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ABSTRACT

A temperature excursion arising through some hypothetical blockage of the cooling system in a liquid-cooled reactor system could lead to the melt-out of some part of the core. To prevent failure of the reactor vessel, suitably designed core catchers are placed below the core to catch the molten debris. This paper considers the heat transfer characteristics of a single catcher in an effectively isothermal sea of coolant, concentrating especially on a slab model. Particulate debris is likely to melt and consolidate into a solid layer with a molten interior. This layer will remain passive provided its central temperature does not exceed its boiling point and provided the supporting catcher remains sufficiently cool not to buckle or melt through. The effectiveness of convection in the coolant in transporting heat is discussed both for a single catcher and an array of catchers.

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1. Introduction

A temperature excursion arising through some hypothetical blockage of the cooling system in a liquid cooled reactor system could lead to the melt-out of the core or some part of the core. If the molten core comes into contact suddenly with the coolant a rapid transfer of energy may occur from fuel to coolant via an FCI (Buchanan [1973]).
In order to prevent failure of the reactor vessel, suitably designed core catchers are placed below the core to catch the molten débris. The overall effectiveness of a core catcher, or an array of core catchers, in cooling the hot core débris depends upon the catchers being able to catch and hold the core initially, and subsequently upon the heat transfer within the core material, the catchers and the coolant being sufficient to avoid the boiling and dispersal of the core material. It is likely for most fast reactors that if the dispersed material subsequently arrives on the floor of the reactor vessel, substantial exterior cooling will be required to prevent the jacket melting through. Hunt and Moore [1970] have already considered this, and they also provide a general background to problems associated with molten fuel, especially as applied to PFR. In the water reactor field there has been an extensive U.S. survey of the problems (Ergen et al. [1967]). In this paper we consider the heat transfer characteristics of a single catcher holding a mass of collapsed core in an isothermal sea of coolant, concentrating especially on a slab model. We also discuss the effectiveness of convection in the coolant as a heat transporting mechanism both for a single catcher and an array of catchers.

2. General Considerations

Material may arrive below the diagrid by various routes. In this section we consider the magnitude of the catcher problem, and examine briefly the case where the debris is in a fragmented state.

If a single sub-assembly or a number of sub-assemblies melts through, the resulting molten fuel/steel mixture may fall onto the diagrid, and there temporarily solidify. Subsequently it may melt and drip down into a core catcher, arriving as a stream of smallish debris which has developed a solid crust if coolant is present, but which might be almost completely molten if coolant is absent. Alternatively the debris on the diagrid may remain there until part of the diagrid itself melts in which case a large mass of material may fall onto the core catchers. A further possibility is for the core debris to arrive below the diagrid in a finely divided state. It is found experimentally (Board et al [1972] , Buchanan and Dullforce [1973]) that after an FCI, the fuel can be in a well fragmented state. Moreover, in all but very new fuel, fission products will exert considerable pressure in fuel which is rapidly heated, and will assist in its dispersion (Farmer [1971]).

These possible modes of arrival in the region below the diagrid suggest that a core catcher must be able to support the core debris as an almost spherical but twisted and heterogeneous mass of material, or as a cylindrical slug if the diagrid melted through over a broad area almost simultaneously, or as a shallow layer originally composed of particulate debris. If the catcher is able to support without thermal collapse the sphere and cylinder configurations, the debris may well melt and flow into the shallow layer configuration. For PFR, the fuel has a volume of 0.4 m^3, and its steel cladding etc $\sim 0.35\ m^3$. The core has a diameter of 1.5 m, the reactor vessel a diameter of 12 m (Hunt and Moore [1970], Frame et al [1966]). Thus we could consider the catcher to be supporting one of the following limiting idealizations (i) a sphere of 0.45 m of UO_2 or 0.5 m of UO_2/steel mixture; (ii) a vertical cylinder of radius 0.75 m (the core radius) and height 0.25 m (UO_2), or 0.47 m (UO_2/steel); (iii) a horizontal slab of radius 16 m (the reactor pot radius) and depth 0.0035 m (UO_2) or 0.0065 m (UO_2/steel). These figures neglect the diagrid material. Since they are for the full core, they provide upper limits of heat-producing material. In considering even momentarily a slab of reactor pot diameter, it is not suggested that a single core catcher of this kind is appropriate; however an array of catcners of equivalent catching area might be suitable. For the melt through of a single sub-assembly, which is about 1% the full core, smaller values are appropriate.

It is not unusual (e.g. Cho, Ivins and Wright [1971]) in attempting to simulate the history of pressure pulses in FCI to postulate a volume of molten fuel-coolant mixture formed in some zone of the reactor pot as a result of fragmentation of the molten fuel. Since the thermal conductivity of liquid sodium is about 30 times that of UO_2 it is reasonable to take the sodium as an isothermal bath for the fuel particles, at least to a good first approximation. If the FCI is a mild one, we may consider the subsequent history of the fuel drops. Clearly solid crusts will rapidly form and the larger fragments will fall downwards to be caught on the catchers or to accumulate at the base of the reactor pot, depending on the location of the catchers and the influence of the convection currents within the coolant. The smaller particles will be carried in suspension and drop as a sediment in the more stagnant regions of sodium.

Reynolds and Whipple (1973) have examined the possibility that the thermal convective flow induced in the coolant around an internally heated particle might be sufficient to make an otherwise sinking particle buoyant. They find using a boundary layer analysis that only if the heating rate exceeds the absurd value of 10^6 Mw/m^3 would this be possible.

It has been suggested that if the core debris is in particulate form, coolant could circulate within it and carry away much of the heat, allowing a larger mass of particles to be safely supported than if the debris has compacted. If heat transfer is solely by natural convection in liquid sodium which is allowed to rise in temperature by up to 400°C, then it has been calculated (Farmer et al [1971]) that for a pile of debris 0.1 m high and heating rate in the particles of 30 MW/m^3 (corresponding to about ½ hour after shutdown of PFR) then the particle diameter must not be less than 5.5 mm, otherwise boiling will occur. For a 0.1m layer of particles of diameter 1000 μ to be kept cooled, the heating rate must not exceed 1 MW/m^3 which is not reached in PFR until several days after shutdown. Even if the heap were only 0.3 cm high, 1000 μ particles could be cooled by natural convection only for heating rates less than 30 MW/m^3. If boiling does occur it envelopes the debris in a vapour blanket which effectively separates the coolant liquid from the debris, reducing heat transfer rates drastically. Baker and Gabor [1972] undertook experiments to heat UO_2 particles in the 100 μ - 1000 μ range in a brine bed (the brine was electrolytically heated rather than the particles themselves but this is immaterial in calculating the heat fluxes carried away through an upper bounding surface). For shallow beds, less than 5 cm in depth they found dry-out fluxes greater than 0.6 MW m^{-2}. For deeper beds e.g. 7.5 cm in depth, this fell to 0.2 MW m^{-2}; the channels formed to enable vapour to reach the top of the bed rapidly were only found in the top 5 cm of the bed. Such dry-out fluxes are quite inadequate for heating rates much in excess of 1 MW/m^3.

