UNIVERSITÀ DI PISA

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Technical Meeting on Phenomenology and Technologies Relevant to In-Vessel Melt Retention and Ex-Vessel Corium Cooling

ORIGINAL CORE CATCHER DESIGN IN ORDER TO MANAGE THE CORE MELTDOWN SEVERE ACCIDENT WITH THE 'IN-VESSEL RETENTION STRATEGY'

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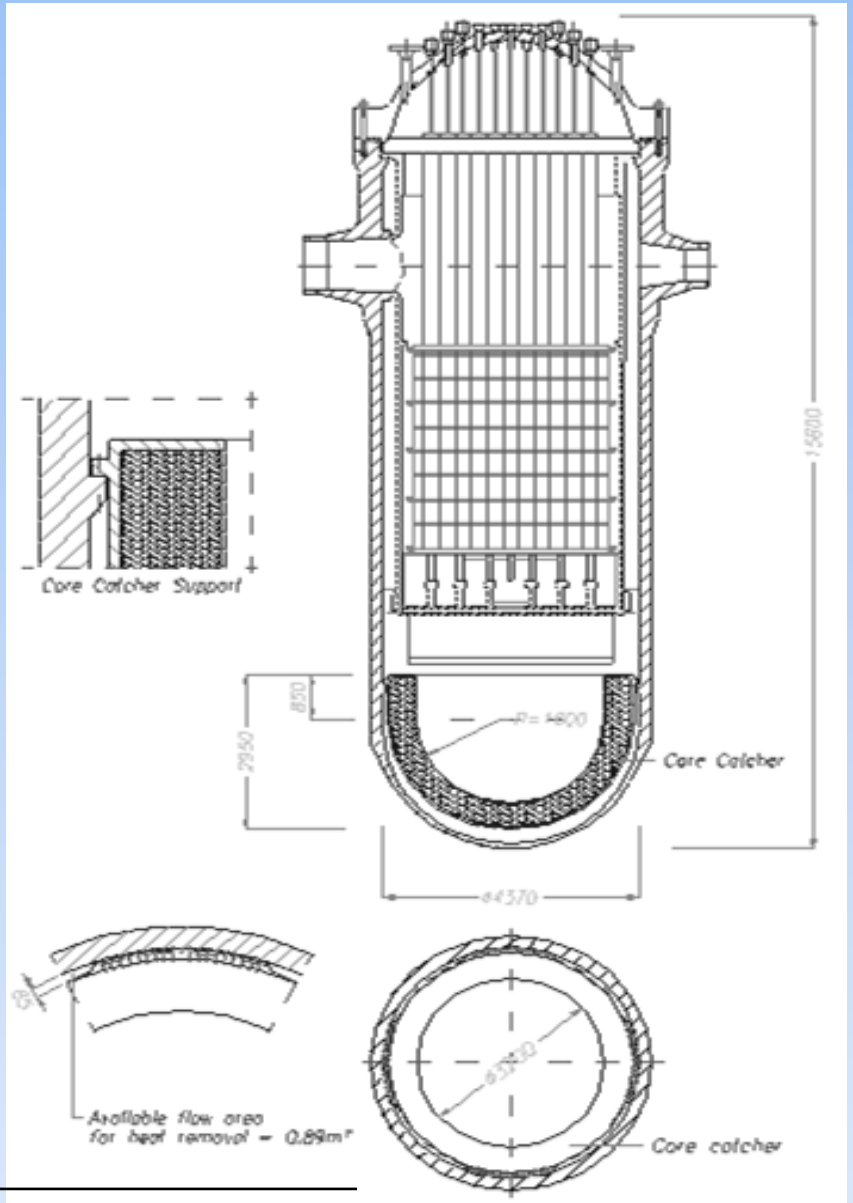
Inadequate cooling during the severe accident may lead to melting of significant amount of core material and, subsequently, relocation to the lower head of the reactor vessel, as in TMI-2 accident.

Core catcher is an envisaged system to improve safety and to manage the corium (mixture of Uranium, Zirconium and Iron oxides) in the case of core meltdown.



INTRODUCTION

In this study:

a design of internal core catcher, made of pebble bed, is presented.

Aim of the study:

…demonstrate that this core catcher is able to delay for a reasonable period of time any contact between corium and lower head of RPV if the Corium power decay is removed from its upper surface by means of various heat transfer mechanism (convection with the water injected in the vessel by the RHR systems or radiation with the vessel walls, cooled externally)..

