Long-term retention of core debris

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LONG-TERM RETENTION OF CORE DEBRIS

ABSTRACT

    Severe accidents which lead to the production of
substantial amounts of core debris can be terminated with
relatively low consequences to the public if the core debris
reaches a state in which it can be cooled indefinitely in an
intact containment either by natural processes or by engineered
safety features. We describe some of the strategies available
for long-term retention of debris, and the current state of
understanding and modelling. Retention in particulate form in a
liquid coolant is practical, and the processes associated with
debris coolability are relatively well understood (this is
illustrated by comparisons between model calculations and
experiments in the Sandia DCC series). However there is a need
for improved understanding of the circumstances in which melts
will quench to form particulates; this is being investigated
with the CHYMES code. The effects of inhomogeneities in debris
beds is examined; there may be the need to provide additional
'wicks' for coolant to overcome the deleterious effects of
stratification. Retention as a predominantly molten mass is
also possible. The CORCON-MOD2 code has been extended to allow
for the effects of thermal conduction into the basemat; initial
calculations show a strong sensitivity to the assumed ablation
temperature, and indicate that a refractory barrier may limit
penetration.

1.   INTRODUCTION

    Severe accidents which lead to the production of
substantial amounts of core debris can be terminated with
relatively low consequences to the public (a condition referred
to below as a benign end-state) if the core debris reaches a
state in which it can be cooled indefinitely in an intact
containment, either by natural processes or by engineered safety
features. The debris may be retained either within the reactor
vessel or in the containment building. (Even if the basemat is
penetrated in an otherwise intact containment, the end-state may
be considered relatively benign as the radiological release is
expected to be small.) In this paper we discuss our current
understanding of the physical processes associated with these
benign end-states, and identify the uncertainties which still
exist.

    Two types of benign end-state are distinguished, viz.

    (I) those in which the debris is in the form of solid
    particles immersed in a liquid (either residual coolant in
    the case of liquid-cooled reactors, or deliberately

introduced liquid for all reactor types). In this case the maximum temperature of the particles is restricted to the boiling point of the liquid.

and

(II) those in which the core debris comes into thermal equilibrium with its surroundings (e.g. the concrete basemat or suitable refractory material) at a relatively high temperature.

Besides demonstrating that the decay heat (and other potential sources of heat) can be removed from the debris, it is necessary to show that the end-state can be reached and sustained without threatening the containment. To achieve this, containment systems may be required to provide heat removal, although the thermal inertia of containment structures obviates this requirement for an initial period of time.

The form of the debris is discussed in Section 2, and the coolability of quenched, fragmented debris in a liquid coolant is considered in Section 3. Section 4 is concerned with the ability to arrest the core debris in a predominantly molten form.

2.   THE FORM OF THE DEBRIS

As a severe accident develops the fuel and clad will overheat. If it is possible to re-introduce reactor coolant before the fuel pins lose their original geometry, it may be possible to recover the accident without the formation of core debris. However, even if the fuel is in its initial configuration, re-entry of coolant may cause fragmentation of the clad and disintegration of the fuel column. This is thought to have occurred in the upper part of the TMI-2 core, following extensive oxidation of the clad [1]. In this case the fuel fragment size is likely to be determined by the cracking of fuel pellets during irradiation, giving particle sizes of a few millimetres [2]. In accidents in which coolant is not re-introduced while the core is in its original geometry, it is expected that a consolidated molten region will form. The failure of a crust or supporting structure, or the re-introduction of liquid coolant, may then give rise to a melt-coolant interaction. This is necessary if type (I) retention is to be claimed.

Although many experiments have been carried out in which molten reactor materials, or simulants have been released into water, sodium or other liquid coolants, there is still no detailed understanding of the mechanisms of the interactions. Dullforce in [3] surveyed particle-size data for uranium dioxide interactions with sodium, and concluded that the median particle size (by mass) varied between 50 μm and about 3 mm, and that the size distributions did not depend in any obvious way upon the

quantities of materials involved or the experimental geometry, provided there was an excess of coolant. Fletcher [4] has recently considered fragmentation data obtained from the interaction of molten uranium dioxide (incorporating 19 per cent Mo) with water. These experiments were performed in the Molten Fuel Test Facility at Winfrith and used up to 24 kg of melt. For experiments in which a steam explosion occurred the median size was typically in the range 100 μm to 1.5 mm, whilst non-explosive interactions produced median particle sizes in the range 2 mm to 8 mm. Fletcher [4] showed that the particle size data was consistent with an upper limit log-normal distribution function, irrespective of the strength of the interaction. In most cases the upper limit to the particle size was in the range 10 - 20 mm, which is consistent with hydrodynamic breakup. However, in one experiment the melt formed a pool at the base of the vessel and debris was only produced as a result of breaking up the frozen melt-pool.

Most assessments have assumed that debris formed in reactor accidents would be of a similar size to that found in the smaller-scale experiments. However it is expected that the hydrodynamics of the cooling process are dependent on scale; this is the argument that has been developed [5,6,7] to suggest that yields from steam explosions will be restricted by a 'limit to mixing'. The CHYMES code [8] has been written to investigate this argument in more detail, and to address the scaling of melt-water interactions to reactor-sized quantities of material.

CHYMES is a transient three-component (melt, water and steam), two-dimensional (cylindrically symmetric) multiphase flow code. The current version of CHYMES assumes that the flow is incompressible and that the water and steam are at saturation. The length-scale of the melt, which features in the particle-to-water heat transfer and the drag laws, is determined from the solution of an advection equation, but there is considerable uncertainty in the fragmentation time-scale.

The CHYMES code has been used to examine the behaviour of melt poured into water for a wide variety of different situations. Simulations of the small-scale mixing experiment CWTI-9 carried out at Argonne National Laboratory [9] gave results which were in excellent agreement with the experimental data [8,10]. In the experiment 2 kg of corium was poured into a pool of water 300 mm deep. In both the simulation and the experiment a considerable amount of melt reached the base of the vessel in liquid form; the water pool underwent rapid boil up on melt entry and the coolant around the falling melt jet was mostly steam.

CHYMES simulations [11] for melts of aluminium, steel and uranium dioxide show a clear effect of temperature, with high temperatures leading to dispersion of the melt in a steam medium. The differences can be attributed largely to the effect of temperature on radiative heat transfer. The degree of

quenching depends on the melt particle size, which is determined by the rate of fragmentation of the melt jet. The mode of fragmentation of such jets is currently being investigated experimentally in US laboratories [12,13].