Overall it is clear that layers of 1 cm or more of particulate core debris will overheat unless the decay heating level is low; thus the pile of debris will become consolidated. In the next section we consider the cooling of consolidated debris.

3. Non-Convecting Slab Models

For high residual heating rates (> 10 MW/m^3) the core material caught in a catcher may compact into a pool of semi-molten material sitting upon the catcher. This core will be a mixture of fuel from the core, steel from the cans and perhaps from the collapse diagrid. It will have a solid crust, liquid core, and some may also be in the vapour phase. The temperature of the debris will be such that we can assume that sodium has been expelled from this mixture. A calculation which will provide an upper limit for the maximum temperature in the centre of the slab, given its depth, can easily be carried out under the assumption that the lump can be treated as a homogeneous mixture of fuel and steel in some proportions $\pi_1:\pi_2$ with an appropriate effective thermal conductivity and heat source term, with an additional assumption that thermal conduction is the only heat transport process present.

A simple model can be considered in which a well mixed horizontal layer of fuel and debris producing radioactive decay heat at a rate of MW/m^3 lies on a horizontal steel plate (the core catcher). Above the fuel and below the steel plate is the coolant, taken to be a perfectly efficient thermal conductor, at some constant temperatures T_1 above the fuel layer and T_2 below the catcher plate. Let α be the thermal flux downwards through the plate, then its constant value is $\{\frac{1}{2}F + (T_2 - T_1)/r_s\}/\{1 + (r_s/r_f)\}$ in the steady state where F is the total heat flux produced and r_s and r_f are the effective thermal resistances of steel and the fuel layer respectively. The temperature of the catcher/fuel interface T_o is $T_2 + \alpha r_s$. Within the fuel mixture the mean temperature profile is parabolic with maximum temperature $T_h = T_o + \alpha^2 r_f/2F$. If the interface temperature is required to be below some specified temperature T_o^* (at which for example the steel plate starts to melt or at least lose its strength) then the core catcher plate thickness d_s must be less than a maximum value d_s^* where

$$d_s^* = k_s R_*^2 r_f/(r_f^2 - R_*^2) \qquad (1)$$

in which $R_*^2 = 2(T_o^* - T_1)/k_f H$. Here k_f is the thermal conductivity of the debris.

If the temperature of the interface of the irradiated support and fuel is allowed to rise to 800°C (say), and if the steel plate is required to be ½ cm to 1 cm thick to be adequately strong, then a pure UO_2 fuel slab producing heat at 2% of full power could not be more than $\sim$ 6 cm or 3.5 cm respectively before the catcher became overheated. If UO_2 and steel are mixed in the slab in the ratio 2 to 1 (close to the value where Hunt and Moore [1970] obtain maximum heat flux) then the thermal conductivity k_{mean} is approximately 5 k_{UO_2} and the heating rate $H_{mean} = \frac{2}{3} H_{UO_2}$. In this case for a steel catcher of thickness ½ cm to 1 cm, the debris layer could not be more than approximately 14.4 cm or 7.5 cm thick respectively before the support became overheated.

The maximum temperature in the interior of the layer of debris is not very sensitive to the thickness of steel plates thinner than 2 cm. If the maximum temperature is taken to be T_{boil}, the boiling point of UO_2 and it is still assumed that no convection is occurring in the partially molten slab of debris, then the debris layer thickness d_f must satisfy

$$d_f < (8\, k_f\, [T_{boil} - T_1]/H)^{\frac{1}{2}} \quad . \tag{2}$$

For pure UO_2 debris this gives $d_f \sim 4.2$ cm.

Layered conduction models of this kind have been worked out by Hunt and Moore [1970] (who have taken into account the formation of steel vapour pockets within the debris), by Bickers and Williams [1968] and by Erzen et al. [1967]. Overall it is clear that in the absence of convective or boiling heat transfer within the consolidated debris material, then the depth of debris on a flat catcher certainly cannot exceed $\sim$ 10 cm without the core catcher failing or the debris material boiling.

4. Convecting Slab Models

The depth of stable slabs of heat-producing but non-convecting debris is restricted by two features. First, as the layer becomes deeper (by for example further accumulation of debris) the flux downwards increases, and the temperature gradient through the catchers also increases in order to transport this flux. A maximum permitted interface temperature (e.g. the melting point of steel) implies a maximum permitted downwards flux, which in turn implies a maximum layer depth. Second, if the slab is not to fragment through pressures arising from internal boiling, then the maximum slab temperature must remain below the boiling point of the fuel, which also implies a maximum layer depth. Two of the main features of convection driven by internal heat sources (Rumford convection) are that (i) for a given layer depth, more of the flux is preferentially carried upward by the thermal convection and escapes through the upper surface of the debris layer - leaving less to pass through the catcher, (ii) the maximum temperature is reduced - the mean temperature profile is flattened by convective mixing. Using idealized models, we attempt in this section to put these two results on a more quantitative footing.

Consider a horizontal layer of radioactive material (UO_2) supported on a (steel) catcher plate and surrounded above and below by slowly moving but isothermal coolant. We consider the regime in which the UO_2 is below boiling point at all times. Then the UO_2 consists of a layer of molten UO_2 between two crusts of solid UO_2 separating the molten layer from the (sodium) coolant above, and the core catcher below (the configuration is shown in the left hand part of figure 1). The molten layer has as its upper and lower boundaries solid surfaces at T_{melt}, the melting point of UO_2. Taking the reduced temperature θ to be $T - T_{melt}$, the molten fuel lies in a layer of depth L containing uniform heat sources producing heat at a rate H, of thermal diffusivity κ, specific heat c_p, and density ρ (see figure 2). The equations describing such a fluid layer are

$$\left.\begin{aligned} \rho_o \left(\frac{\partial u}{\partial t} + \underline{u}.\nabla \underline{u} \right) + \nabla p &= \rho_o \nu \nabla^2 \underline{u} + \rho \underline{g} \\ \frac{\partial \theta}{\partial t} + \underline{u}.\nabla\theta &= \kappa \nabla^2 \theta + \gamma \end{aligned}\right\} \quad (3)$$

where $\underline{u}$ is the fluid velocity, g gravity, ν the kinematic viscosity, γ the rate of temperature rise due to the heat sources ($\equiv H/\rho c_p$). The Boussinesq approximation can be used which takes the density as constant except as it affects the buoyancy term : $\rho = \rho_o + \delta\rho$ where $\delta\rho = -\alpha g(\delta\theta)$ for perturbations $\delta\rho$ and $\delta\theta$. Here, α is the coefficient of thermal expansion.

