CLM-P591

CLM-P591

UKAEA

Preprint

MODELS OF CORE MELT BEHAVIOUR AFTER A POSTULATED REACTOR VESSEL MELT-THROUGH

R. S. PECKOVER
T. A. DULLFORCE
B. D. TURLAND

CULHAM LABORATORY
Abingdon Oxfordshire

1979

CLM-P 591

MODELS OF CORE MELT BEHAVIOUR AFTER A POSTULATED REACTOR VESSEL MELT-THROUGH

R S Peckover, T A Dullforce and B D Turland

UKAEA Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, UK

ABSTRACT

In the unlikely event of reactor core debris melting through the reactor vessel after a postulated core meltdown it will contact the underlying substrate material. The subsequent behaviour of the core-melt depends on the fractions of oxide fuel and stainless steel in the melt. At one extreme the core debris forms a single phase oxide pool miscible with the substrate material. At the other extreme the metallic phase (including metallic fission products) may separate from the oxide fuel and its penetration into the substrate needs to be calculated separately. Models for the penetration of an immiscible phase into a lower melting point substrate are developed and illustrative calculations presented. Factors where a more detailed understanding would enable the range of models considered to be reduced are indicated.

(Paper presented at International Meeting on Fast Reactor Technology, Seattle, 20 August 1979).

August 1979

1. INTRODUCTION

In fast reactor designs, the possibility of a whole-core melt-down accident occurring can be made so low that a detailed consideration of its effects might be deemed unnecessary. However, a requirement that the reactor shall be made as safe as practicable means that the results of such hypothetical accidents are explored to see if containment capability can be further enhanced.

In the unlikely occurrence of the meltdown of the core of a fast reactor such fuel as becomes molten is likely to fragment on contact with the sodium [1] and then fall onto horizontal structures inside the reactor vessel. If a particulate bed of sufficient depth were to form this might overheat and melt the underlying support structure. The potential for dry-out and relocation of such beds under sodium is still rather uncertain; it is anticipated that the experiments in ACRR at Sandia [2] will help to clarify this point. If the bottom of the reactor vessel were melted through, the debris would penetrate into the solid substrate beneath. Criteria for the circumstances under which steel plates under sodium will melt-through are considered in [3]. The term 'substrate' is used as a generic term to denote the concrete of the basemat, solid rock, or a specially chosen ex-vessel sacrificial material.

The constituents of core debris are oxide fuel, stainless steel from the cladding and support structures, and the fission products. The non-volatile fission products can be divided into two classes (i) oxide fission products which are miscible with the oxide fuel and (ii) metallic fission products which are not miscible with the fuel, but are miscible with the steel to which they preferentially migrate [4,5,6]. Thus the melt pool which formed beneath the reactor vessel could consist of two immiscible phases, oxide and metallic, each containing appropriate fission products as internal heat sources. The relative fractions of oxide and metallic phase reaching the substrate depend on the dynamics of particulate bed formation and structural melt-through.

The mode of meltpool growth depends on how homogeneous the pool is. If sufficient oxygen is available as a result of the heating of the substrate then the steel may become oxidized, and in this case essentially all the core debris will be mixed into a single oxide phase into which the molten rock is incorporated as the melting front of the pool advances (fig.1a). If the metallic phase is not oxidized but remains finely divided and held in suspension by convective motions within the pool, then the meltpool may still be considered as a single entity which is diluted by substrate material as it grows (see §2). However the existing data on mutual solubilities of coria with substrate materials [7,8], and the behaviour of multi-component pools do not enable us to say with any confidence that a miscible pool provides the only appropriate model for core debris behaviour. If the pool is rich in metallic phase, then some of the metallic phase may settle into the lower part of the pool and coalesce. This liquid metallic phase is more dense than a liquid formed by melting the substrate(if this is rock or concrete) and would also be denser than the urania-based liquid after this had been diluted once by volume by molten substrate. Thus if the metallic phase melts material beneath it, the material will be displaced and the metallic phase will sink. The spatial dependence of the heat flux density around the melting front determines the shape of the front which itself largely determines the depth of penetration for a given quantity of fission products in the metallic phase. If the heat flux density vertically downwards is a minimum the interface will tend to spread out into a pancake shape (see fig.1b), whilst if the maximum heat flux density is vertically downwards the material will descend as a 'tongue' (see fig.1c), or several tongues, which may break up into distinct globules. In §3 a simplified model of substrate penetration by a metallic phase taking the form of a gradually broadening pancake or 'lens' is developed. In §4 the penetration of globules or tongues, for which little lateral broadening of the metallic phase is to be expected, is examined.