INTRODUCTION

The proposed core catcher is based on the concept of In-Vessel Retention (IVR), that allows:

- to ensure the vessel lower head remains intact so that relocated core material is retained within the vessel.

- to ensure that any molten material will not attack the plant foundations or even reach the outside of the building.

- to enhance the plant safety and reduce concerns about containment failure and associated risks

PHYSICAL PROBLEMS ASSUMPTIONS

The basic assumptions of Theofanous et al. 1998 [1]- [2]developed for the AP600 nuclear power plant design, are considered in this study:

- the core degradation occurs in a depressurized primary system
- the vessel cavity must be flooded before core debris touch the bottom head. In this case the bottom head assumes an external temperature equal to 100°C, that is the saturation temperature of the water at atmosphere pressure. The bottom head external surface , then, remains in nucleate boiling at 100°C , provided that the critical heat flux is not exceed in any point.
- being the primary system depressurized, a very small thickness is needed to support dead-weight loads (the ablation of internal surface due to the Corium would not impair the resistance of bottom head)
- failure mechanisms are due to thermal stresses and creep

PHYSICAL PROBLEMS ASSUMPTIONS

- the failure to supply coolant into the reactor vessel persists indefinitely

- - the in vessel retention strategy is analyzed considering only representative enveloping configurations and performing quantification of uncertainties.

The first configuration appropriate (Fig.1) for detailed examination and quantification is the following:
-all the corium (as a solid oxidic crust or a molten oxidic pool) is contained in the bottom head
-a molten steel layer, due to the steel components of the core region, is located on the top of the crust of the oxidic-pool.

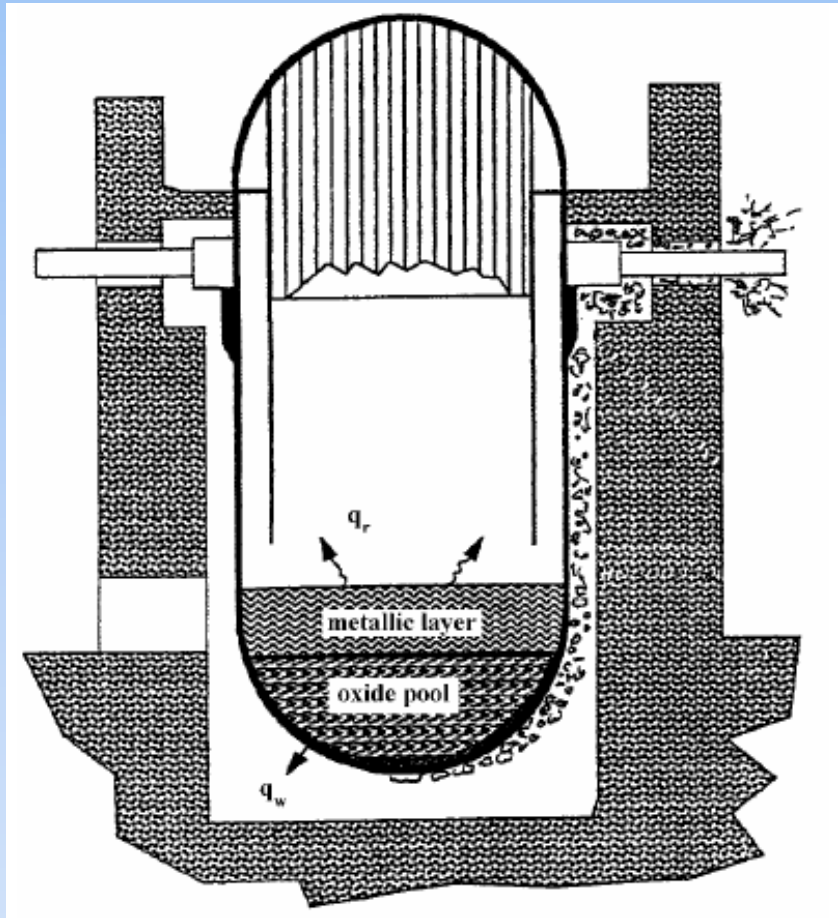


Fig. 1 Configuration showing the final state of the in-vessel retention scenario [1° configuration -Theofanous Nucl.Eng. Des.vol 169-1998]

PHYSICAL PROBLEMS ASSUMPTIONS

The failure mechanism of the bottom head is the ‘ Boiling Crisis’ :

