius is approached the cooling system to begin with (for a day or more) will not remove an appreciable amount of heat. The demands on a cooling system at fixed radii are summarized in Table 4 and an example shown in Fig. 3.

In applying these results to melt-pools in which cooling of the top surface is significant it should be recognised that although the downward growth will be slower than that suggested here the radial growth is likely to be similar since the lateral heat flux density will be comparable with that through the top. Thus if efficient cooling cannot be guaranteed it seems that a large radius bed is required unless the pool can be restricted by a more refractory barrier (see below) and the heat forced upwards.

An approximate expression for the radius of the hemispherical melt-pool is $R(t) = S(t) - (k(\theta_m - \theta_o)/(u(t)\rho L^*)$, where $S(t) \equiv \int u(t)dt$ from (3) ignores thermal leakage. The second term is a correction taking into account the heat content of the thermal front calculated from (2). Differentiation leads to an equation for the time (t_s) at which the maximum radius is reached:

$$Q_o^{2/3}[2\pi\rho L^*/3]^{1/3} = 6\pi k(\theta_m - \theta_o)F(t_s)$$

where $F(t) = f^{-2}\ \tau^{4/3}[2/3(f/\tau) - (df/dt)/f]$.

This may be solved for t_s or more readily for Q_o given several values of t_s, and the maximum radius of the melt-pool evaluated. Specimen results are compared with ISOTHM data in Fig. 4. For $Q_o = 10^8$W the maximum radius is underestimated by 30% while for $Q_o = 3 \times 10^9$W it is 10% below the ISOTHM value.

3. POOL GROWTH USING PAMPUR

In BASALT and ISOTHM a hemispherical pool with an insulated lid is assumed. In the PAMPUR computer code, the pool shape is allowed to evolve and efficient (sodium) top cooling is incorporated. The original model, PAMPUR1, consists of a disc-shaped pool whose aspect ratio changes with time. A two sub-layer model based on the heat content of the pool, with pure conduction downwards (c.f. [7]) is used to calculate the vertical heat transfer at each time step; the lateral heat flux density is taken to be a fraction α of that upwards where computer simulations [8,9] suggest that $0.5 < \alpha < 1.0$. Like BASALT, the pool growth in PAMPUR1 is calculated assuming no thermal conduction leakage into the bed.

Results for the complete meltdown of a 3.2 GWt core onto a basalt bed are shown in Fig. 5. After a day the pool has a large aspect ratio and its temperature is typically 160 K above the melting point of the bed. Other sacrificial materials give similar behaviour; after 10^6 seconds the downward penetration in either an alumina or a depleted UO_2 bed is typically 1 m and the pool radius $\sim$ 7.5 m, resulting in a pool volume about one third of that predicted for a basalt bed. With PAMPUR1, 75-85% of the decay heat generated is rejected to the sodium, giving appropriately smaller volumes than for insulated lid calculations.

Experiments with wax [10] show that in some circumstances a hemispheroid is a more realistic shape than a disc for a melt-pool; essentially PAMPUR2 differs from PAMPUR1 only in that the vertical section of the melting front is elliptic, with variable ellipticity. As table 5 illustrates, the results for disc shaped and ellipsoidal pools differ typically by up to 10%, and such small differences are explicable in terms of varying volume to surface ratios. Thus the general characteristics of a pool are not very sensitive to shape assumptions.

The thermal conduction leakage into the sacrificial material must be included in the modelling to calculate the maximum extent of molten pool. In the computer code PAMPUR3 this is done on the assumption that the isotherms, including the melting front, are ellipsoidal and so completely determined by the lengths of the semi-major and semi-minor axes - $r(\theta)$ and $D(\theta)$. The isotherm migration method (cf ISOTHM) is used here to solve the diffusion equation along the vertical axis of the spheroid for $D(\theta,t)$ and at the pool surface periphery for $r(\theta,t)$. Specimen results are given in table 5 for conduction into a basalt bed ($k = 2Wm^{-1}K^{-1}$). After 10 hours conduction begins to restrict the downward growth of the pool, and after three days this amounts to a 20% reduction in pool volume. Conduction at the sides near the pool is not well treated by the ellipsoidal assumption, however, the restriction in depth depends little on pool shape, and is a genuine effect. Given the assumption of a quiescent conduction layer a maximum pool depth of about 1 m is expected.