2. MISCIBLE MOLTEN POOL BEHAVIOUR

Detailed studies of the growth of molten pools when the core debris and the substrate become rapidly intermingled as the substrate material is absorbed into the molten pool have already been described elsewhere [3,9,10,11]. The properties of the pool of interest are (i) the maximum depth (ii) the maximum diameter (iii) the time to reach maximum size. These depend on the mean irradiation time t_q of the fuel in the reactor at shutdown, since the total rate Q at which decay heat is supplied to the melting front as a whole can be expressed in a form such as [11]

$$Q = Q_1\{(t_f/t)^{1/4} - (t_f/[t+t_q])^{1/4}\} \tag{2.1}$$

in which t is the time elapsed since shutdown, $t_f=1.5\times10^{-4}$sec for a fast reactor, and $Q_1=\lambda Q_o$ is some fraction $\lambda(\leq 1)$ of the nominal power Q_o of the reactor on stream. The appropriate choice of λ is discussed below. A typical length scale b_o can be defined by $b_o=10^{-3}Q_o/2\pi k\Delta T$. A typical time scale t_1 for the system can then be defined by

$$t_1 = (2\pi b_o^3/3)\ \rho[L+(1+\gamma)c\Delta T]/Q_1 \tag{2.2}$$

The numerator of (2.2) is the sum of the enthalpy in a pool of radius b_o and the enthalpy gained by the surrounding substrate (measured above ambient temperature). Detailed studies [11] show that when the pool reaches its maximum size, the numerical constant γ is ≈ 4.

For infinite burnup, under the assumptions listed below, the maximum dimension of the pool r_∞ is given by

$$r_\infty = 25\ b_o(t_f/t_1)^{1/6} \tag{2.3}$$

and the time to reach maximum size is approximately t_∞ where

$$t_\infty = 0.2\times10^6(t_f\ t_1{}^2)^{1/3} \tag{2.4}$$

For finite burnup the maximum dimension of the pool r_m is given by

$$\left.\begin{aligned} r_m &= r_\infty && \text{if } t_q\geq t_\infty \\ &= r_\infty(t_q/t_\infty)^{1/4} && \text{if } t_q\leq t_\infty \end{aligned}\right\} \tag{2.5}$$

The time to maximum pool size is $\sim t_\infty$ for high burnup ($t_q\geq t_\infty$) and $\sim (t_q{}^2 t_\infty{}^3)^{1/5}$ for low burnup ($t_q\leq t_\infty$). The significant assumptions made in deriving these formulae are (i) the core debris and the molten substrate material form a well-mixed pool (ii) the pool grows as a hemisphere. (Pool volumes based on (2.5) will be approximately correct even if the pool grows in a somewhat different shape - it is likely to be broader and shallower) (iii) heat generated from chemical reactions have been ignored. (These only contribute at most a few per cent).

The fraction λ can be considered as the product of two factors λ_1 and λ_2 where λ_1 is the fraction of the core debris which reaches the substrate and λ_2 is the fraction of the decay heat generated in the pool which is not transported upwards to the overlying sodium. If one assumed rather pessimistically that one third of the core debris escaped through the bottom of the tank, and realistically that 80% of the heat in the pool is transported upwards to the overlying sodium, then $\lambda = 0.06$. In practice λ will be almost always very much smaller than this, because of debris dispersal within the reactor vessel and the presence of structures within the vessel which act as barriers to the downward penetration of core debris.