Without a full quench in a free pour, it may be necessary to investigate means of supplying liquid coolant from underneath the settled debris to promote the formation of particulate material.

3. THE COOLABILITY OF QUENCHED, FRAGMENTED DEBRIS

Once particulate material has formed it will only remain in this state provided the decay heat can be removed either through a continuing influx of coolant into the bed, or, in the case of shallow beds, by a combination of convection and radiation to the remainder of the containment. Models for the coolability of volumetrically-heated particulate debris in a boiling coolant based on the concepts of flow through porous media have been developed [14,15]. Predicted values of dryout heat flux (the largest at which liquid coolant reaches all particles) were found to agree with experimental data for a wide range of coolants to within about a factor of two for homogeneous beds in which re-arrangement did not occur [14]. Re-arrangements, such as channelling in fine particle beds (thought to be caused by capillary effects) and disturbances caused by sudden vapour generation in packed beds, can enhance the dryout heat flux considerably, but a fully predictive model is not available (developments of a channelling model are discussed in [14] and [16]).

For homogeneous packed beds there remain a number of uncertainties. The dryout heat flux is only one parameter predicted by the porous medium model, and it is now possible to compare transient calculations for dryout with experimental data. Figure 1 shows a comparison of the predicted size of a dried-out region and the temperature in the dried-out region, with data for one of the dryout transients in the Sandia DCC-2 test [17]. In the test a 0.5 m deep bed of uranium dioxide particles with an effective diameter of 1.42 mm was fission-heated; the coolant was water. This, and similar [18], comparisons show that although there is good qualitative agreement between theory and experiment, the agreement is by no means exact (the comparison becomes much worse for the quenching of dry regions). Failure to get exact agreement can be attributed to inhomogeneities in the bed (which are not in the idealised model), a need to improve the phenomenological functions used by the model (relative permeabilities etc.), and the effect of the crucible in the experiment.

We have used the porous media model to examine the effect of horizontal variations in bed properties and heating rates which it has been suggested [19] might induce two or three dimensional motions leading to enhanced coolability. The

analysis is complicated because of the strong non-linearities in the flow equations, which become particularly important as dryout is approached; this restricts the applicability of traditional linear perturbation techniques. A number of simplified problems have been examined. These include

(i)   A bottom heated bed with an impermeable base in which there are small variations in bottom heating. For cases where capillary pressure effects are small it can be shown that the change to saturation induced by the non-uniform heating is independent of vertical position in the bed and its value at any horizontal position is the same as that for a uniformly heated bed with the bottom heat flux set to the local (non-uniform) value.

(ii)   Edge effects in a volumetrically heated bed, where the porosity of the bed increases as the wall is approached. This problem has been investigated using the method of matched asymptotic expansions (see e.g. [20]). It is found that far from the wall the one-dimensional solution for the uniform bed dominates, and there is no evidence for significant multi-dimensional flows except in the region where the heating and porosity are changing rapidly.

(iii)   A symmetric U-tube of volumetrically heated porous media, open to a coolant pool at both ends of the tube. In this case the basic solution is symmetric, and similar to two one-dimensional beds joined at the bottom. Non-symmetric flows (i.e. preferential flow of liquid in one leg and vapour out the other) might be expected to enhance the dryout heat flux. However a numerical search has found no such solutions when the constraint that the pressure at the ends of the U-tube should be equal is applied.

From these examples it is concluded that the porous medium model predicts that, except where regions of enhanced permeability occupy a large fraction of the cross-section of the bed, there is no significant increase in coolability over that of the least coolable region based on one-dimensional considerations.

One strong type of inhomogeneity that has been examined both experimentally and theoretically is that of stratification, where the effective particle diameter changes abruptly at a horizontal interface. This could arise if debris is formed in a series of events rather than a single one. Low dryout heat fluxes found in stratified beds with coarse particles below fine particles in experiments at Winfrith [21] and Karlsruhe [22] have been explained by the requirement that capillary pressure (the local difference in pressure between the vapour and liquid phases caused by surface tension; the capillary pressure is a function of pore size and saturation) should be continuous

across the stratification interface [14,23]. Flow across an interface becomes impossible when the fully saturated capillary pressure of the fine layer at break-through exceeds the capillary pressure in the coarse layer at zero saturation.

The DCC-3 [24] test at Sandia was a stratified bed, and as noted in [24], if the form for the capillary pressure function is that proposed by [22] the argument above implies that the dryout heat flux would have been zero. In fact small, but non-negligible dryout heat fluxes (of order 200 kW/m^2) were measured. This has been attributed to the effect of the thermocouples crossing the stratification interface. To model these effects it is assumed that the region occupied by the thermocouples has properties similar to that of a bed with debris of the same diameter as that of the thermocouples (1.5 mm), and with a porosity suited to the arrangement of the thermocouples (about 0.2). It is assumed that the relative permeabilities and passabilities in the thermocouple region are linear and quadratic functions of the saturation respectively (because the pores between the thermocouples are highly connected), and that the pressure drops across the thermocouple and particulate regions are equal. With these assumptions the results of Fig. 2 are obtained. It is seen that the modified model, described above, gives better agreement with the data when there was no inlet flow, but then overestimates the effect of a small inlet flow. As stratification of debris is a possibility, any retention device for the two-phase cooling of particle beds that does not rely on active pumping of the coolant should include sufficient 'wicks' (analogues of the DCC-3 thermocouples) to promote the supply of coolant to lower layers.

4. THE RETENTION OF DEBRIS IN MOLTEN FORM

Although retaining the debris in particulate form is desirable (particularly as the low temperature of the debris will impede further fission product release, and the state of the debris prevents further energetic melt-coolant interactions), the uncertainties in the form of the debris and the need to have liquid coolant available are judged to be sufficiently important that retention in a consolidated form (type II) should also be considered. In many plants the concrete basemat would form a useful heat sink for the debris, at the expense of releasing both combustible and non-combustible gases to the containment volume. The effect of these gases and other heat transfer to the containment may be assessed using the SIMCON module [25], in conjunction with a containment thermohydraulics code. Initial scoping calculations have indicated that low non-condensable gas producing materials, and the absorption of thermal radiation in structures rather than the containment atmosphere, lead to significantly lower pressures in the containment building in the absence of active heat removal.