Thermal convection in the layer is a function of two non-dimensional groups: 1) the Prandtl number $Pr \equiv \nu/\kappa$; 2) the Rumford number $Ra_H \equiv \alpha g \gamma L^5/\nu\kappa^2$. The Rumford number is a modified Rayleigh number based on heating rate rather than mean temperature gradient. It is convenient to introduce the convective cooling parameter $H \equiv \theta^*/\overline{\theta}_{max}$, where θ^* is the maximum reduced temperature in the absence of convection (i.e. the maximum of the parabolic profile), and $\overline{\theta}_{max}$ is the maximum for the horizontally averaged reduced temperature when convection is occurring. The flux ratio μ is defined to be the fraction of the total flux which emerges through the top surface. Clearly in the absence of convection M = 1 and $\mu = \frac{1}{2}$. In general, for Rumford convection, $M \geq 1$ and $1 \geq \mu \geq \frac{1}{2}$. From a two-dimensional numerical simulation, in the steady state, we find that, for stress-free horizontal boundaries, (Peckover and Hutchinson 1973),

$$M - 1 \simeq 0.02 \, (Ra_H - Ra_H^{crit})^{\frac{1}{4}} \quad (4)$$

$$\mu - 1 \simeq 0.01 \, (Ra_H - Ra_H^{crit})^{1/5} \quad (5)$$

for $Ra_H/Ra_H^{crit} \leq 80$, when the Prandtl number is 8 (appropriate for electrolytic internal heating experiments) and periodicity is 2L (at the onset of convection the critical wavelength is 2.075 L). The maximum velocities found were $u_{max}^2 \sim 5 \times 10^{-3}(Ra_H - Ra_H^{crit})/Ra_H^{crit}$. Ra_H^{crit} is the value of the Rumford number at which convection sets in. Its value in this normalization is $\sim 2 \times 10^4$. Figure 3 shows the isotherms and streamlines which are appropriate for $Ra_H \sim 10^{5-6}$. The convective pattern consists of narrow falling regions separating broad regions of upwelling. The isotherms dip sharply in the region of downflow. The region of maximum temperature (enclosed by the innermost contour) is displaced upwards from its symmetric conduction position.

The mean heat transfer coefficient from the molten layer downwards could be defined as $h_{down} \equiv (k \, \partial\overline{\theta}/\partial z)_b/\overline{\theta}_{max}$ where the subscript b indicates that the temperature gradient is evaluated at the lower boundary. k is the thermal conductivity. Similarly $h_{up} \equiv (k \, \partial\overline{\theta}/\partial z)_t/\overline{\theta}_{max}$ is the heat transfer coefficient from the molten layer upwards. These heat transfer coefficients are related to appropriate Nusselt numbers Nu, the convective cooling parameter and the flux ratio by the formulae :

$$\left.\begin{aligned} h_{down} &= \frac{k}{L} Nu_{down} = \frac{8k}{L} M(1-\mu) \\ h_{up} &= \frac{k}{L} Nu_{up} = \frac{8k}{L} M \mu \end{aligned}\right\} . \quad (6)$$

Kulacki and Goldstein (1972) have carried out Rumford convection experiments with a weak electrolyte between two copper plates above and below. They obtained correlations approximately of the form:-

$$\left.\begin{aligned} Nu_{down} - 4 &= 0.0012\ (Ra_H - Ra_H^{crit})^{\frac{1}{2}} \\ Nu_{up} - 4 &= 0.0046\ (Ra_H - Ra_H^{crit})^{\frac{1}{2}} \end{aligned}\right\} \quad (7)$$

In the absence of convection $Nu_{down} = Nu_{up} = 4$. When $Ra_H = 10^6$ and convection occurs, $\mu \simeq \frac{2}{3}$, $M \simeq 2$; the numerical simulation gives $Nu_{down} = 5.3$, $Nu_{up} = 10.6$ for stress-free boundaries. Kulacki and Goldstein obtain $Nu_{down} = 5.25$, $Nu_{up} = 8.6$ for no slip boundaries. Figure 4 shows the Nusselt numbers obtained for varying Ra_H for both top and bottom surfaces. The results of Kulacki and Goldstein are plotted on the same figure. Note that convection sets in with no slip boundaries at a Rumford number approximately twice that for no stress boundaries.

Using a power density of 2% of full PFR power, and with parameters as in appendix I, then $Ra_H = 10^6$ corresponds to a molten layer thickness of 1.35 cm. This gives a heat transfer coefficient h_{down} of 9.81×10^2 watts/(m^2 K) (cf. 9.71×10^2 based on Kulacki and Goldstein's experiments) and a maximum temperature of 3290 K (reduced from 3420 K which would be the non-convecting maximum). The mean temperature gradients in UO_2 at the solidus temperature are 1100 K/cm and 540 K/cm upwards and downwards respectively. If the molten UO_2 is enclosed between horizontal crusts, the upper in contact with sodium at 600°C, the lower in contact with steel at 800°C, then the crusts have thickness of 1.35cm and 1.58cm respectively. Thus a layer of UO_2 of thickness of 4.3cm will have a maximum temperature less that the boiling point of UO_2, and an interface temperature with the catcher of 800°C provided the catcher thickness is less than 1.25cm. Extrapolating the formulae (4) to (7) to higher Rumford number, we obtain that a layer of thickness 5.1cm would remain stably upon the catcher, convecting internally with Rumford number 6×10^7. Kulacki and Goldstein's correlation leads to 5.9cm and 5×10^8 respectively. The depth of a stable layer of UO_2 is thus clear. We see that even with internal convection a consolidated layer of UO_2/steel core dèbris greater than ~ 10cm in an isothermal sea of coolant will not sit passively upon a core catcher.

Another aspect of thermal convection in a fluid layer is that it results in non-uniform heat fluxes through the lower surface. Hot spots develop. Figure 5 shows the non-dimensional temperature gradient for a number of cases when $Ra_H^{crit} < Ra_H < 30\ Ra_H^{crit}$. The quantity plotted, h**, is related to h_{down} by $h_{down} = 12\ kh^{**}$, where k is the thermal conductivity of the fluid. The Prandtl number is 8 for this figure. The peaks in h** correspond to positions of downward flow in the convecting fluid. For more vigorous convection (larger Ra_H) the peaks are higher. The flux downwards in the low flux troughs of figure 5 is much less sensitive to Ra_H. The magnitude of the peak of the heat transfer coefficient downwards is also a function of Prandtl number. In Figure 6 the effect of varying the Prandtl number through the range 10^{-2} to 10 is shown when $Ra_H \approx 3Ra_H^{crit}$. In this case, h** has its maximum for a Prandtl number of order unity.

5. Shaped Catchers

The simplest calculations for core catchers supporting fuel dèbris involve a horizontal catcher plate and a uniform layer of core material. Such models were considered in sections 3 and 4. As it is desirable that the fuel dèbris should remain on a catcher, catchers need sides or lips, and for some catcher shapes the sides make significant contributions to the heat transfer. Two other rather idealized shapes which have been studied are the hemispherical bowl and the V-shaped trough. Lumps of core dèbris capped by layers of steel cladding dèbris are also considered.

The hemispherical catcher consists of a hemispherical shell or cup supported either by "handles" of some sort, or upon a vertical stalk. The cooling of such a shell is considered later. Here we are concerned only with a cauldron of molten core dèbris immersed in an isothermal sea of coolant.