The variation of the maximum pool dimension with irradiation time is plotted in fig.2 for an alumina bed. The results both of detailed calculations using the ISOTHM code and those derived from equations (2.4) and (2.5) are given. If Q_o = 3GWt and λ = 0.06 then r_∞ = 3.3 m and $t_\infty = 5 \times 10^6$ sec. For 240 day burn-up, $t_q = 2.1 \times 10^7$ sec giving $r_m \approx r_\infty$. The shape of the pool will vary with time. At early times the oxide debris is much heavier than any concrete or bedrock, and so the pool will tend to be deep [12]. The bubbling of material through the pool will also tend to favour downward rather than sideward penetration. At later times when the pool has been significantly diluted it will grow preferentially sideways. Fig.3 shows the shape of the pool after 1 year calculated (using a 2-D generalization of the isotherm migration method [13]) for a 1GWe core using a simplified heat transfer model allowing for heat transfer to the overlying sodium. Roughly speaking the maximum *horizontal* dimension of the pool can be calculated from the formulae above, neglecting the heat transfer to the sodium, (i.e. setting λ_2 = 1); for the maximum *depth* a realistic value of λ_2 should be used.

3. LENSLIKE PENETRATION INTO THE SUBSTRATE BY METALLIC PHASE CORE DEBRIS

We consider now the situation in which the steel-based phase in the molten pool settles at the bottom of the main pool as a shallow lens-shaped subpool (see fig.1b)., which is not miscible with the substrate material. A simplified description is made here to determine how significant this mode of pool growth might be.

It is assumed that (i) the immiscible phase forms a pool of fixed volume V_o and fixed fission product inventory (ii) the heat flux density through the lower surface of the pool is distributed as a uniform heat flux density and (iii) the lower surface of the pool forms part of a spherical surface, whose radius of curvature R increases with time but whose centre of curvature is fixed. Assumptions (ii) and (iii) are self-consistent in the sense that uniform heat flux density to and beyond the melting front will lead to it maintaining a spherical form if it had it initially. The semi-angle θ subtended by the metallic phase pool satisfies

$$V_o = (\pi R^3/3)(2 - 3\cos\theta + \cos^3\theta) \qquad (3.1)$$

The nomenclature is given in fig.4. As the pool sinks, θ decreases and when $\theta \ll 1$, (3.1) becomes $V_o = (\pi R^3/4)\theta^4$ with $z \approx R$ and $r \approx R.\theta$. Thus when θ is small, the pool spreads laterally rather slowly since r scales as $z^{1/4}$ (see fig.5)

The heat flux density is $Q(t)/A(t)$ where Q is the total heat flux rejected through the lower surface, and the rate of melting of the substrate is determined by the Stefan condition at the melting front. These conditions were used in conjunction with the ISOTHM code [9] which gives a self-consistent treatment of the movement of the melting front with heat conduction into the substrate. For Q(t), the form (2.1) was used, in which $Q_1 = \lambda Q_o$ and λ is now the fraction of the fission product inventory whose heat is transported to the lower surface of the metallic phase pool. Since only ~ 30% of the decay heat comes from fission products which may migrate to the metallic phase, and at least half the heat generated in the metallic phase is likely to be transferred upwards, then if one third of the core debris escapes through the bottom of the reactor vessel, λ is ~ 0.05. Table 1 shows the results for values of Q_1 between 10^7 and 2.10^8W for a bed with the properties of basalt for various initial configurations, defined by the metallic phase volume V_o and the initial semi-angle θ_o.

A further parametric study was undertaken in which the thermal conductivity of the bed was varied. An initial volume of metallic debris of $3m^3$ was assumed with $\cos\theta_o = 0.9$. Fig.6 shows the calculated maximum penetration and the time at which penetration ceases as functions of Q_1 and k. Thus in this model, significant penetration depths can be obtained for substantial accumulations of metallic phase, but over rather long times.