The degree of penetration of the basemat, or similar structure, depends on the heat required to ablate unit volume of the basemat material, the degree of spreading of the debris, the availability of cooling within the basemat and above the debris, and the heat transfer mechanisms within the debris region. An extensive review of molten debris heat transfer was carried out by Morgan in [26], concentrating on cases without gas injection. Although most simulant tests suggest that a very small fraction of heat (less than 10 per cent) generated in a molten layer with equal temperature boundaries will be transferred downwards (because of the production of a sub-layer with a stable temperature profile), some data show a more even distribution of heat flux. Experimental data [27] indicates that gas injection (e.g. from concrete decomposition) can considerably enhance the fraction of heat that erodes the basemat.

The CORCON-MOD2 code [28] provides a detailed model of the penetration of a concrete basemat. In order to apply this code to long term retention we have added a model for thermal penetration into the concrete (the original code does not allow heat to be conducted away from the melt-front). At each position on the interface between the debris and the concrete, an approximate one-dimensional solution of the thermal diffusion equation is solved, giving the interface temperature and the thermal penetration distance. The thermal penetration model is similar to that developed for the INTERUK code [29].

This enhanced version of CORCON-MOD2 has been applied to the plant calculations described in [24] (melt of a 3.4 GW(th) reactor onto a siliceous concrete basemat of area 60 m^2). Predictions of vertical penetration against time are shown in Fig. 3 for two cases (a) where the ablation temperature was set to the liquidus of the concrete and (b) where it was set to the solidus. It is seen that with the CORCON heat transfer models, penetration is predicted to stop early on in case (a) but continue in case (b). This arises because in case (a) the code predicts that the debris, when sufficiently diluted by concrete decomposition products, behaves substantially as a liquid even below the liquidus of the concrete. It is still uncertain as to whether it is more appropriate to set the basemat ablation temperature close to the solidus or liquidus (or whether it will be necessary to allow for more subtle chemical effects, such as eutectic formation with components of the debris). However, it may be possible to produce case (a) in practice by placing a more refractory material below a layer of concrete diluent; the choice of refractory is not straightforward as it should be chemically inert in the presence of the mixed oxide and metallic debris. As noted above any material, or base cooling that reduces or stops gas flow through the melt will produce enhanced upward heat fluxes, which are likely to necessitate the use of active heat removal systems to prevent long term over-pressurisation of the containment.

5. CONCLUSIONS

In this paper we have described some of the strategies available for long-term retention of debris, and the current state of understanding and modelling. Retention in particulate form in a liquid coolant is practical, and the processes associated with debris coolability are relatively well understood. However, there is a need for improved understanding of the circumstances in which melts will quench to form particulates, and there may be the need to provide additional 'wicks' for coolant to overcome the deleterious effects of stratification. Retention as a predominantly molten mass is also possible. The CORCON-MOD2 code has been extended to allow for the effects of thermal conduction into the basemat; initial calculations show a strong sensitivity to the assumed ablation temperature, and indicate that a refractory barrier may limit penetration.

6. ACKNOWLEDGEMENTS

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(a)

Power step 255 - 625 kW reactor power at 0 s

625 - 990 kW reactor power at 400 s

Onset of dry-out at 74.43 s

420 s   480   540   600   660   720   780   831.22 s

HEIGHT (m)

TEMPERATURE (°C)

(b)

Onset of dry-out at 100 s

400 s   880 s
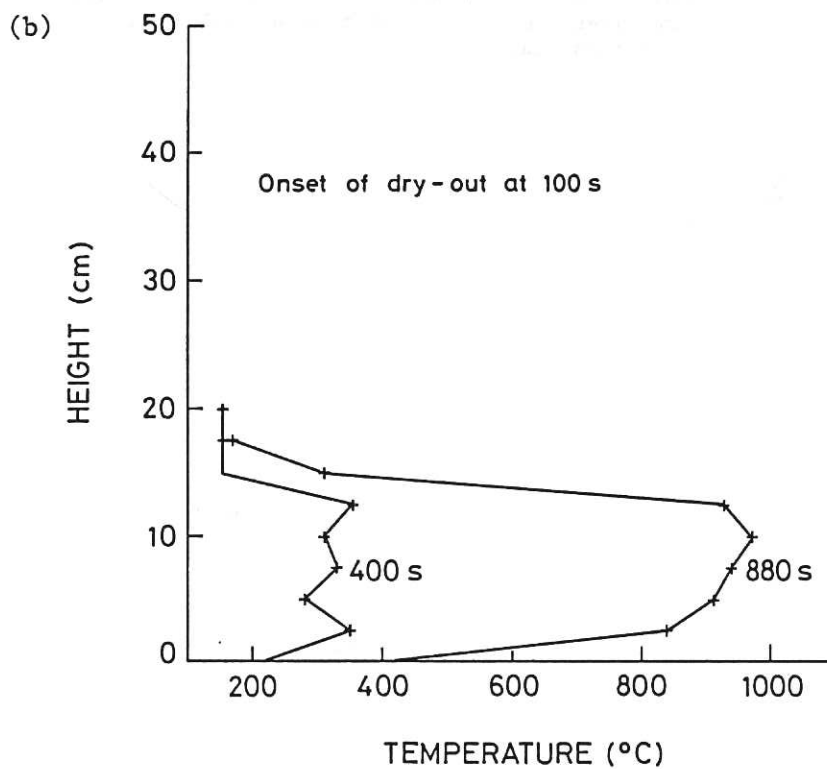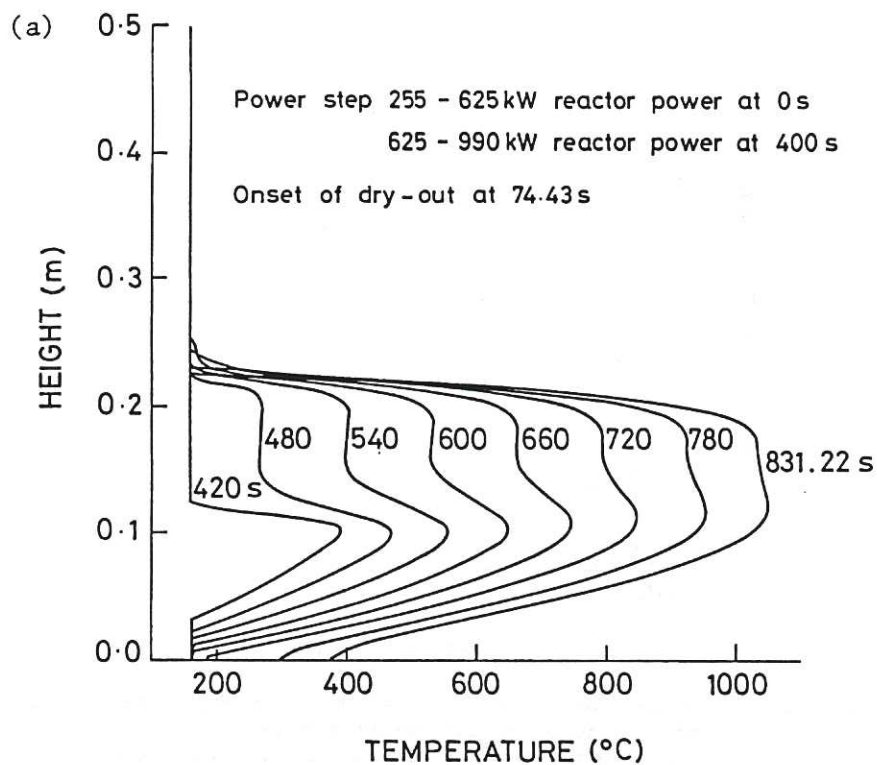
HEIGHT (cm)