In §2 the restriction of hemispherical melt-pools by means of additional cooling was considered. Above it was shown that the downward penetration would halt at quite shallow depths if the lower part of the molten pool is quiescent. It might also be desirable to arrest the lateral growth, and a highly refractory insulator would provide an appropriate barrier [1]; its melting point should be well above that of the pool when the pool has reached the radius of the barrier. Such a wall can be modelled in PAMPUR1 by setting α to zero when the pool reaches the specified radius. Results for a basalt bed and an initial pool depth of 0.3 m are given in table 6. In these circumstances a 4 m radius wall would need to withstand $1600^{o}C$; a 6 m one only $1250^{o}C$. The pool depths are increased somewhat by the presence of the refractory wall, but substantially decreased volumes are predicted.

4. DISCUSSION/CONCLUSIONS

The purpose of the work described has been to consider various idealizations of the problem rather than to put all the possible effects, many of which are still rather uncertain, into one model. Although there may be many provisos necessary before applying our work to a specific problem it does allow fairly general conclusions to be drawn. We discuss here the main simplifications employed:

(i) a single phase model is used throughout. It is assumed that the steel phase and its associated fission products do not settle at the bottom of the pool. If they do then the shape of the pool may be distorted although its volume will be less than that found in the BASALT and ISOTHM codes (but greater than that given by PAMPUR).

(ii) the agitation of gas released from the sacrificial material and by the molten sacrificial material bubbling through the bed have not been specifically included. In the PAMPUR model this agitation would lead to increased downward penetration, larger pool volumes and somewhat lower pool temperatures. The BASALT and ISOTHM models solve the limiting case of sufficient agitation to provide a uniform Nusselt number at the pool edges.

(iii) the formation of crusts on the top of the pool are not considered in detail. It is likely that some crust or slag will form between the pool and the sodium covering although its composition and stability have not been investigated. In PAMPUR it is assumed that the upper boundary temperature of the pool is the melting (solidification) point of the sacrificial material and a crust thickness is calculated by requiring that the upwards heat flux from the pool should be removed. The predicted thickness of the crust is small for times less than a day. The BASALT and ISOTHM models use an insulated lid (no top-cooling) which is certainly conservative.

(iv) the heat transfer model at early times is unrealistic. BASALT and PAMPUR both use quasi-equilibrium models for the heat transfer; when temperatures and dimensions are changing rapidly these will be suspect particularly in the PAMPUR model where a lower conduction layer $\sim$ 5-10% of the depth is predicted. Additional heat transfer may occur because of vaporization of either fuel or sacrificial material, and in the BASALT case radiative cooling of the upper surface. The effect of all these mechanisms is to lower the temperature of the pool; the PAMPUR model may also underestimate downward penetration at this stage.

(v) there are many chemical uncertainties which have been ignored. Provided that the necessary solubilities occur and that heats of reaction are small compared with the decay heating rate this omission is acceptable.

Restriction of pool growth by a refractory insulator looks promising. For example provided there are no problems with low melting point eutectics, a basalt bed with alumina walls might be acceptable. The choice of insulator, which could be subject to severe thermal shock, may be eased if the original sacrificial material has a relatively low melting point ($\sim 1000^oC$). Downward growth may also be restricted by an insulator at a later stage thus forcing almost all the decay heat back up into the sodium.

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NOMENCLATURE

C	specific heat
D	depth of pool; vertical co-ordinate
$f(t)$	$= Q(t)/Q_o$
F	defined in text
H	modified initial radius
k	thermal conductivity
L	latent heat
L^*	$= L + C(\theta_m - \theta_o)$
$Q(t)$	rate of decay heating
Q_o	thermal power of reactor on-stream
R	radius of meltpool
R^*	characteristic radius defined in text
r	radial co-ordinate
s	separation of meltpool from cooling pipes
t	time since meltdown (shutdown of chain reaction)
t_r	time at which most cooling is required
t_s	time at maximum extent of pool
u	velocity of meltfront when thermal leakage is negligible
α	lateral convection parameter
β,γ	parameters in equation (1)
θ	temperature
θ_o	ambient temperature
θ_m	melting point of bed
θ_1	pool temperature
$\tau(t)=\int_o^t f(t)dt$	
τ_o	= (3600 seconds)
κ	thermal diffusivity
ρ	density
Φ	heat flux density

<u>Subscripts</u>

2	= property of bed
t,θ	= partial derivatives with respect to these variables.