4. GLOBULE AND TONGUELIKE PENETRATION INTO THE SUBSTRATE

An alternative model is one in which the immiscible phase is concentrated into a tongue or a globule. The essential characteristic of the descent of a hot globule through a solid substrate of lower melting point is that it does so by melting a transient liquid cavity in which the globule falls. The rate of fall is essentially determined by the downward heat flux density to the melting front immediately beneath the globule, and as the same is true for a tongue whose horizontal dimension does not grow with time, the case of a descending tongue may be considered as the descent of a globule with a 'tail' of the same material. To make the model specific we shall consider the globule to be a sphere so that its size and shape are fixed. A gap (filled with liquid) exists between the bottom of the sphere and the melting front; and the gap thickness is found to be self-regulating so that the reduced weight of the sphere is just balanced by the drag exerted by the liquid, which is determined by the fall velocity.

The rate of downward advance of the melting front $dz/dt(\equiv U(t))$ can be represented [11] to a good approximation by

$$\rho(L+c\Delta T)\,U = (\Gamma Q/4\pi a^2) - (k\Delta T/R) \qquad (4.1)$$

where a is the sphere radius, R is the radius of curvature of the melting front at its lowest point, Q(t) is the heat generation rate within the sphere, and the adjustable coefficient Γ is of order unity. Note that Γ must be less than 4, to allow for some lateral conduction into the substrate material.

To test the validity of equation (4.1) laboratory experiments have been carried out using electrically heated copper spheres in a wax bed, in which the sphere descends steadily. Fig.7 shows the resulting cavity shape. The important point is that the layer of melted material ahead of the sphere is so thin that the radius of curvature R at the lower point of the melting front can be well approximated by the radius a of the sphere. Fig.8 shows the correlation for the copper spheres between the sphere fall velocity U and the mean heat flux density $Q/4\pi a^2$ to the surface of the globule when the input power is maintained constant. The agreement between these results and equation (4.1) when $\Gamma \approx 2$ is remarkably good, implying that half the heat generated in the sphere is used to maintain the melting front advance.

For core debris, the heat generation rate Q(t) is given by (2.1) in which λ is the fraction of the fission products of the whole core which is present in the globule. With R = a, and $\Gamma = 2$ (as the copper sphere experiments suggest), the maximum depth of penetration z_m can be obtained. It is of some interest to see how z_m depends on the globule size when the density of the fission products within the globule is fixed (which implies λ scales as a^3). Write $\lambda = \mu a^3$ where μ is constant and define a characteristic globule radius a_p by $a_p^2 = 2/(\mu a_o)$. Then $z_m/(a_p.N)$ is a function of (a/a_p) only where $N = 8\mu\kappa_1 t_q a_o$ is a dimensionless number (see the list of symbols for κ_1 and a_o). The form of z_m, and the time t_m when penetration ceases, are shown in fig.9.

There are two limiting cases. When $a<<a_p$, corresponding to $t_m<<t_q$, then $z_m=\kappa_1 t_m/a$ in which $t_m = t_f(\mu b a^2)^4$. Thus t_m scales as a^8 and z_m scales as a^7. For the other limit, we note that an upper bound z_∞ for the maximum distance of penetration can be obtained by supposing that all the heat generated was used to melt a cylinder of depth z_∞ and radius just greater than a, with no heat conducted away. For constant $\mu, z_\infty \propto a$ (see fig 9). In fact when $a>>a_p$, $z_m \approx \frac{1}{2}z_\infty$. These results can be summarised in the form

$$z_m/(a_p.N) = \begin{cases} (a/a_p)^7 & \text{if } a<<a_p \\ \frac{1}{2}(a/a_p) & \text{if } a>>a_p \end{cases} \qquad (4.2);$$

when $a \approx a_p$, equation (4.2) *over* estimates z_m(see fig 9).