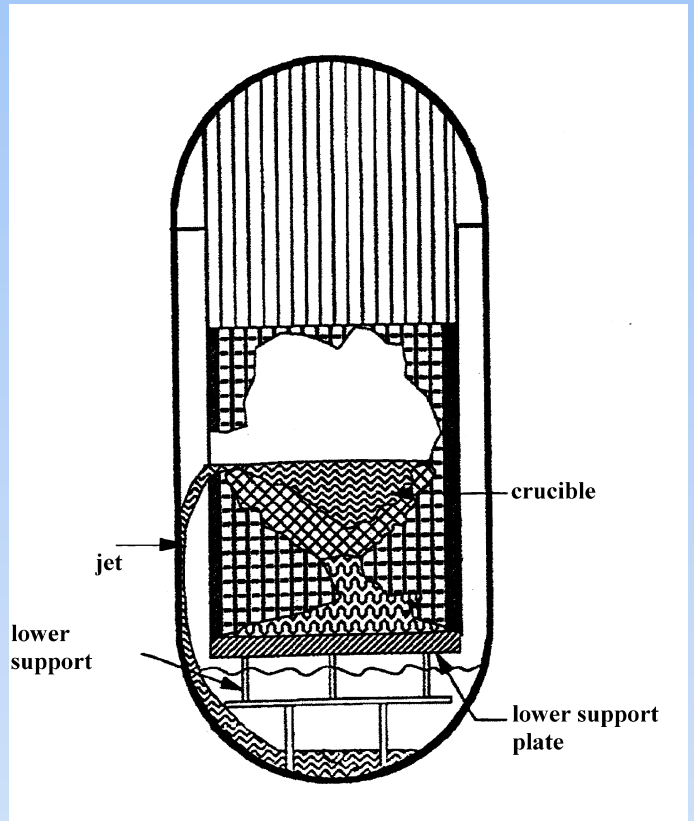
-the heat flux exceeds the Critical Heat Flux (CHF) and it determines a sudden transition of the flow regimen from nucleate to film boiling.

As consequence the surface temperature rises at very high values of temperature (as example : the film boiling determines a surface temperature of 1200°C in order to transfer, in saturated water, a heat flux of 400 Kw/m^2 ; while in the nucleate boiling , for the same heat flux the surface temperature is equal about at 100°C).
At the high surface temperature , occurred in the boiling crisis, the steel loses its strength and it could fails for creep or for structural instability.

PHYSICAL PROBLEMS TO BE ADDRESSED

The second configuration taken into consideration by Theophanous (Fig.2) involves a ‘wall jet’ released from the top of the molten core pool, through the downcomer and into the bottom head.

In fact the melting and freezing phenomena (corium melts in the inner higher power density region and freezes when it relocates in the outer colder region) forms a sort of crucible above the Lower Support Plate. The failure of this crucible, located inside the core, determines a discharge dominated by forced convection and impingement effects



2° configuration which occurs before the final relocation of the Corium in the bottom head

PHYSICAL PROBLEMS TO BE ADDRESSED

Theophanous demonstrated that assuming the primary system depressurized, the bottom head is able to sustain the stresses caused also from a very high heat flux equal to the critical heat flux if the heat transfer mechanism remains the nucleate boiling and therefore the Boiling Crisis does not occur.

Nevertheless, the enormous research work that Theophanous and his colleagues have performed is excellent from the thermal hydraulic, the heat transfer in the Corium and the risk analysis point of view but it is less exhaustive from the structural point of view.

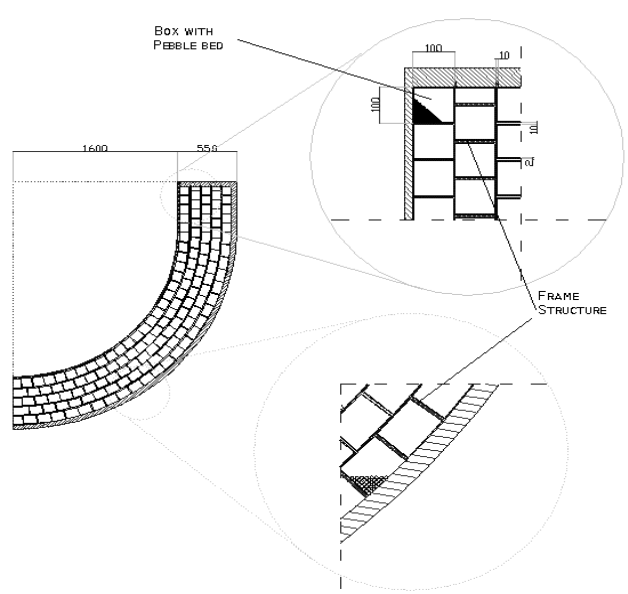
International Experts, who reviewed the structural aspects, considered the performed analyses very crude.