TEMPERATURE (°C)

Fig. 1.   Comparison of calculations, using the ENTH code
           [18], with experimental data for dryout 70 in the
           DCC-2 experiment. The calculated temperature
           profile is shown at a number of times in Fig. 1(a);
           experimentally determined temperature profiles are
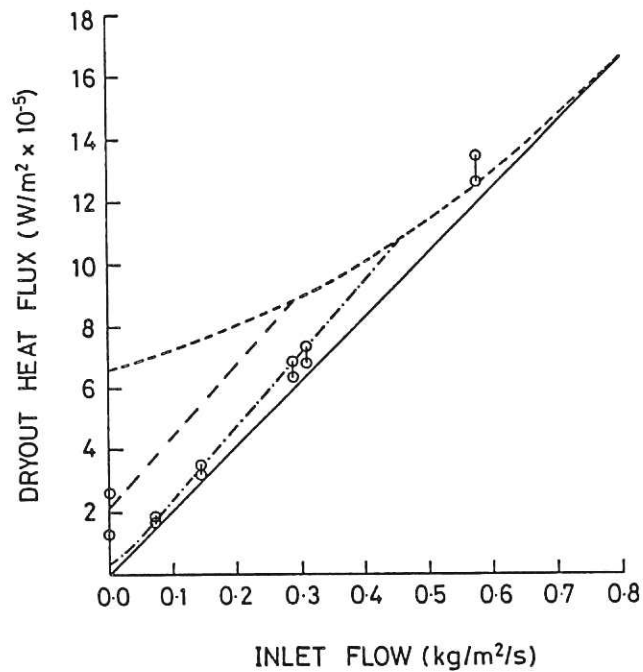   shown in Fig. 1(b).

Fig. 2.   Comparison of experimental data (circles) with model
           calculations for the stratified debris bed
           experiment DCC-3. Short dashes indicate the dryout
           heat flux of the finer particles only, the
           dot-dashed line indicates the standard porous medium
           model prediction, the longer dashes are for the
           modified model described in the text, and the solid
           line gives the dryout heat flux equivalent to the
           inlet mass flux.
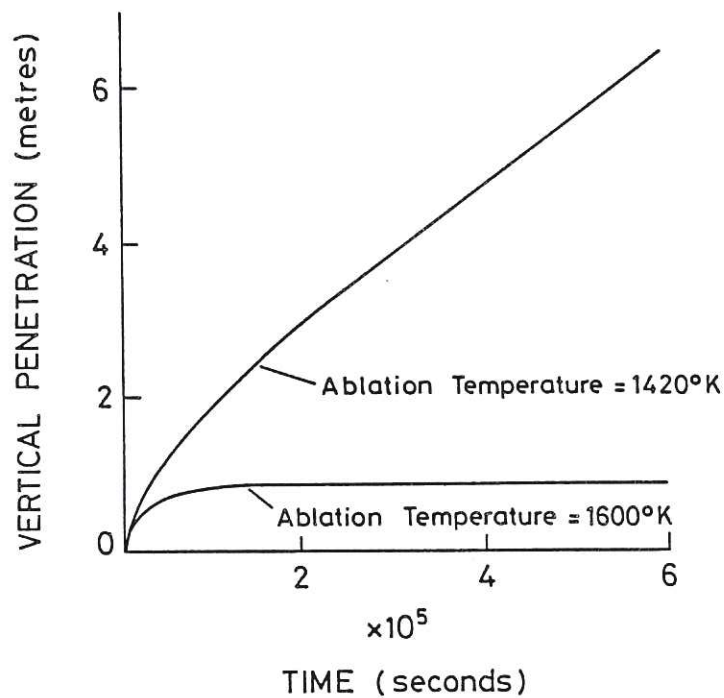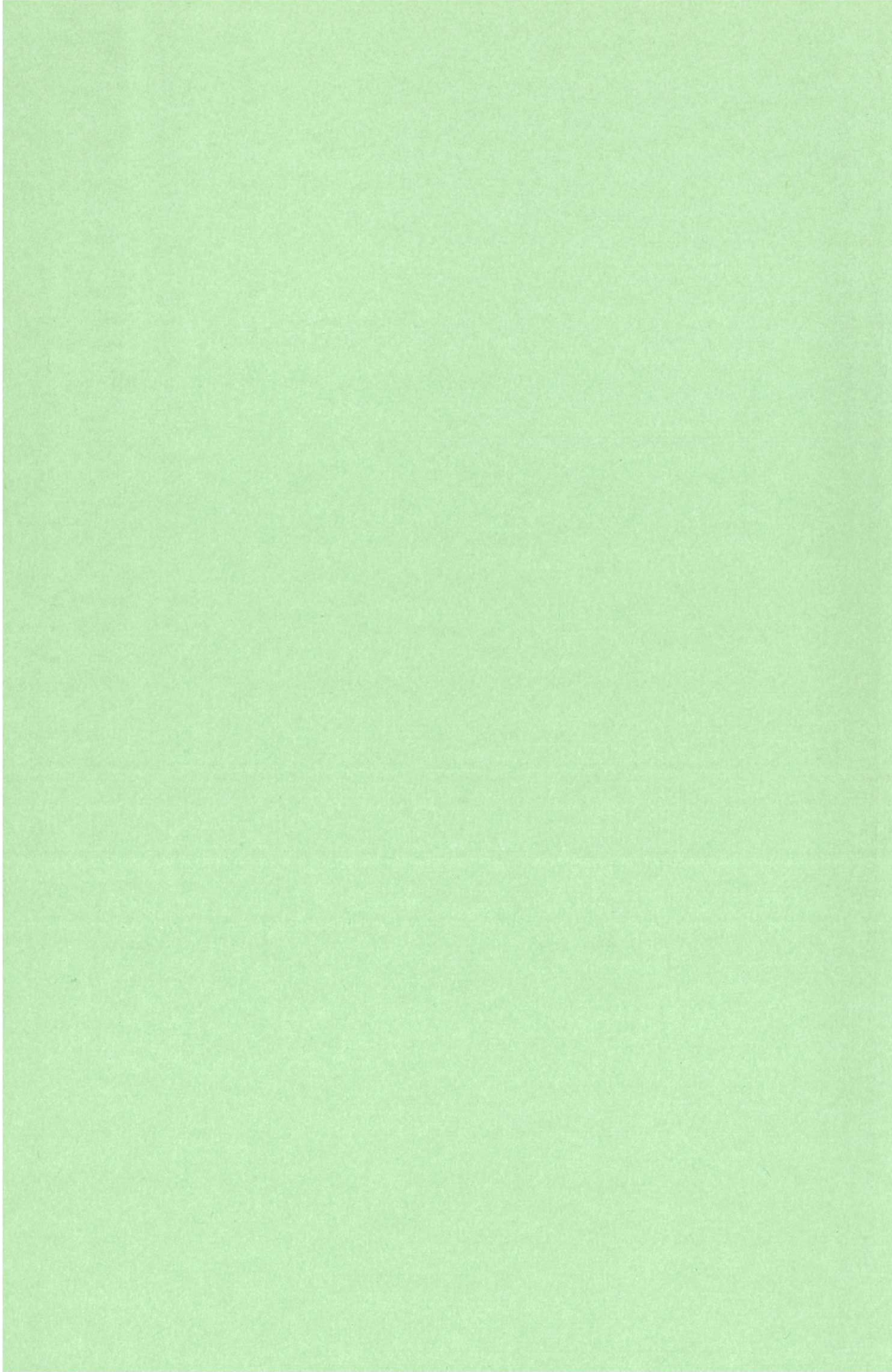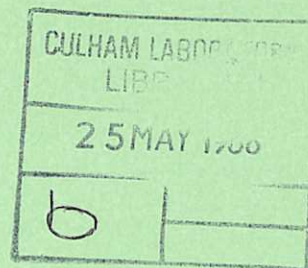