It is easily shown that a sphere of radius R with fixed outer temperature T_o and internal heat sources H, develops, if only conduction is present as a transport process, a temperature profile of the form

$$T = T_o + \frac{H}{6k}(R^2 - r^2) \qquad (8)$$

where k is the thermal conductivity (Chandrasekhor [1961]). Assuming the values given in the appendix, this means that a sphere of UO_2 immersed in sodium held at 600^oC will have a solid crust of thickness only $\frac{1}{20}$ cm for a radius of 10cm. The calculation for a hemisphere (Carslaw and Jaeger [1959]) gives a similar result. For any cauldron of radius greater than 1.06cm, the core material may be molten and convection must be taken into account. Of course the core dèbris may contain a large proportion of non-heat-producing material in which case a much larger volume could remain solid, as we indicated for the slab case in section 3. Since there is no reason to suppose this will always occur, we must examine the most pessimistic assumption, namely that the molten material is totally UO_2.

Jahn and Reineke (1972) has carried out some preliminary calculations for convection in a molten pool of UO_2 when the catcher is the hemispherical reactor pot bottom itself, and the coolant is absent. During calculations of the transient slow development, they find convection occuring with the UO_2 in the form of small cells concentrated near the top of the pool. For the whole reactor pot the Rumford number is large ($\sim 10^{11}$) and turbulent convection can be expected. It must be stressed that the effect of thermal convection is to carry the heat upwards and to lower the mean thermal flux through the floor of the core catcher. This arises in an uneven way with most flux occurring in 'hot spots' beneath the downward plumes of the convective motions. It is of the nature of Rumford convection, not to have upward moving narrow plumes, but rather a broad relatively slowly moving upwelling

The dependence of the spatial distribution of downward heat flux on thermal conductivity in a horizontal layer can be compared with Jahn and Reineke's results for the hemisphere. They plot the heat transfer coefficient h, downwards, defined as $k\left(\frac{\partial T}{\partial r}\right)_{wall} \Big/ (T_{max} - T_{wall})$ and obtain its highest peak at one spatial hot point (actually a ring for the hemisphere) for a particular thermal conductivity (k = 7.16 W/(m.K) .

Figure 7 shows how for fixed heat content and viscosity of the liquid, the mean and maximum heat transfer ceofficients at the upper and lower surfaces vary as a function of thermal conductivity (for the horizontal layer). This may imply that Jahn and Reineke's peak is a temporary one, exceeded as k is decreased still further. Figure 8a shows small convective cells obtained during an early transient whereas the final steady state is shown in Figure 8b. Transient states may not be simple mappings of the final state. The accurate calculation of temperature gradients close to the boundaries requires fine spatial resolution, and dependable numerical calculations with a uniform polar mesh would require for the reactor pot $\sim 10^4$ mesh prints (assuming 2% PFR power).

A different type of catcher shape is the long V-shaped trough. One might envisage several arrays of these. Figure 9 shows the isotherms and stream line pattern for a trough semi-angle 45^o and Rumford number 10^6 based on the depth of the trough at its deepest point. Naturally the sides inhibit convection (no slip boundaries), and the critical Rumford number is substantially higher than for a plane slab. For a given Rumford number, convection is less vigorous and one might expect the central temperature to be much higher than for the slab. However, the catcher sides also make a contribution to the cooling and the overall result is a reduction in maximum temperature. Figures 10 and 11 show the effects of narrow semi-angle and broad semi-angle respectively. These are preliminary results of a more exhaustive analysis (Peckover [1973]).

The thermal diffusivity of steel is about one tenth of that sodium, and one could reasonably imagine a brick of débris sitting on a catcher such that heat escapes preferentially through the sides of the block of débris (see Figure 12). Such a situation might be quasi-stable for a period long compared with convective heat transport times within the UO_2. In a limiting case, one might consider all the heat flux to escape horizontally and for the top and bottom surfaces to be perfect thermal insulators. Smith and Hammitt (1966) studied experimentally and theoretically such a model and obtained the relation $Nu = c.(A.Ra_H)^{\frac{1}{4}}$ for the Nusselt number, where A is the aspect ratio of the molten region, Ra_H, is the Rumford number, and c is a constant between 0.1 and 0.33. If the molten UO_2 is not to boil this relation imposes a constraint on the thickness of the layer. Smith and Hammitt's calculations would also apply to a complete reactor pot of sodium in which UO_2 is finely distributed, or indeed to regions in a Molten Salt Fast Reactor. It is interesting to remark that Smith and Hammitt find convection in such a system to consist of narrow downflows near the walls with slow upflow in the middle of the region where the horizontal temperature profile is reasonably flat.

Murgatroyd and Watson (1970) have done experiments for convection in very tall cylinders of internally heated fluid. If part of the core arrived on a core catcher in a tower-like structure, convection patterns within can be expected to follow those of Murgatroyd and Watson for a short period. However, the walls of the tower will melt out and the configuration collapse fairly quickly.

6. The Cooling of Catchers

In calculations on heat transfer within the core débris in the previous sections, it has been convenient to assume that the coolant remains at a constant temperature because of its own natural convection, i.e. that it has an effectively infinite thermal conductivity. In bulk, the mean coolant temperature certainly changes slowly. Hunt and Moore [1970] have calculated that the 900 tons of sodium in PFR would only increase in temperature by $100^{\circ}K$ after 4 hours of decay heating (i.e. on average at less than ½ K/minute). However, the temperature differences within the coolant are smaller in general than within the core dèbris, and so temperature variations on the interface between coolant and the catcher with its contents are more significant. A convenient upper limit to the steady state interface temperature can be calculated by considering two semi-infinite slabs at prescribed temperatures. If one slab is taken to be molten UO_2 at 3100 K and the other to be liquid sodium at normal reactor temperature (800 K) the interface temperature is found to be 1420 K (Farmer et al [1970]) in the absence of convective motions. This is still $\sim$ 1400 K below the melting point of UO_2 and if the interface temperature was taken to be this value, rather than $600^{\circ}C$, the only effect on the earlier calculations would be to reduce the thickness of the upper crust of solid UO_2 corresponding to a given depth for the molten layer of UO_2. For the coolant the effect is more significant. This temperature is 300 K above the boiling point of sodium so boiling heat transfer would need to be taken into account.

Natural thermal convection in confined regions is of course a familiar phenomenon; the actual form of the convection in terms of detailed streamlines varies enormously and depends upon the location of the struts and supports within the confining vessel, in this case, the reactor pot. In the hypothetical event that one is trying to cool core dèbris in catchers, the catchers themselves, and their load of core dèbris in whatever geometry it is, also contribute complication to the flow patterns. Each catcher acts as a thermal source driving a pattern of free convection within the reactor pot. Each catcher also acts as a physical obstacle retarding the free convection set up by the remainder of the catchers. The convection in the coolant could be forced (jets injected at the bottom of the reactor pot, for example). We shall not consider that possibility here further (clearly in practice no one will use forced convection if free convection is adequate), except in as much as the free convection produced by one catcher appears to be a form of forced convection to the other catchers. Rather than study in detail one particular design and arrangement of core catchers, it is more sensible to examine a few models to see what conclusions can be drawn from these.