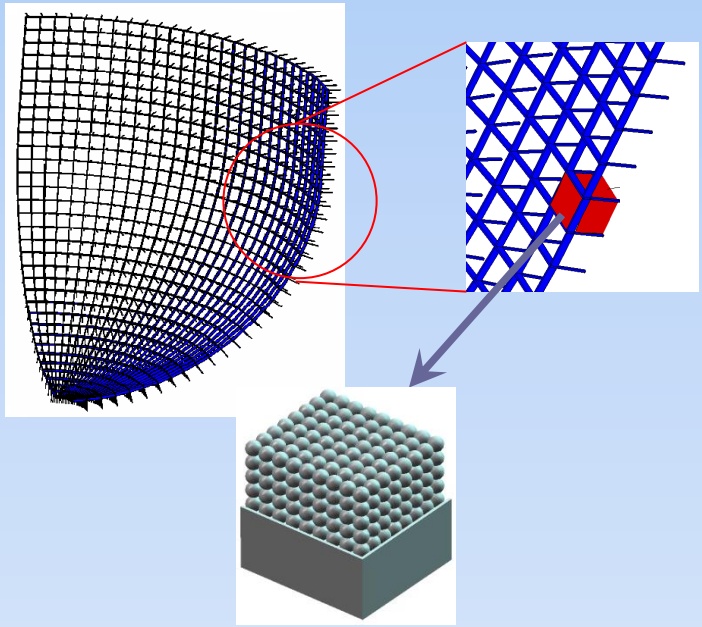
Actually, the TMI-II accident , which produced a partial core meltdown and its relocation on the bottom vessel, demonstrated that the Corium has been cooled and retained in the vessel without producing failures. But this accident does not assure that these failures did not occur by a lucky chance.

PHYSICAL PROBLEMS TO BE ADDRESSED

An internal core catcher could avoid the contact between Corium and bottom head or at least to delay this contact in manner that the decay power decreases and the emergency cooling systems can enter in operation.

The envisaged solution of core catcher is made of alumina pebble bed, located in alumina boxes. The boxes are assembled like bricks of masonry.
The alumina pebble beds have an high refractoriness and they can accommodate the thermal expansion without developing high thermal stresses.



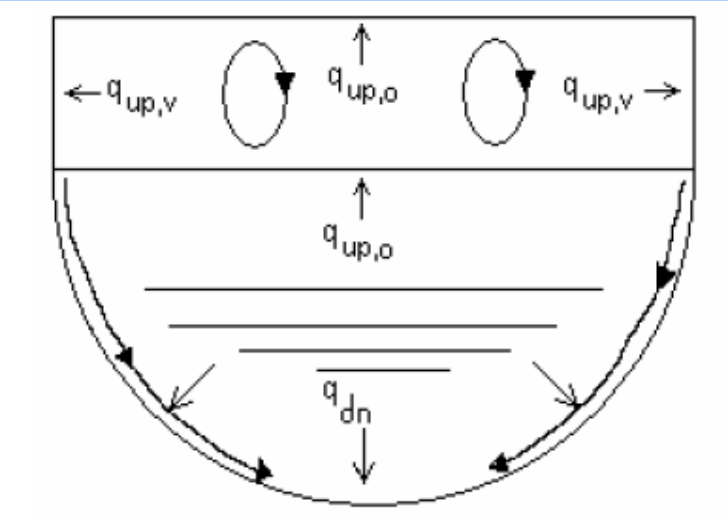


PHYSICAL PROBLEMS TO BE ADDRESSED

The thermal analysis of core catcher can exploit the results obtained by Theophanous for the first configuration examined. In fact the heat transfer mechanism in the Corium are similar.

The energy partition between the upper part and lower part is different because the core catcher has a thermal resistance about one thousand times greater than of the bottom head.