Fig. 3.   CORCON-MOD2 predictions for a siliceous concrete
           basemat, including thermal conduction into the
           concrete. The concrete is assumed to have a solidus
           of 1420K and a liquidus of 1600K. The calculations
           are identical except for the choice of concrete
           ablation temperature (see text for discussion).

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1. INTRODUCTION

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Two types of benign end-state are distinguished, viz.

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(II) those in which the core debris comes into thermal equilibrium with its surroundings (e.g. the concrete basemat or suitable refractory material) at a relatively high temperature.

Besides demonstrating that the decay heat (and other potential sources of heat) can be removed from the debris, it is necessary to show that the end-state can be reached and sustained without threatening the containment. To achieve this, containment systems may be required to provide heat removal, although the thermal inertia of containment structures obviates this requirement for an initial period of time.

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2. THE FORM OF THE DEBRIS

As a severe accident develops the fuel and clad will overheat. If it is possible to re-introduce reactor coolant before the fuel pins lose their original geometry, it may be possible to recover the accident without the formation of core debris. However, even if the fuel is in its initial configuration, re-entry of coolant may cause fragmentation of the clad and disintegration of the fuel column. This is thought to have occurred in the upper part of the TMI-2 core, following extensive oxidation of the clad [1]. In this case the fuel fragment size is likely to be determined by the cracking of fuel pellets during irradiation, giving particle sizes of a few millimetres [2]. In accidents in which coolant is not re-introduced while the core is in its original geometry, it is expected that a consolidated molten region will form. The failure of a crust or supporting structure, or the re-introduction of liquid coolant, may then give rise to a melt-coolant interaction. This is necessary if type (I) retention is to be claimed.

Although many experiments have been carried out in which molten reactor materials, or simulants have been released into water, sodium or other liquid coolants, there is still no detailed understanding of the mechanisms of the interactions. Dullforce in [3] surveyed particle-size data for uranium dioxide interactions with sodium, and concluded that the median particle size (by mass) varied between 50 μm and about 3 mm, and that the size distributions did not depend in any obvious way upon the

quantities of materials involved or the experimental geometry, provided there was an excess of coolant. Fletcher [4] has recently considered fragmentation data obtained from the interaction of molten uranium dioxide (incorporating 19 per cent Mo) with water. These experiments were performed in the Molten Fuel Test Facility at Winfrith and used up to 24 kg of melt. For experiments in which a steam explosion occurred the median size was typically in the range 100 μm to 1.5 mm, whilst non-explosive interactions produced median particle sizes in the range 2 mm to 8 mm. Fletcher [4] showed that the particle size data was consistent with an upper limit log-normal distribution function, irrespective of the strength of the interaction. In most cases the upper limit to the particle size was in the range 10 - 20 mm, which is consistent with hydrodynamic breakup. However, in one experiment the melt formed a pool at the base of the vessel and debris was only produced as a result of breaking up the frozen melt-pool.

Most assessments have assumed that debris formed in reactor accidents would be of a similar size to that found in the smaller-scale experiments. However it is expected that the hydrodynamics of the cooling process are dependent on scale; this is the argument that has been developed [5,6,7] to suggest that yields from steam explosions will be restricted by a 'limit to mixing'. The CHYMES code [8] has been written to investigate this argument in more detail, and to address the scaling of melt-water interactions to reactor-sized quantities of material.

CHYMES is a transient three-component (melt, water and steam), two-dimensional (cylindrically symmetric) multiphase flow code. The current version of CHYMES assumes that the flow is incompressible and that the water and steam are at saturation. The length-scale of the melt, which features in the particle-to-water heat transfer and the drag laws, is determined from the solution of an advection equation, but there is considerable uncertainty in the fragmentation time-scale.