TABLE 1

Assumed Thermal Properties

PROPERTY	UNITS	CORIUM	BASALT	ALUMINA	UO_2	MgO
Melting point	^oC	-	1100	2047	2796	2852
Density (solid & liquid)	$kg\ m^{-3}$	9×10^3	2.2×10^3	3.79×10^3	9.73×10^3	3.5×10^3
Specific heat	$J\ kg^{-1}\ K^{-1}$	340	1590	1150	340	1310
Latent heat	$J\ kg^{-1}$	-	3.88×10^5	10.67×10^5	2.75×10^5	17.9×10^5
Solid thermal conductivity	$Wm^{-1}\ K^{-1}$	2	2	5.5	2	6.5
Liquid thermal conductivity (PAMPUR)	$Wm^{-1}\ K^{-1}$	2	2	2	2	2
Liquid volume coefficient of expansion	K^{-1}	3.2×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	-
Kinematic viscosity	$m^2\ s^{-1}$	10^{-6}	10^{-6}	10^{-6}	10^{-6}	-

	$(\rho_2 L_2^*)^{-1}$	$\left(\frac{3\tau_o}{2\pi\rho_2 L_2^*}\right)$	R^*		R_2 (ISOTHM)		R_2/R^*	
Q_o			670 MW	3.2 GW	670 MW	3.2 GW	670 MW	3.2 GW
	$m^3\ J^{-1}$	$m^3\ J^{-1}$	m	m	m	m		
BASALT	23.0×10^{-11}	3.95×10^{-7}	6.4	10.8	7.6	15.3	1.19	1.41
UO_2	8.3×10^{-11}	1.43×10^{-7}	4.6	7.7	4.6	9.8	1.00	1.27
Al_2O_3	7.6×10^{-11}	1.32×10^{-7}	4.4	7.5	4.0	8.7	0.90	1.16
MgO	5.3×10^{-11}	0.91×10^{-7}	4.0	6.6	3.2	7.0	0.81	1.05

TABLE 2: The characteristic length R^* for various materials. The maximum radius of the melt-pool in these materials R_2 is taken from the ISOTHM calculations and the ratio R_2/R^* evaluated.

Q_o (GW)	MATERIAL	POOL RADIUS (metres) AFTER 1 day	3 days	10 days	29 days	100 days	1 year	3 years	MAX RADIUS (m)	TIME TO REACH MAX. RAD. (s)
0.672	BASALT	3.4	4.5	5.7	6.6	7.4	7.0	3.3	7.6	1.7×10^7
	UO_2	2.4	3.1	3.8	4.4	4.6	3.7	-	4.6	7×10^6
	ALUMINA	2.4	3.0	3.7	4.0	3.8	2.1	-	4.0	3.5×10^6
	MAGNESIA	2.0	2.6	3.1	3.2	2.8	-	-	3.2	2×10^6
3.223	BASALT	5.9	7.7	9.8	11.7	13.9	15.2	12.2	15.3	2.5×10^7
	UO_2	4.1	5.3	6.7	8.0	9.3	9.5	5.8	9.8	2×10^7
	ALUMINA	4.1	5.3	6.7	7.8	8.6	7.9	2.7	8.7	1.3×10^7
	MAGNESIA	3.6	4.6	5.7	6.6	7.0	5.7	-	7.0	8×10^6

TABLE 3

Results of ISOTHM for Phillips (CFR) decay heating rate

MATERIAL	Q_o = 3.223 GW				Q_o = 0.672 GW			
	r_c(m)	t_r(s)	$\Phi(t_r)$ (kWm^{-2})	s(m)	r_c(m)	t_r(s)	$\Phi(t_r)$ (kWm^{-2})	s(m)
BASALT	10	8×10^5	11	0.20	8	6×10^6	1.2	∿1.8
	8	3×10^5	28	0.08	6	1×10^6	5.6	0.4
	6	9×10^4	75	0.03	5	3.5×10^5	14	0.15
					4	1.5×10^5	30	0.07
UO_2	8	2×10^6	10	0.55	5	3×10^6	4.7	∿1.1
	6	4×10^5	43	0.13	4	8×10^5	14	0.4
	5	1.8×10^5	87	0.06				
ALUMINA	8	1.8×10^6	11	1.0	5	3×10^6	47	∿2
	6	4×10^5	43	0.26	4	8×10^5	14	0.8
	5	1.8×10^5	87	0.13				
MAGNESIA	8	5×10^6	6.6	∿2	4	3×10^6	7.3	∿1
	6	8×10^5	31	0.6				
	5	3×10^5	71	0.26				

TABLE 4: COOLING REQUIRED TO RESTRICT THE GROWTH OF A HEMISPHERICAL MELT-POOL

The cooling is at radius r_c. The maximum heat flux density to be removed is $\Phi(t_r)$ and occurs at t_r seconds after the accident. At shorter times little heat reaches the cooling system. The closest approach to the cooled walls is s; the values are only approximate when s is a significant fraction of r_c. Phillips decay heating formulae were used.