By way of illustration let us consider a substrate with properties $k = 2W/(m.K)$, $\Delta T = 1300K$, $\kappa = 10^{-6}m^2/s$ and $S = 2$ (which are typical of basaltic concrete). Now ~ 30% of the decay heat is produced by fission products which remain in metallic form [5]. Let us suppose that half of those from a 3 GWt reactor core migrate to ~ $3m^3$ of steel and are uniformly distributed within it. Since there is ~ $1\frac{1}{2}m^3$ of oxide fuel, then $\mu=0.25/m^3$. Hence if $a<<a_p, z_m \approx 15.(10a)^7$; and if $a>>a_p, z_m \sim 5.10^{-3} t_q^{3/4}$ a where $a \approx 0.02 t_q^{1/8}$. If $t_q=2.10^7$sec, $a_p \approx 16$ cm. Thus a globule of radius 12cm with this illustrative fission product density would have a maximum penetration depth of ~ 7m and a fall time of ~ 3 weeks. If the fission product density in the steel of the globule is lower, either because the fission products could migrate to a larger volume of steel or because more metallic fission products remained embedded in the oxide fuel, then the maximum penetration depth is sharply reduced since $z_m \propto \mu^4$ when $a<<a_p$.

In this model it has been tacitly assumed that the globule has formed outside the reactor vessel immediately after shutdown. This is of course a very conservative assumption. Considerable delays will actually occur before vessel penetration during which the decay heat level will decrease markedly. Nevertheless for larger globules with $t_m \sim t_q$ such delays would only reduce the maximum penetration by 25%.

If the immiscible phase forms a descending tongue which has a constant diameter in the vicinity of its base, then the model outlined above should be appropriate and (4.2) should still apply, with suitable choice of λ.

5. DISCUSSION

Three models of the way in which core debris may penetrate into the substrate beneath a reactor vessel have been examined. In the first the debris is assumed to be easily miscible with the substrate, and penetrations of the order of a few metres only are to be expected. In the other two the immiscible phase is conceived of as remaining distinct and descending in the form of a 'pancake' which broadens slightly or as a 'globule' or 'tongue' which remains narrow. The penetration distances for either of the latter models would be quite large if significant fractions of the steel from the core picked up a substantial fission product inventory, found its way beneath the reactor vessel, and came together as a single metallic phase 'lump'.

It must be stressed that the models considered here must be considered to be limiting cases. The following factors all depend on the complex fluid-dynamical behaviour of rather ill-determined multi-phase mixtures:-

(i) the rate at which oxide fuel is diluted by substrate material
(ii) the level of agitation in a melt-pool as a result of gas evolution from the substrate
(iii) the ease with which metallic fission products migrate from an oxide phase to a metallic phase
(iv) the extent to which the metallic phase is oxidized.

The first two factors modify the shape of miscible pools. The last two are important for immiscible models, since the results are strongly dependent on the volume of immiscible phase involved, and the extent to which metallic fission products actually migrate to the steel. Further studies of these factors under non-equilibrium conditions are required if the range of models considered is to be reduced. In particular more dependable data is needed on the rates of oxidation when molten refractory oxides and the gases from their partial decomposition are bubbled through pools of molten iron.

Nevertheless the models described here enable us to put a fairly restrictive envelope around the potential movements of core debris. As a consequence one can estimate the extent of penetration into the substrate whether the postulated quantity of core debris involved is large or small. In practice the structures within the reactor vessel itself will provide barriers to the descent of core debris and the excellent heat transfer properties of sodium should ensure that particulate beds of core debris under sodium will be coolable.

LIST OF COMMON SYMBOLS

ρ, c, k, and $\kappa \equiv (k/\rho c)$ are the density, specific heat, thermal conductivity and thermal diffusivity of the substrate material; L and T_m are its latent heat of melting and its melting point. T_o is the ambient substrate temperature. Q_o is the reactor (thermal) power on stream, t is the time since shutdown, and t_q is the mean irradiation time of the fuel. μ is the 'density' of fission products in the globule, t_f is a reactor time constant($=1.5 \times 10^{-4}$s). $\Delta T=T_m-T_o$; S = Stefan number $(c\Delta T/L)$; $\kappa_1=\kappa S/[3(1+S)]$ $b=Q_o/2\pi k\Delta T$; $a_o=b.(t_f/t_q)^{1/4}$; $N = 8\mu\kappa_1 t_q a_o$.