The CHYMES code has been used to examine the behaviour of melt poured into water for a wide variety of different situations. Simulations of the small-scale mixing experiment CWTI-9 carried out at Argonne National Laboratory [9] gave results which were in excellent agreement with the experimental data [8,10]. In the experiment 2 kg of corium was poured into a pool of water 300 mm deep. In both the simulation and the experiment a considerable amount of melt reached the base of the vessel in liquid form; the water pool underwent rapid boil up on melt entry and the coolant around the falling melt jet was mostly steam.

CHYMES simulations [11] for melts of aluminium, steel and uranium dioxide show a clear effect of temperature, with high temperatures leading to dispersion of the melt in a steam medium. The differences can be attributed largely to the effect of temperature on radiative heat transfer. The degree of

quenching depends on the melt particle size, which is determined by the rate of fragmentation of the melt jet. The mode of fragmentation of such jets is currently being investigated experimentally in US laboratories [12,13].

Without a full quench in a free pour, it may be necessary to investigate means of supplying liquid coolant from underneath the settled debris to promote the formation of particulate material.

3.   THE COOLABILITY OF QUENCHED, FRAGMENTED DEBRIS

Once particulate material has formed it will only remain in this state provided the decay heat can be removed either through a continuing influx of coolant into the bed, or, in the case of shallow beds, by a combination of convection and radiation to the remainder of the containment. Models for the coolability of volumetrically-heated particulate debris in a boiling coolant based on the concepts of flow through porous media have been developed [14,15]. Predicted values of dryout heat flux (the largest at which liquid coolant reaches all particles) were found to agree with experimental data for a wide range of coolants to within about a factor of two for homogeneous beds in which re-arrangement did not occur [14]. Re-arrangements, such as channelling in fine particle beds (thought to be caused by capillary effects) and disturbances caused by sudden vapour generation in packed beds, can enhance the dryout heat flux considerably, but a fully predictive model is not available (developments of a channelling model are discussed in [14] and [16]).

For homogeneous packed beds there remain a number of uncertainties. The dryout heat flux is only one parameter predicted by the porous medium model, and it is now possible to compare transient calculations for dryout with experimental data. Figure 1 shows a comparison of the predicted size of a dried-out region and the temperature in the dried-out region, with data for one of the dryout transients in the Sandia DCC-2 test [17]. In the test a 0.5 m deep bed of uranium dioxide particles with an effective diameter of 1.42 mm was fission-heated; the coolant was water. This, and similar [18], comparisons show that although there is good qualitative agreement between theory and experiment, the agreement is by no means exact (the comparison becomes much worse for the quenching of dry regions). Failure to get exact agreement can be attributed to inhomogeneities in the bed (which are not in the idealised model), a need to improve the phenomenological functions used by the model (relative permeabilities etc.), and the effect of the crucible in the experiment.

We have used the porous media model to examine the effect of horizontal variations in bed properties and heating rates which it has been suggested [19] might induce two or three dimensional motions leading to enhanced coolability. The

analysis is complicated because of the strong non-linearities in the flow equations, which become particularly important as dryout is approached; this restricts the applicability of traditional linear perturbation techniques. A number of simplified problems have been examined. These include

(i)   A bottom heated bed with an impermeable base in which there are small variations in bottom heating. For cases where capillary pressure effects are small it can be shown that the change to saturation induced by the non-uniform heating is independent of vertical position in the bed and its value at any horizontal position is the same as that for a uniformally heated bed with the bottom heat flux set to the local (non-uniform) value.

(ii)   Edge effects in a volumetrically heated bed, where the porosity of the bed increases as the wall is approached. This problem has been investigated using the method of matched asymptotic expansions (see e.g. [20]). It is found that far from the wall the one-dimensional solution for the uniform bed dominates, and there is no evidence for significant multi-dimensional flows except in the region where the heating and porosity are changing rapidly.

(iii)   A symmetric U-tube of volumetrically heated porous media, open to a coolant pool at both ends of the tube. In this case the basic solution is symmetric, and similar to two one-dimensional beds joined at the bottom. Non-symmetric flows (i.e. preferential flow of liquid in one leg and vapour out the other) might be expected to enhance the dryout heat flux. However a numerical search has found no such solutions when the constraint that the pressure at the ends of the U-tube should be equal is applied.

From these examples it is concluded that the porous medium model predicts that, except where regions of enhanced permeability occupy a large fraction of the cross-section of the bed, there is no significant increase in coolability over that of the least coolable region based on one-dimensional considerations.

One strong type of inhomogeneity that has been examined both experimentally and theoretically is that of stratification, where the effective particle diameter changes abruptly at a horizontal interface. This could arise if debris is formed in a series of events rather than a single one. Low dryout heat fluxes found in stratified beds with coarse particles below fine particles in experiments at Winfrith [21] and Karlsruhe [22] have been explained by the requirement that capillary pressure (the local difference in pressure between the vapour and liquid phases caused by surface tension; the capillary pressure is a function of pore size and saturation) should be continuous

across the stratification interface [14,23]. Flow across an interface becomes impossible when the fully saturated capillary pressure of the fine layer at break-through exceeds the capillary pressure in the coarse layer at zero saturation.

The DCC-3 [24] test at Sandia was a stratified bed, and as noted in [24], if the form for the capillary pressure function is that proposed by [22] the argument above implies that the dryout heat flux would have been zero. In fact small, but non-negligible dryout heat fluxes (of order 200 kW/m^2) were measured. This has been attributed to the effect of the thermocouples crossing the stratification interface. To model these effects it is assumed that the region occupied by the thermocouples has properties similar to that of a bed with debris of the same diameter as that of the thermocouples (1.5 mm), and with a porosity suited to the arrangement of the thermocouples (about 0.2). It is assumed that the relative permeabilities and passabilities in the thermocouple region are linear and quadratic functions of the saturation respectively (because the pores between the thermocouples are highly connected), and that the pressure drops across the thermocouple and particulate regions are equal. With these assumptions the results of Fig. 2 are obtained. It is seen that the modified model, described above, gives better agreement with the data when there was no inlet flow, but then overestimates the effect of a small inlet flow. As stratification of debris is a possibility, any retention device for the two-phase cooling of particle beds that does not rely on active pumping of the coolant should include sufficient 'wicks' (analogues of the DCC-3 thermocouples) to promote the supply of coolant to lower layers.