t	UNRESTRICTED				R_W = 6m			R_W = 5m			R_W = 4m		
	r	D	V	θ_1	D	V	θ_1	D	V	θ_1	D	V	θ_1
10^3	1.38	0.30	1.8	3332		Wall			Wall			Wall	
3×10^3	2.20	0.42	6.4	2379		reached			reached			reached	
10^4	3.17	0.56	18	1709		1.1×10^5			5×10^4sec			2×10^4sec	
3×10^4	4.34	0.72	43	1402		sec.					0.73	37	1492
10^5	5.83	0.93	99	1253				0.96	75	1320	1.08	54	1415
3×10^5	7.71	1.18	221	1177	1.28	145	1229	1.44	113	1274	1.74	87	1352
10^6	10.1	1.50	480	1138	1.97	222	1200	2.32	182	1235	2.93	148	1296

TABLE 5: The effect of an insulating wall at a fixed radius. Results for basalt with α = 0.6

TIME	DISC - NO CONDUCTION				ELLIPSOID - NO CONDUCTION				ELLIPSOID - CONDUCTION			
t	θ_1	D	r	V	θ_1	D	r	V	θ_1	D	r	V
10^3	3332	0.30	1.38	1.80	3338	0.30	1.69	1.80	3306	0.30	1.69	1.80
3×10^3	2379	0.42	2.20	6.4	2493	0.43	2.58	6.0	2437	0.43	2.63	6.2
10^4	1709	0.56	3.17	18	1774	0.58	3.68	16	1748	0.56	3.75	16
3×10^4	1402	0.72	4.34	43	1437	0.76	5.02	40	1421	0.68	5.15	37
10^5	1253	0.93	5.83	99	1270	0.98	6.72	93	1261	0.80	6.90	80
3×10^5	1177	1.18	7.71	221	1168	1.26	8.88	209	1193*	0.89*	8.63*	138*
10^6	1138	1.50	10.1	480	1143	1.61	11.6	456				

*Values at 2.5×10^5 seconds.

TABLE 6: Comparison of results for growth of a disc-shaped pool and a hemispheroidal (ellipsoid) pool in basalt, with and without conduction. α = 0.6.

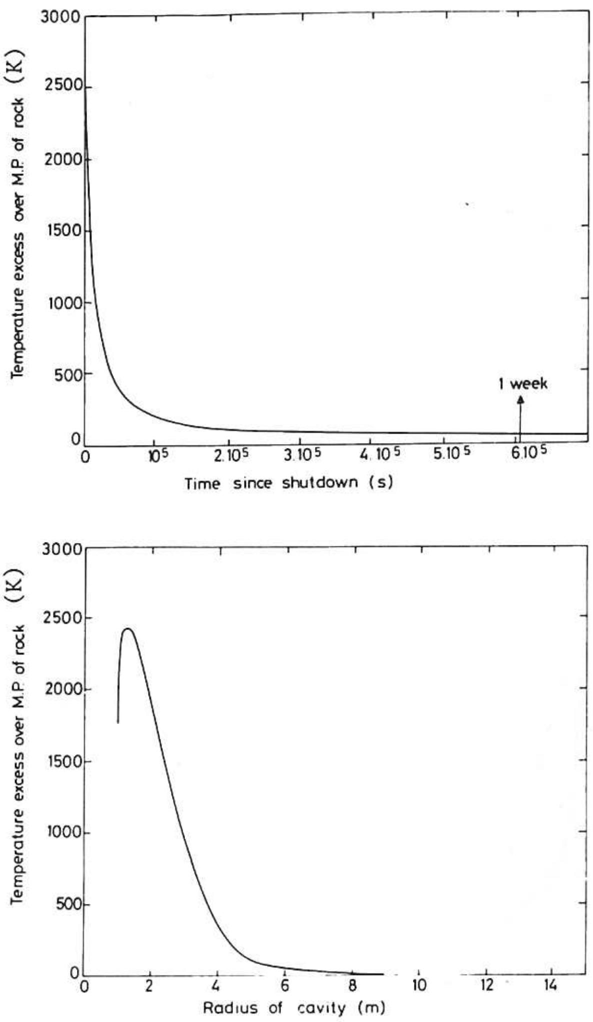

FIG. 1. Results for the BASALT code. Meltdown of a 672 MW(th) core onto a basalt bed.