ACKNOWLEDGEMENTS

This work has been carried out under the auspices of the UK Safety and Reliability Directorate,Culcheth. M.A.Johnson assisted with the experiments.

TABLE I

Maximum penetration depths and corresponding times for lens-shaped pool ; k = 2.5 W/(m.K).

λQ_o (Mw)	TIME (10^7s)	DEPTH (m)	TIME (10^7s)	DEPTH (m)	TIME (10^7s)	DEPTH (m)	TIME (10^7s)	DEPTH (m)
200	16.8	53.3	16.7	50.9	9.4	29.0	8.9	21.9
100	8.2	27.7	8.2	25.6	4.3	12.9	3.82	8.5
60	4.6	16.1	4.6	14.1	2.16	6.1	1.72	3.6
40	2.72	9.8	2.71	8.1	1.08	3.0	0.69	1.4
20	0.79	3.4	0.82	2.3	-	-	0.019	0.33
10	-	-	0.06	0.34	-	-	0.002	0.22
$\cos\theta_o$	0.0		0.9		0.9		0.99	
V_o	1.0		1.0		3.0		3.0	

REFERENCES

1. E.L GLUEKLER and L BAKER JR.,"Post-accident heat removal in LMFBR's" in Symposium on Thermal and Hydraulic Aspects of Nuclear Reactor Safety Volume 2 p285, A.S.M.E (1977).
2. J B RIVARD,"Cooling of particulate debris beds: analysis of the initial D-series experiments." Proc.4th PAHR Information Exchange,Ispra,October 1978(in press).
3. B D TURLAND and R S PECKOVER,"Melting front phenomena - analysis and computation." Proc.4th PAHR Information Exchange,Ispra,October 1978 (in press) (Also Culham report CLM-P564).
4. M S KAZIMI and J C CHEN, "A condensed review of the technology of Post-Accident Heat Removal for the LMFBR."Nuclear Technology,38,339(1978).
5. B D TURLAND and R S PECKOVER,"The Distribution of fission product decay heat." Proc.3rd PAHR Information Exchange(ANL-78-10,p17) (1978).
6. D J HODKIN, P E POTTER and R.F HILLS,"The constitution of a molten oxide fast reactor core. "Proc.4th PAHR Information Exchange,Ispra October 1978 (In Press).
7. M G CHASANOV et al."Reactor Safety and Physical Property Studies"Argonne Nat.Laboratory Report ANL-8120(1974).
8. P D CAPP et al."Sacrificial material/Uranium Dioxide Interactions" Proc. 4th PAHR Information Exchange,Ispra,October 1978 (in press).
9. R S PECKOVER,B D TURLAND and R.T.P.WHIPPLE,"On the growth of melting pools in sacrificial materials."Proc.3rd PAHR Information Exchange(ANL-78-10,P 179)(1978).
10. J J PYUN et al.,"Ex.vessel containment response to a core meltdown".Proc 3rd PAHR Information Exchange(ANL-78-10,p327) (1978).
11. R S PECKOVER,"Thermal moving boundary problems arising in reactor safety" paper presented Durham symposium on free and moving boundary problems in heat flow and diffusion. Culham report CLM-P562 (1978).
12. R FARADIEH, L BAKER Jr., and R E FAW,"Studies of Pool Growth with simulant materials". Proc.2nd PAHR Information Exchange (Sandia Laboratories Report SAND 76-9008,p271)(1975).
13. B D TURLAND,"A general formulation of the isotherm migration method reactor accident analysis"Proc.5th Conf. on Structural Mechanics in Reactor Technology,Berlin ,paper B3/5 North-Holland(Commission of the European Communities)(1979).