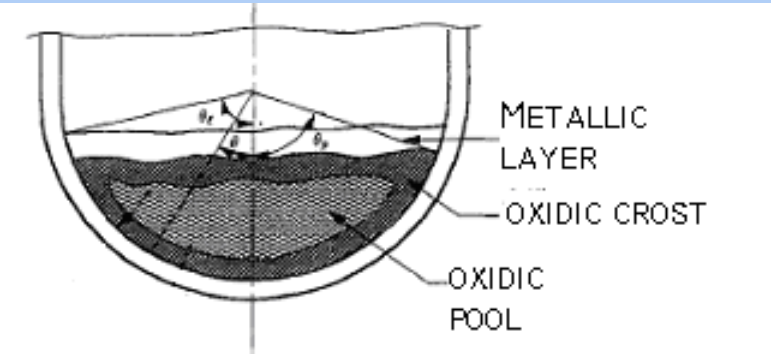
Moreover the thermal hydraulic aspects, related to the natural convection in the flooded reactor cavity, are not relevant for the case in exam.



Heat flux path on core catcher and basic features of the flow regime in the oxidic pool

HEAT TRANSFER MECHANISMS IN THE CORIUM

Theophanous considers an AP600 reactor. The first configuration is characterized by the bottom head filled by the oxide pool up to $\theta_p \cong 75°$, while the metal layer , located on the top, reaches the equatorial position ($\theta_1 \cong 90°$).



In this application, the dimensionless groups (Rayleigh and Prandl numbers) ranges are:

- oxidic pool: $10^{15} < Ra' < 6\ 10^{15}$ $Pr \cong 0.6$
- metallic layer $5\ 10^{9} < Ra < 2\ 10^{10}$ $Pr \cong 0.1$

the Rayleigh number is given:

-in the metallic layer (without volumetric heating)

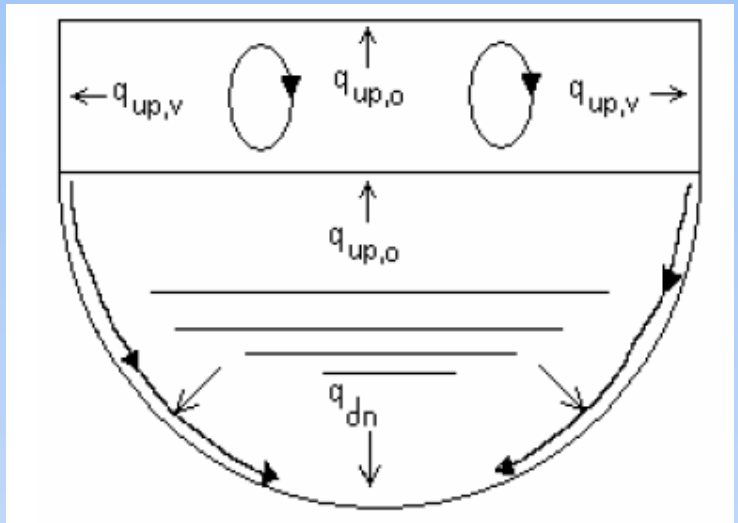
$$Ra = Gr\,\mathrm{Pr} = \frac{g\beta\Delta T H^3}{\nu^2}\frac{\nu}{\alpha} = \frac{g\beta\Delta T H^3}{\nu\alpha}$$

-in the oxidic pool (with volumetric heating) Ra'=GrPrDa

$$Ra' = GrDa\,\mathrm{Pr} = \frac{g\beta\Delta T H^3}{\nu^2}\frac{\dot{Q} H^2}{k\Delta T}\frac{\nu}{\alpha} = \frac{g\beta\dot{Q} H^5}{\nu\alpha k}$$

where Gr, Pr and Da are the Grashof, Prandl and Dammkohler dimensionless number,

HEAT TRANSFER MECHANISMS IN THE CORIUM



Property	Oxide phase	Metallic phase
Melting temperature (K)	2973	1600
Densityρ (Kg/m^3)	8740	7020
Thermal conductivity k (w/mK)	5.3	32
Viscosity μ(Pa s)	5.3 10^{-3}	4.096 10^{-3}
Specific heat cp (J/KgK)	485	835
Volume thermal expansion coefficient β (1/K)	1.05 10^{-4}	1.1 10^{-4}

The basic features of the flow regime in the oxidic pool are: a steep boundary layer adjacent to the boundary, a well mixed upper pool volume and a broadly stratified lower pool portion.

g acceleration of gravity (9.8 m/s^2);α thermal diffusivity
β volumetric thermal expansion; $\nu=\mu/\rho$ kinematic viscosity
μ viscosity;ρ density;k thermal conductivity; H oxidic pool height;
H_1 metallic layer height; R internal radius of core catcher
s_{cc} thickness of core catcher