4.   THE RETENTION OF DEBRIS IN MOLTEN FORM

Although retaining the debris in particulate form is desirable (particularly as the low temperature of the debris will impede further fission product release, and the state of the debris prevents further energetic melt-coolant interactions), the uncertainties in the form of the debris and the need to have liquid coolant available are judged to be sufficiently important that retention in a consolidated form (type II) should also be considered. In many plants the concrete basemat would form a useful heat sink for the debris, at the expense of releasing both combustible and non-combustible gases to the containment volume. The effect of these gases and other heat transfer to the containment may be assessed using the SIMCON module [25], in conjunction with a containment thermohydraulics code. Initial scoping calculations have indicated that low non-condensable gas producing materials, and the absorption of thermal radiation in structures rather than the containment atmosphere, lead to significantly lower pressures in the containment building in the absence of active heat removal.

The degree of penetration of the basemat, or similar structure, depends on the heat required to ablate unit volume of the basemat material, the degree of spreading of the debris, the availability of cooling within the basemat and above the debris, and the heat transfer mechanisms within the debris region. An extensive review of molten debris heat transfer was carried out by Morgan in [26], concentrating on cases without gas injection. Although most simulant tests suggest that a very small fraction of heat (less than 10 per cent) generated in a molten layer with equal temperature boundaries will be transferred downwards (because of the production of a sub-layer with a stable temperature profile), some data show a more even distribution of heat flux. Experimental data [27] indicates that gas injection (e.g. from concrete decomposition) can considerably enhance the fraction of heat that erodes the basemat.

The CORCON-MOD2 code [28] provides a detailed model of the penetration of a concrete basemat. In order to apply this code to long term retention we have added a model for thermal penetration into the concrete (the original code does not allow heat to be conducted away from the melt-front). At each position on the interface between the debris and the concrete, an approximate one-dimensional solution of the thermal diffusion equation is solved, giving the interface temperature and the thermal penetration distance. The thermal penetration model is similar to that developed for the INTERUK code [29].

This enhanced version of CORCON-MOD2 has been applied to the plant calculations described in [24] (melt of a 3.4 GW(th) reactor onto a siliceous concrete basemat of area 60 m^2). Predictions of vertical penetration against time are shown in Fig. 3 for two cases (a) where the ablation temperature was set to the liquidus of the concrete and (b) where it was set to the solidus. It is seen that with the CORCON heat transfer models, penetration is predicted to stop early on in case (a) but continue in case (b). This arises because in case (a) the code predicts that the debris, when sufficiently diluted by concrete decomposition products, behaves substantially as a liquid even below the liquidus of the concrete. It is still uncertain as to whether it is more appropriate to set the basemat ablation temperature close to the solidus or liquidus (or whether it will be necessary to allow for more subtle chemical effects, such as eutectic formation with components of the debris). However, it may be possible to produce case (a) in practice by placing a more refractory material below a layer of concrete diluent; the choice of refractory is not straightforward as it should be chemically inert in the presence of the mixed oxide and metallic debris. As noted above any material, or base cooling that reduces or stops gas flow through the melt will produce enhanced upward heat fluxes, which are likely to necessitate the use of active heat removal systems to prevent long term over-pressurisation of the containment.

5. CONCLUSIONS

In this paper we have described some of the strategies available for long-term retention of debris, and the current state of understanding and modelling. Retention in particulate form in a liquid coolant is practical, and the processes associated with debris coolability are relatively well understood. However, there is a need for improved understanding of the circumstances in which melts will quench to form particulates, and there may be the need to provide additional 'wicks' for coolant to overcome the deleterious effects of stratification. Retention as a predominantly molten mass is also possible. The CORCON-MOD2 code has been extended to allow for the effects of thermal conduction into the basemat; initial calculations show a strong sensitivity to the assumed ablation temperature, and indicate that a refractory barrier may limit penetration.

6. ACKNOWLEDGEMENTS

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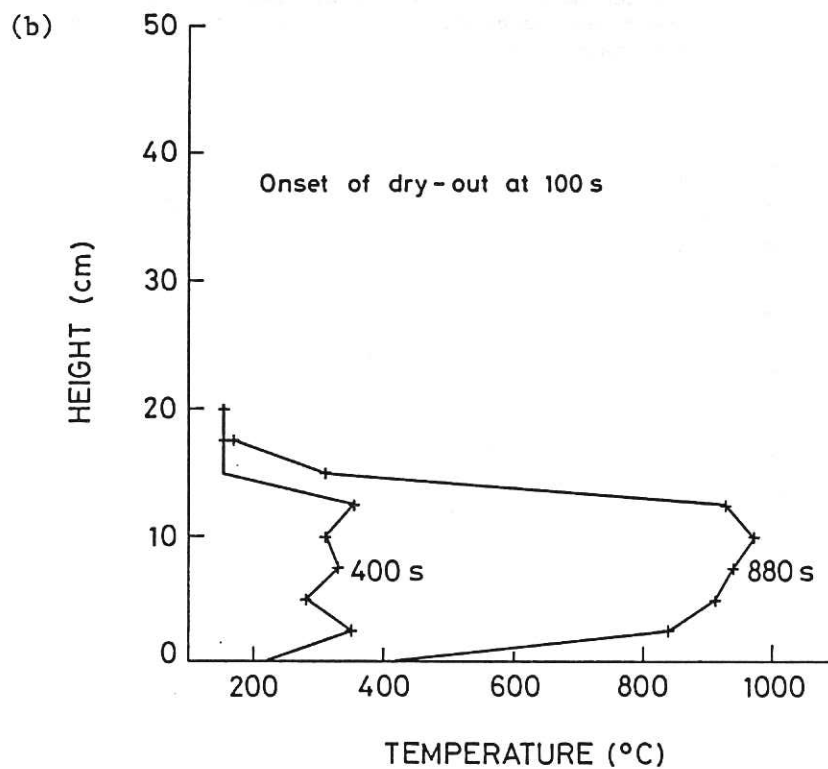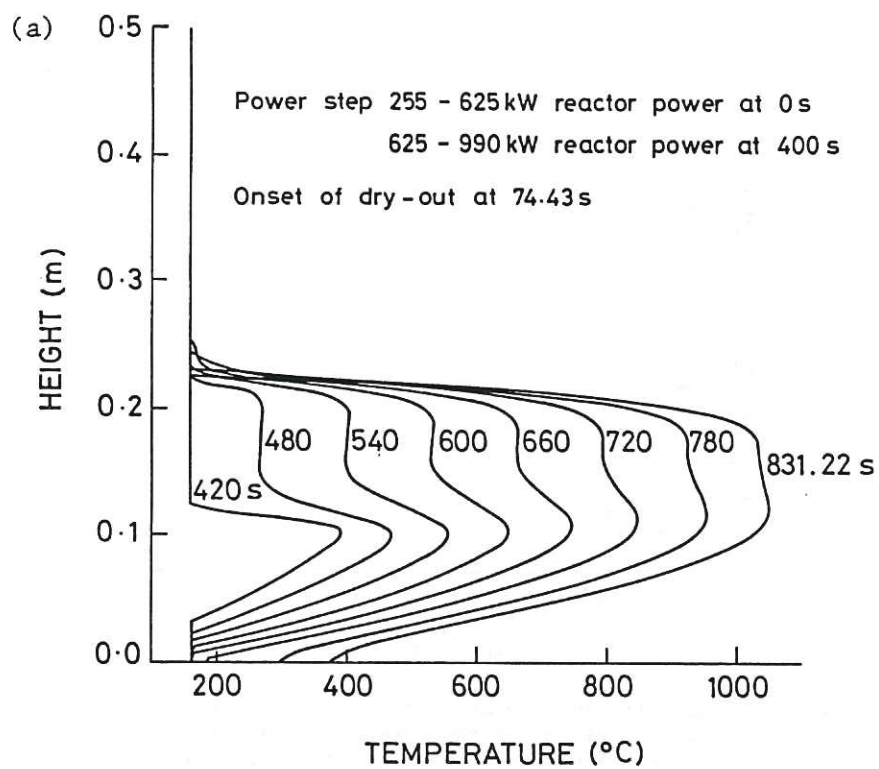
(a)