Whipple [1972] has carried out calculations for natural convection in the sodium filled space between two concentric spheres - the outer one representing the reactor pot, the inner one the core dèbris (see Figure 13). If the Rayleigh number Ra is $\sim$ 100, the sodium flow will be laminar but the behaviour is dominated by boundary layers. On dimensional grounds, the Nusselt-Rayleigh relation has the form $Nu = C_L(Ra)^{\frac{1}{4}}$ where C_L is a constant. For reasonable values this gives a temperature difference between hottest and coldest part of the sodium of $\Delta T = 350\ C_L^{-4/5}$ K. If $C_L \sim 1$ then $\Delta T = 300$ K. Hence in this régime part of the catcher and core dèbris might interface with the sodium at $700^{\circ}C$ assuming an inlet temperature of $400^{\circ}C$. When some of the core dèbris is molten, at temperatures $\sim 3000^{\circ}C$, such a variation may be neglected for calculations within the catcher and the coolant assumed isothermal at $\sim 600^{\circ}C$. For a high Rayleigh number, the flow is turbulent and the Nusselt-Rayleigh relation has the form $Nu = C_T(Ra)^{\frac{1}{2}}$ where C_T is a constant. For reasonable values this gives $\Delta T = 5.C_T^{-3/2}$ K. If $C_T \sim 1$, the mean temperature variation is small as one would expect for turbulent convection.

In Whipple's spherical model, in the laminar règime, convection in the sodium is assumed in the main to form a single large eddy transporting heat from the core dèbris to the reactor walls, maintained at a constant temperature. The heat flux from the catcher and dèbris is assumed to be constant over the surface of this spherical lump. This implies a non-uniform surface temperature which Whipple calculates in the laminar regime to have a maximum given by

$$T_{max}(K) \sim 900 + 60(2a^3/3b^3)^{\frac{1}{2}} (\ell n\ Ub/\lambda + 1.4) \qquad (9)$$

for a>>b, where a and b are the radii of the outer and inner sphere, λ is the thermal diffusivity of sodium and U is a typical velocity in the sodium. This is the temperature at the hot spot on the top of the axis of the catcher, where a stagnation point occurs in the flow, which is consequently only cooled by conduction. One might expect turbulent flow to occur in the neighbourhood of this hot spot reducing the temperature contrast.

Whipple's model applies particularly for a large centrally placed catcher and ignores all hardware in the reactor pot apart from the core catcher and dèbris. Work has also been done on eccentrically placed spheres - more relevant to the situation where the core catcher complex is situated low in the reactor pot. Weber et al [1973] find experimentally that heat transfer rates are increased when the inner sphere is moved downwards, and that convection is enhanced. They find that, for a wide range of eccentricities, Prandtl number, and sphere diameter ratios, the Nusselt-Rayleigh relation can be expressed as $Nu = 0.228\ (Ra^*)^{0.226}$ where Ra^* is a Rayleigh number based on a hybrid length scale which is a function of the eccentricity and the sphere radii. This supports the idea that Whipple's constant C_L is of order unity.

Shallow troughs and flattish bottomed catchers can be idealized as horizontal plates of finite extent for which heat transfer rates are needed both upwards into the coolant above and downwards into the coolant below. Analytically, Singh et al [1969] find, for heat transfer from isothermal downward facing plates into coolant which freely convects laminarly, that in the mean for large Prandtl number $Nu = C_5(Ra)^{1/5}$ where for square plates, circular plates and an infinite strip, C_5 is a constant between 0.5 and 1.0. In agreement with experimental observation they find that the temperature and velocity boundary layers are thickest in the centre of the plate and thinning towards the edges; the coolant also flows, predictably enough, from plate centre to plate edges within the boundary layer, having been drawn in from below. This suggests that unless a vapour bubble forms plate, a stagnation point will occur under the centre of the plate which may result in overheating. Fujii et al [1973] have done a theoretical study for the related case of uniform downward heat flux, and obtain similar results with C_5 between 0.5 and 1.0 for $Pr > 1$. For $Pr < 1$, C_5 varies slowly, decreasing as Pr decreases.

For heat transfer upwards from a hot horizontal plate into freely convecting sodium Kudryavtsev et al [1967] found experimentally that $Nu = 0.67\ (Ra.Pr/[I + Pr])^{\frac{1}{4}}$ in the laminar règime, and $Nu = 0.38\ (Ra.Pr)^{1/3}$ in the turbulent. Theoretical studies have been carried out for laminar combined convective flows over hot horizontal plates

(Hiber [1973]; Oosthuizen and Hart [1973]). For an array of catchers it is desirable for a study of laminar combined convective flows below a hot plate to be made. Figure 14 shows the way in which a multiple layering of core catchers could produce such a flow.

For V-shaped troughs and inverted conical structures which lead to flow below a hot inclined surface, Collier [1969] and more recently Whipple [1973] have carried out investigations.

One way to attack the problem of the heating from the underside of a V-shaped trough is to consider each as an isolated inclined plate, and to assume that the flow beneath the inclined plane has the same general characteristics as that in the boundary layer adjacent to a vertical heated plate, but that the induced flow is slower because only the component of gravity parallel to the plate is effectively acting, This is Collier's approach, and he consequently used the correlations $Nu = 0.546\ (Ra.Pr)^{1/4}/(0.800 + Pr)^{1/4}$ for laminar flow and $Nu = 0.295(Ra/[1 + 0.494\ Pr^{2/3}])^{0.4}.Pr^{0.066}$ for turbulent flow. Here Ra contains $g \sin \theta$ as the component of gravity parallel to the plate (which is inclined at an angle θ to the horizontal). For an inclined plate 1.2 m long inclined at 15^{o}, with sodium as coolant at 700 K ($Pr = 4.6 \times 10^{-3}$) he obtains $Ra = 3.1 \times 10^{7}\ \Delta T$ where ΔT is the temperature jump between plate and bulk coolant. For any significant temperature differences this makes $Ra \geqslant 10^{6}$, so that the flow is turbulent. If a temperature jump of $400^{o}C$ is assumed, one obtains a heat transfer coefficient of 15 kW/(m^2 K). This value can reasonably be expected to hold over much of the plate surface, but near to the apex of the trough laminar flow can be expected with a lower heat transfer coefficient, and overheating is more likely.

An alternative attack has been carried out by Whipple [1973]. As a preliminary, the rate of heat conduction through the sides of the catcher can be calculated, and for a catcher with small semi-angle and no internal convection, the flux is proportional to r, the distance up the side of the catcher from the trough apex, except close to the upper lips of the trough when one would expect most of the flux to be upwards. Assuming this dependence for the emerging thermal flux, one can then carry out a boundary layer analysis within the laminar thermal boundary layer (the viscous boundary layer in sodium is negligible in comparison since $Pr \sim 4 \times 10^{-3}$). The Nusselt-Rayleigh relation has the usual form $Nu = C_1 (Ra.Pr)^{1/4}$, and in the relation $Re = C_2\ Nu/Pr$, the Reynolds number is based on the boundary larger velocity. For the wedge-shaped trough an exact similarity solution can be found, in which both the temperature and the flow velocity of the catcher are proportion to $re^{-\xi}$ where ξ is the normal co-ordinate, n/a, normalized by the boundary-layer thickness a. The constant C_1 and C_2 are approximately unity. A very similar analysis can be carried out for an inverted conical catcher, in which case C_1 and C_2 are 1.5 and 0.4 respectively. On the basis of this analysis for laminar flow in the coolant boundary layer, the hottest part of the trough will be some distance up the sides. With convection within the core dèbris, heat is preferentially carried upwards and consequently melt-out of the catcher is less likely to occur in the downward pointing apex region.