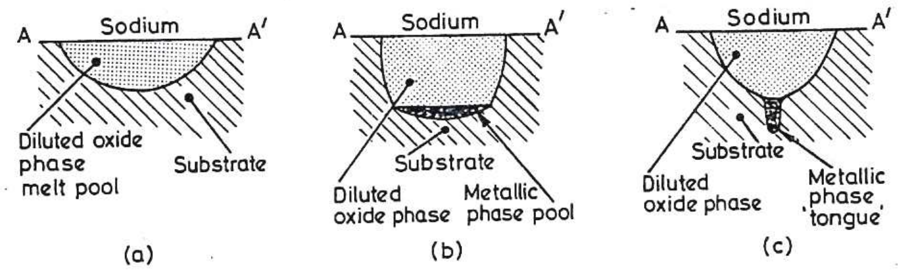
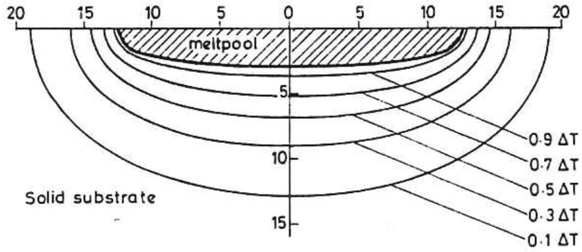


Fig.1. Models of melt pool growth. The curve AA′ is the reactor vessel bottom. In (b) and (c) parts of the diluted oxide phase may have resolidified.



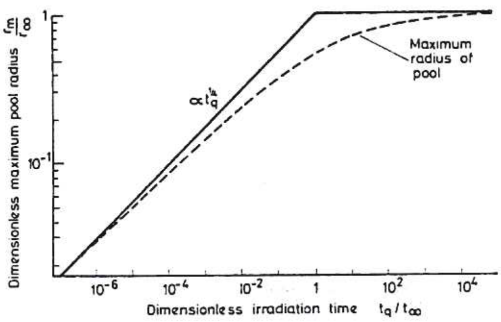


Fig.2. Dependence of maximum pool dimension r_m on the irradiation time t_q (log-log plot)

Fig.3. Shape after 1 year of an axisymmetric miscible pool for core debris from 3GWt core(gas agitation neglected).The substrate isotherms are labelled with their temperature excess above ambient.

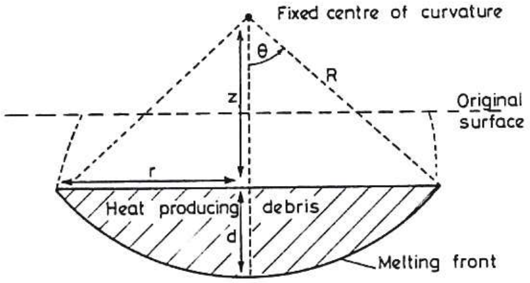


Fig.4. Geometry of lens-shaped pool of immiscible core debris

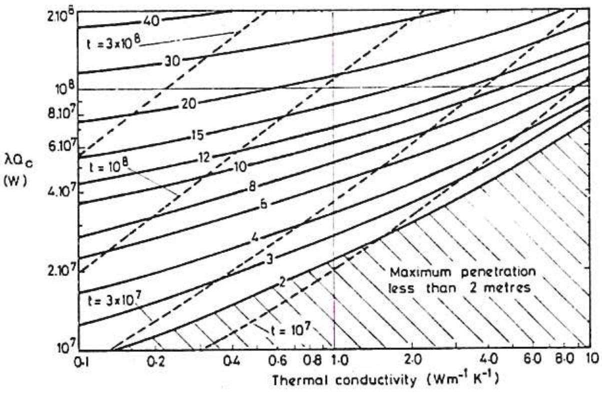


Fig.6. Penetration by a lens-shaped metallic debris pool:dependence on k of (i) maximum penetration (in metres) [solid lines](ii) time (in seconds) of maximum penetration [dashed lines] for a range of fission product inventories [see text for definition of λQ_o]