Power step 255 – 625 kW reactor power at 0 s

625 – 990 kW reactor power at 400 s

Onset of dry-out at 74.43 s

480   540   600   660   720   780

420 s   831.22 s

HEIGHT (m)

TEMPERATURE (°C)

(b)

Onset of dry-out at 100 s

400 s   880 s

HEIGHT (cm)

TEMPERATURE (°C)

Fig. 1.   Comparison of calculations, using the ENTH code
           [18], with experimental data for dryout 70 in the
           DCC-2 experiment. The calculated temperature
           profile is shown at a number of times in Fig. 1(a);
           experimentally determined temperature profiles are
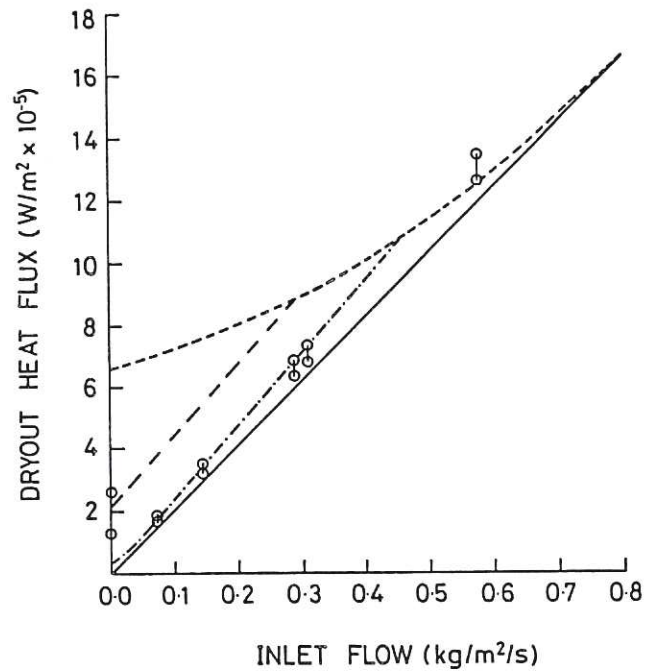   shown in Fig. 1(b).

Fig. 2.   Comparison of experimental data (circles) with model
calculations for the stratified debris bed
experiment DCC-3. Short dashes indicate the dryout
heat flux of the finer particles only, the
dot-dashed line indicates the standard porous medium
model prediction, the longer dashes are for the
modified model described in the text, and the solid
line gives the dryout heat flux equivalent to the
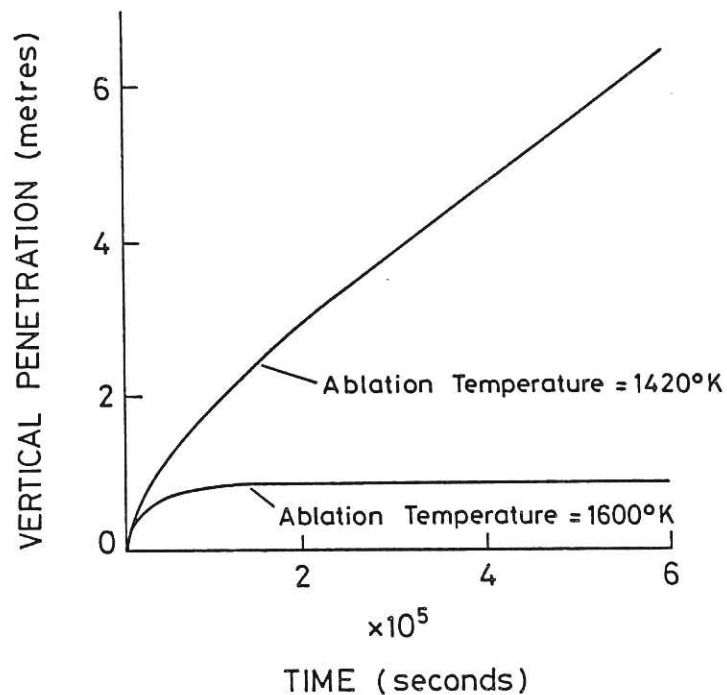inlet mass flux.

Fig. 3.   CORCON-MOD2 predictions for a siliceous concrete
basemat, including thermal conduction into the
concrete. The concrete is assumed to have a solidus
of 1420K and a liquidus of 1600K. The calculations
are identical except for the choice of concrete
ablation temperature (see text for discussion).