For the cooling of a single catcher, a number of types of model are available; flat plates, spheres, troughs and for all of them provided the catcher temperature is high enough above that of the coolant the sodium can satisfactorily transport the heat away. Locally however this may entail catcher hot spots and melt through.

7. Multiple Catchers

From the foregoing discussion it seems without forced cooling to be difficult for a single catcher to support more than at most 10-15 cm of core dèbris without melting through after a relatively short time. Some multiple array of core catchers is required.

One possible configuration is shown in Figure 14 in which catchers are arranged in staggered rows. Initially the core materia is caught in the upper two rows of catchers. If the dèbris descends in smallish fragments such an arrangement would be likely to produce even amounts of core dèbris on each of several catchers and the core material could be supported, provided the second row of catchers is sufficiently far below that of the first row for some of the cooler coolant to present itself to the underside of the upper row of catchers. Clearly if the layers of catchers are too close, then the underside of the upper layer is not satisfactory cooled, and two layers behave in some respects as a single layer.

For V-shaped trough catchers another configuration is shown in Figure 15 in which the catchers are not only staggered but alternate in direction. At least four layers would be required to screen the bottom of the reactor pot from a descending core. For circular dishpan catchers, girders would be needed to give them adequate support, resulting in a pattern similar to an open network of V-shaped troughs.

In all arrangements of multiple catchers it is important that the horizontal gaps between catchers should be large enough to minimize the likelihood of bridging between adjacent catchers. If bridging does occur the upflow of the coolant around the catchers is impeded and melt-through is more likely. Multiple catchers presenting the same area to the descending core as a large single catcher have the considerable advantage that much more surface of the catcher and dèbris is exposed to the coolant. Moreover the coolant can rise buoyantly more easily so that convective heat transport should be more effective.

8. Discussion and Conclusions

In any practical consideration of core catchers, the mode of support must be considered. If a hemisphere is supported by handles or super structure of any sort there is a danger that core dèbris may lodge on such supports and melt through somewhere, allowing the core catcher to drop and become ineffectual. On the other hand the use of a single stalk beneath the cup is likely to lead to a high temperature arising in the steel at the top of the stalk. The convection in the coolant may be weak there and the stalk may well be in danger of snapping off there. Also it is necessary that the stalk should be strong enough to uphold the catcher during the impact from above of the molten core and associated dèbris in the worse cases. A pedestal and also supporting girders would provide a more dependable arrangement. Similar arguments apply to any shape of catcher.

The calculations in earlier sections of heat fluxes from spheres and slabs which are solid and lose heat only by conduction were inaccurate because convection was neglected.

It was also assumed that heat sources and steel dèbris were well mixed to give a lower but uniform distribution of heating. This is a gross simplification; to do detailed calculations scanning a wide range of possible distributions, suitable kernels should be inserted into the extensive formulae of Melese - d'Hospital and Wilkins [1973] for calculating the temperature profiles from the spatially dependent heat source distribution.

It seems inevitable that some configurations will arise in which deep piles of dèbris form on a catcher. In some cases the dèbris will boil and throw off surplus until the layer is shallow enough to be passive. Some of the fragmented fuel is likely to find its way to the bottom of the reactor pot. Provided the material is sufficiently finely divided to form a shallow layer, this will cool satisfactorily. In other cases the catcher will melt through first. A multiple layering of catchers provides additional insurance against this. Yet again the pile of dèbris may collapse and spread itself out into a shallow passive layer. This is the most satisfactory outcome.

It is concluded that

(i) for core dèbris with decay heating of 2% of full power of PFR layers of particulate dèbris greater than 1 cm will overheat and consolidate.

(ii) slabs of consolidated dèbris sitting on a flat catcher will boil or melt the catcher if the dèbris depth is more than ~ 10 cm, depending to some extent on the amount of cladding mixed in with the fuel. The use of hemispherical or V-shaped catchers will not modify this conclusion significantly. It is likely that

(iii) the cooling of a single catcher with 10 cm depth of core dèbris can be satisfactorily achieved with sodium.

(iv) in the absence of forced cooling, an array of catchers each capable of holding shallow layers of depth ~ 10 cm of fuel dèbris can be expected to support much of the core material away from the bottom of the reactor pot.

(v) the catchers need to be well spaced horizontally to avoid bridging, need to be in layers sufficiently separated vertically that the lower ones do not effectively heat the underside of the upper ones; and need to be staggered and overlap each other to shield the reactor pot bottom from falling dèbris.

Acknowledgements

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APPENDIX 1

TABLE 1

Property	Units	Value	Reference
(a) Molten UO_2			
dynamic viscosity	centipoise	7	(1)
thermal conductivity*	watts/(m K)	2.5	(2)
melting point	K	3130	(2)
density	kg/m^3	9.8×10^3	(3)
specific heat	J/(kg K)	3.4×10^2	(3)
boiling point	K	3600	(6)
thermometric conductivity	m^2/s	7.5×10^{-6}	(2)
kinematic viscosity	m^2/s	7×10^{-7}	(1)
Prandtl number		10^{-1}	
coefficient of thermal expansion	K^{-1}	10^{-4}	(5)
volume of UO_2 in PFR	m^3	0.4	(4)
radius of equivalent sphere	m	0.45	(4)
width of reactor pot	m	12.21	(4)
depth of equivalent slab	cm	0.35	(4)
core radius	m	0.78	(4)
depth of equivalent cylinder	m	0.25	(4)
heat source density (2% full power)	$MW.m^{-3}$	30	(4)
(b) Steel			
thermal conductivity	watts/(m K)	34	(5)
melting point	K	1700	(6)
density	kg/m^3	7.9×10^3	(6)
specific heat	J/(kg K)	6.39×10^2	(6)
boiling point	K	3073	(5)
thermometric conductivity	m^2/s	6.7×10^{-6}	(6)
maximum expedient load bearing temperature	K	1100	(7)
(c) Sodium			
thermal conductivity	watts/(m K)	60	(5)
boiling point	K	1156	(5)

* value for solid at 2500^oK

Material Properties

References: (1) Tsai and Olander (1972); (2) Thermophysical Properties of Matter (1970); (3) Roberts (1971); (4) Frame et al (1966); (5) Reynolds (private communications); (6) Bickers and Williams (1968); (7) Hunt (private communication).