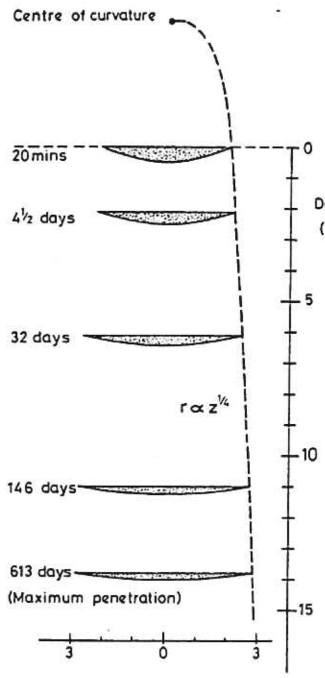


Fig .5. Descent of lens-shaped pool (of volume $3m^3$).λQ_o=100MW, k=2W/(m.K).

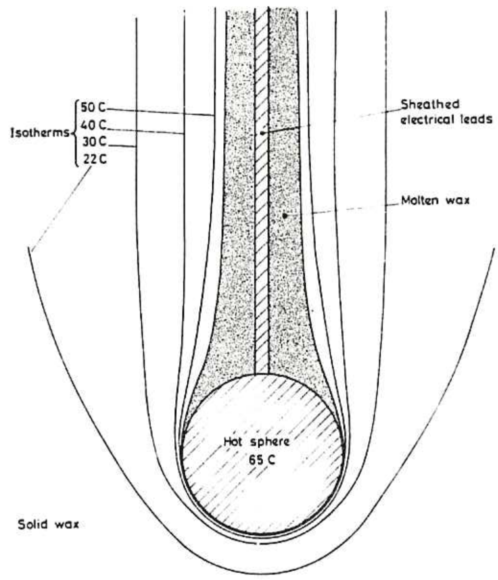


Fig.7. Heated copper sphere descending through wax at 0.06 mm/s. Input power is 20W, sphere diameter is 35 mm.

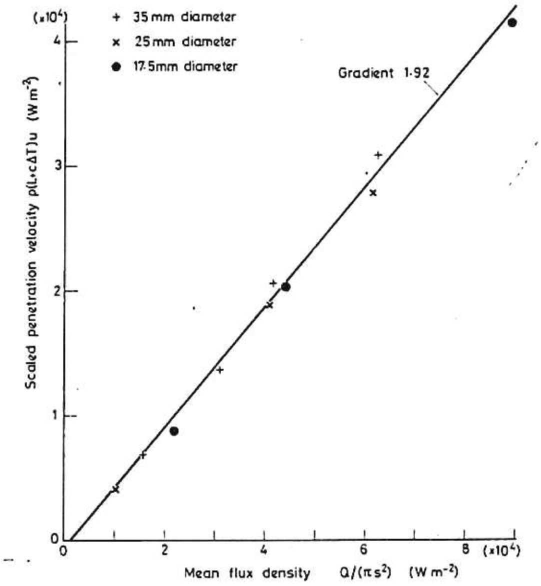


Fig.8. Correlation between the steady fall velocity U of copper spheres through wax and the mean heat flux density $Q/4\pi a^2$. The gradient Γ=1.92.

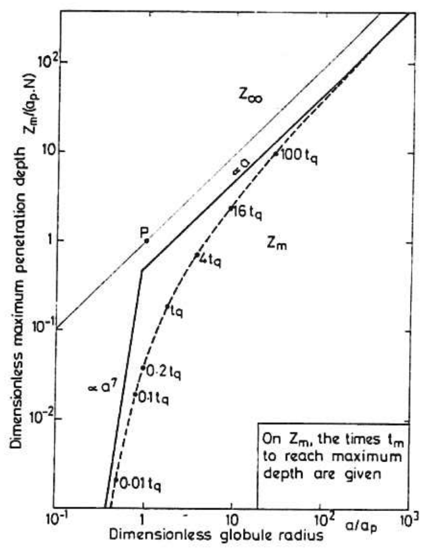


Fig.9. The dependence of the maximum penetration depth z_m on the globule radius a for fixed fission product density. The solid lines represent bounding curves-the dashed line gives the likely behaviour.