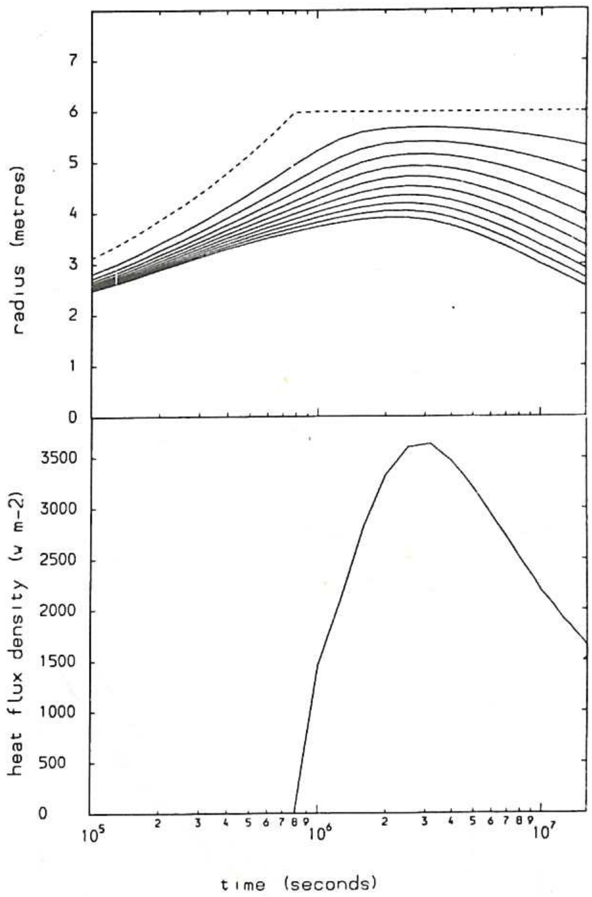

FIG. 3. Alumina sacrificial bed with cooling at 6 m radius; 672 MW core. The isotherms are shown in the upper frame and the demand on the cooling system is shown in the lower frame.

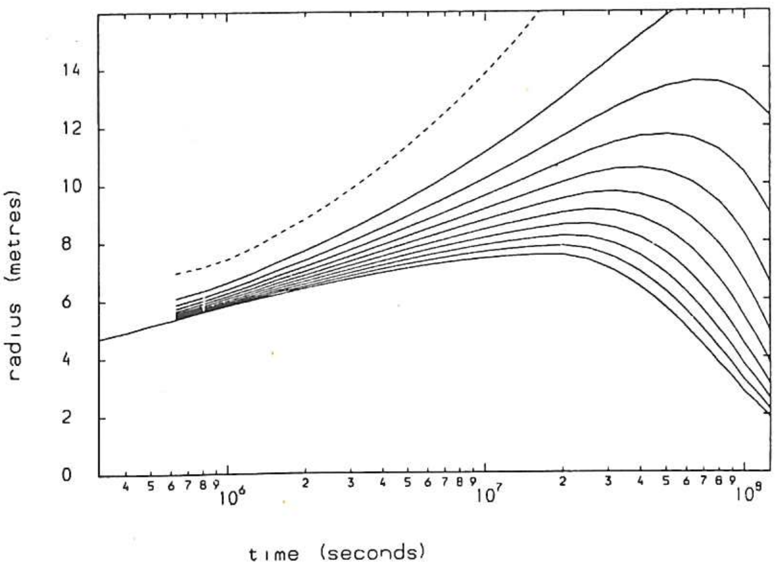

FIG. 2. ISOTHM results for case of Fig. 1. The isotherms between ambient temperature (dashed) and the melting front are shown for equal temperature intervals.

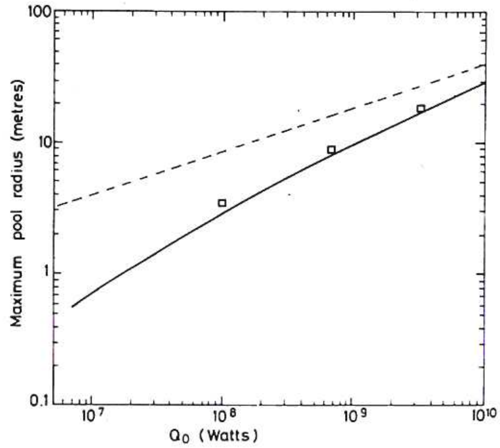

FIG. 4. Results for the approximate maximum radius of the meltpool (continuous line) compared with the detailed ISOTHM calculations (□). The dashed line shows the maximum radius if there were no thermal leakage (2.5 R*). A basalt bed is assumed.

FIG. 5. Results from PAMPUR 1 for meltdown of a 3.2 GW(th) core onto a basalt bed. Initial debris volume = 1.8 m^3.

- - - - - D_o = 0.1, α = 1.0 ——— D_o = 0.1, α = 0.6

— — — — D_o = 0.3, α = 0.6.