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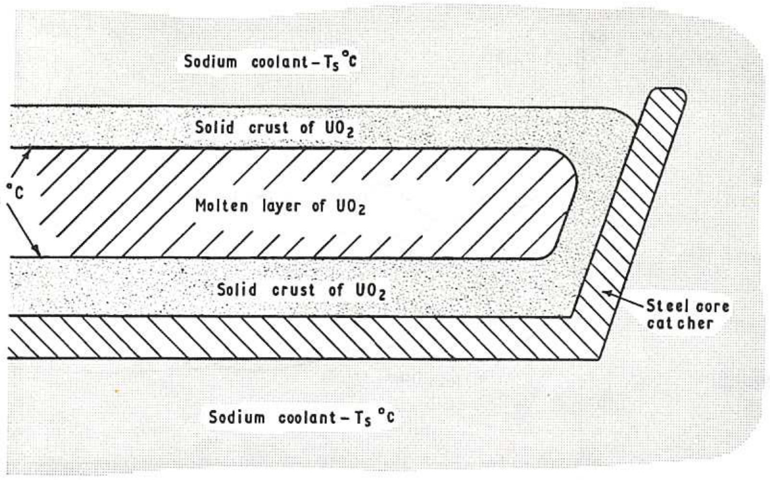


Figure 1

UO_2 layer on a steel core-catcher

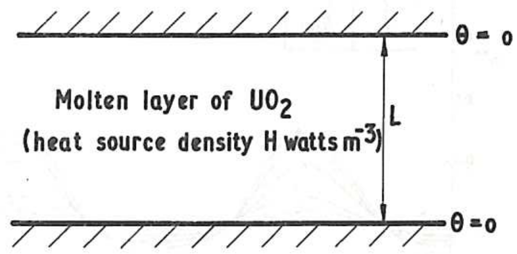


Figure 2

Infinite plane slab of molten fuel

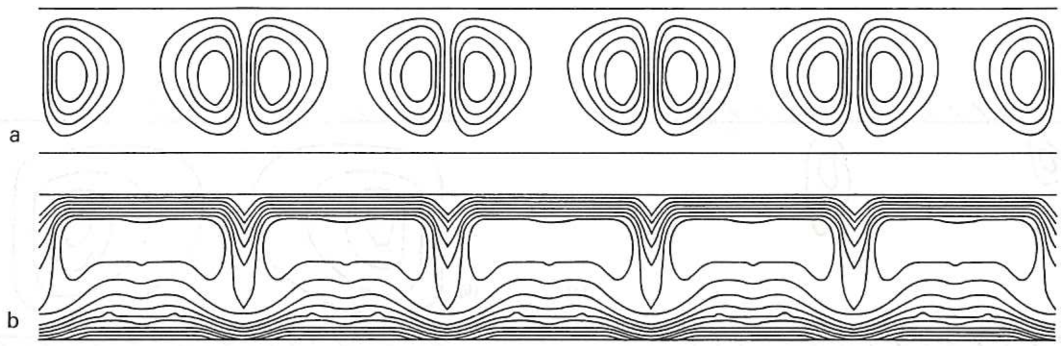


Figure 3

(a) Convective eddies within the molten layer of UO_2

(b) Isotherms within the molten layer of UO_2

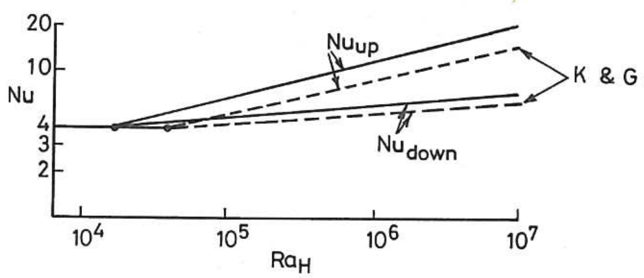


Figure 4

Calculated Nusselt number as a function of Rumford number, for no stress boundaries, compared with experimental results of Kulacki and Goldstein (K&G) for no slip boundaries.

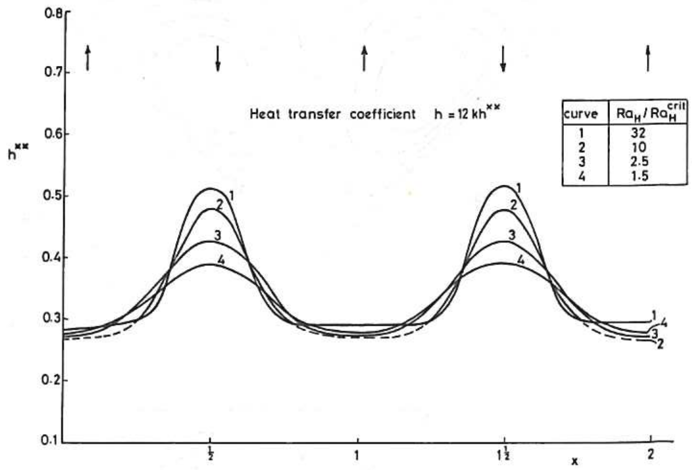


Figure 5

The heat transfer coefficient has a function of position on the lower surface of the convecting fluid. The arrows indicate the position of upflow and downflow in the fluid above this surface.

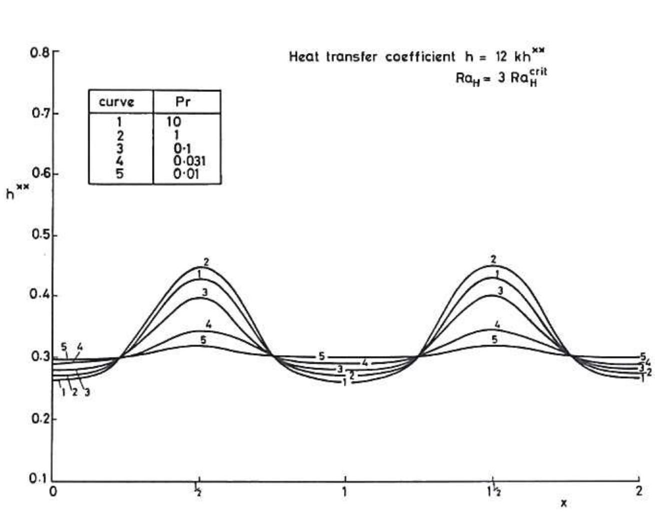


Figure 6

As for Figure 5, but with variable Prandtl number and fixed Ra_H

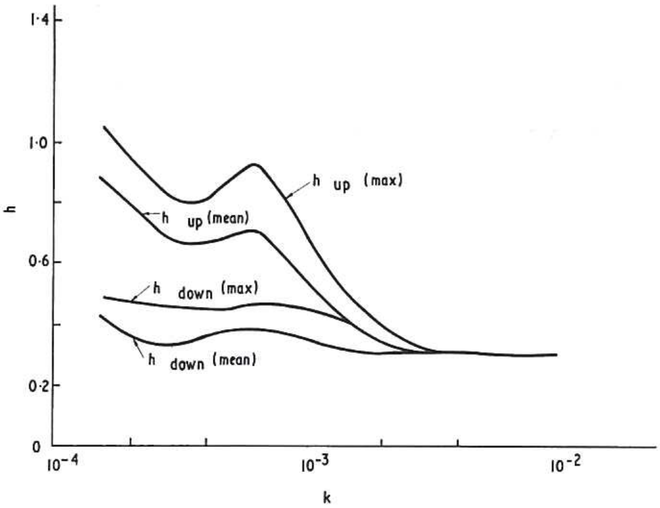


Figure 7

The heat transfer coefficient as a function of the thermal conductivity k for the flux through the lower surface.

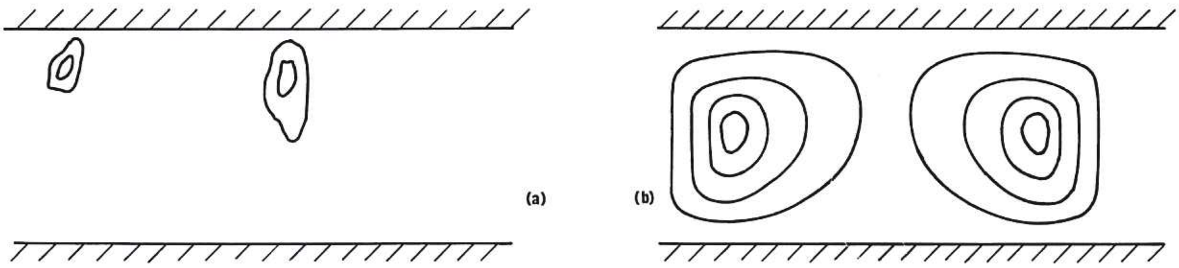
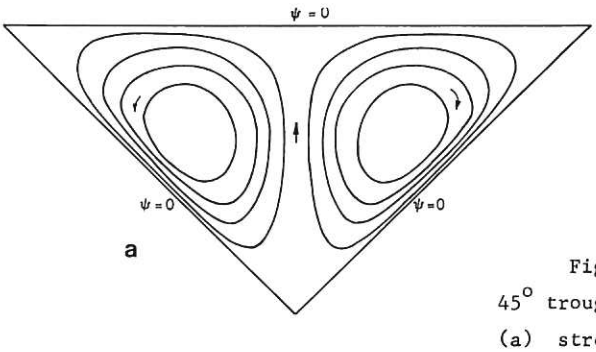


Figure 8 (a) Early stage in transient development of convection

(b) Final steady configuration of streamlines



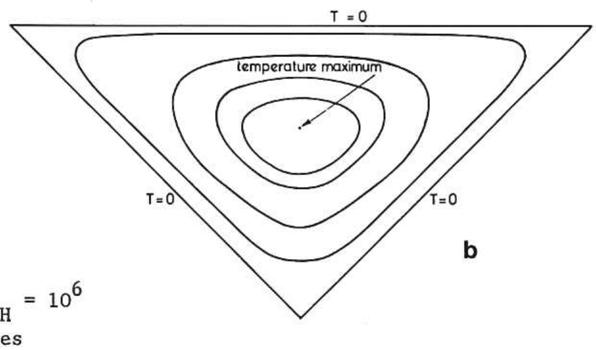
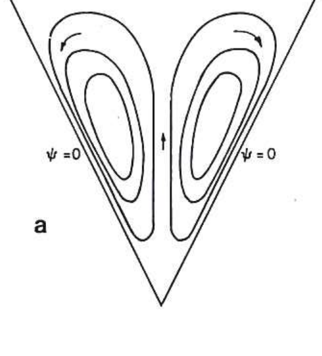


Figure 9

45° trough; $Ra_H = 10^6$

(a) streamlines

(b) isotherms



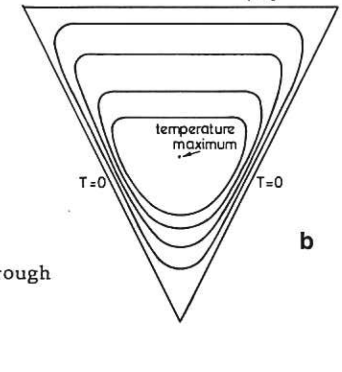


Figure 10

Narrow semi-angle trough

(a) streamlines

(b) isotherms

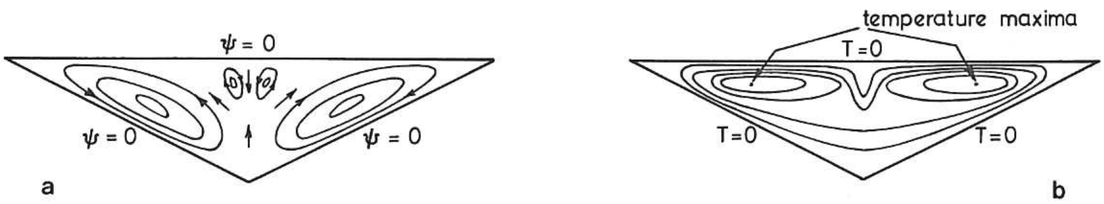


Figure 11
Broad semi-angle trough
(a) streamlines
(b) isotherms

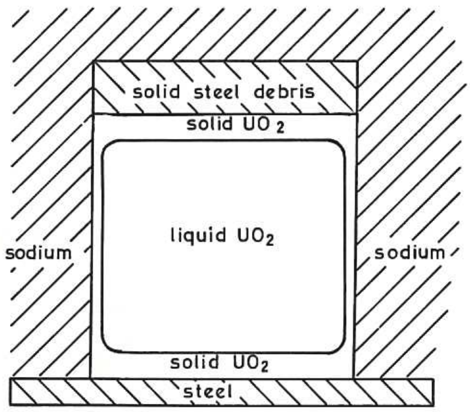


Figure 12
A brick of UO_2 with a liquid core sitting on a catcher, surmounted by steel débris

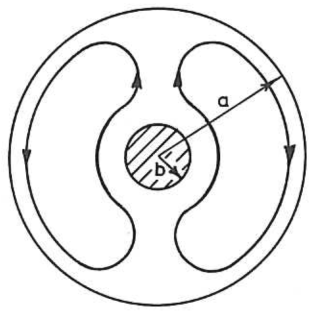


Figure 13
Inner sphere represents decay heated core débris; outer sphere represents the reactor pot.

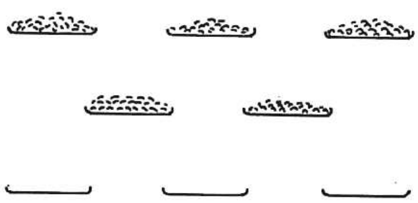


Figure 14
Three staggered layers of catchers

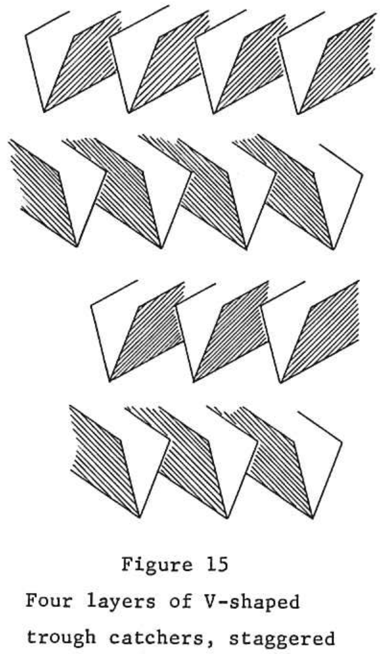


Figure 15
Four layers of V-shaped trough catchers, staggered and alternated.