Subscripts

Cc core catcher; l,I metallic layer in contact with the oxide pool
l,o upper surface of metallic layer

HEAT TRANSFER MECHANISMS IN THE CORIUM

The heat flux towards the upper boundary (flat region) is obtained by the relation of Steinberner-Reineke [3]:

$$Nu_{up} = 0.345 Ra'^{0.233} \qquad (1)$$

valid for 10^7<Ra'<3 10^{13} Pr ≅7 This formula can be extrapolated at the range of interest on the basis of Theofanous' assumptions that is, the phenomenon is independent of the Prandtl number. This assumption has been verified in various tests (mini-ACOPO experiments[5]).

The heat transfer towards the hemispherical boundary can be determined by the following relations:

(Mayinger et alii [4]) for 7 10^6<Ra'<5 10^{14} Pr ≅0.5 $Nu_{dn}=0.55Ra'^{0.2}$ *(2)*

(mini-ACOPO experiments[5]) 3 10^{13}<Ra'<7 10^{14},2.6<Pr<10.8 $Nu_{dn}=0.0038Ra'^{0.35}$ (3)

While the heat flux distribution along the hemispherical boundary- (mini-ACOPO experiments[5])

- for $0.1\theta_p \le \theta \le 0.6\theta_p$

$$\frac{Nu_{dn}(\theta)}{Nu_{dn}} = 0.1 + 1.08\left(\frac{\theta}{\theta_p}\right) - 4.5\left(\frac{\theta}{\theta_p}\right)^2 + 8.6\left(\frac{\theta}{\theta_p}\right)^3 \qquad (4a)$$

HEAT TRANSFER MECHANISMS IN THE CORIUM

for *0.6* $\theta_p \le \theta \le \theta_p$

$$\frac{Nu_{dn}(\theta)}{Nu_{dn}} = 0.41 + 0.35\left(\frac{\theta}{\theta_p}\right) + \left(\frac{\theta}{\theta_p}\right)^2 \qquad (4b)$$

The previous relations allow us to determine the energy partition from the oxidic pool to the upper flat zone and to the lower hemispherical zone. In addition, the local heat flux along the hemispherical boundary can be calculated by the relations (4).

Heat transfer mechanisms which affect the metallic layer :

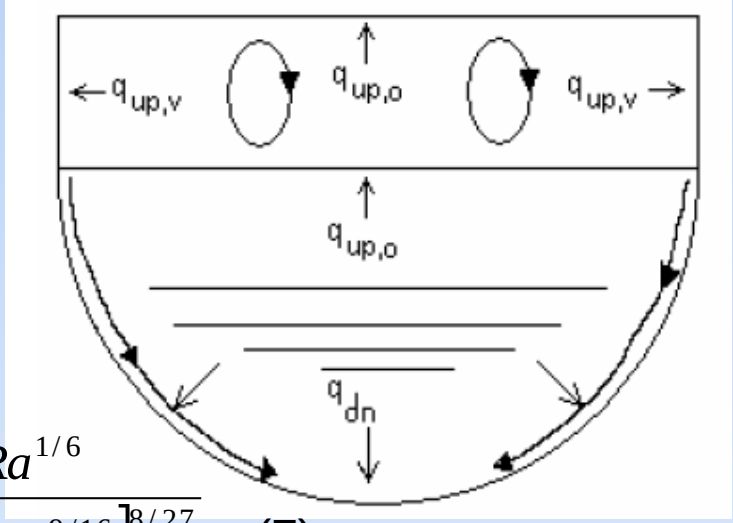
- natural convection in the liquid layer heated from below and cooled on the top
- natural convection to a vertical, cooled wall

The first mechanism can be described by the Globe and Dropkin [6] correlation: for $3 10^5 < Ra < 7 10^9$ $0.02 < Pr < 8750$

$$Nu = 0.069 Ra^{1/3} \Pr^{0.074} \qquad (5)$$

This correlation for *Pr=0.13* becomes:

$$Nu = 0.059 Ra^{1/3} \qquad (6)$$



The heat transfer for the second mechanism can be obtained from the Churchill and Chu [7] correlation: (valid for any Prandl number and $Ra < 10^{12}$)

$$Nu^{1/2} = 0.825 + \frac{0.387 Ra^{1/6}}{\left[1 + (0.492/\Pr)^{9/16}\right]^{8/27}} \qquad (7)$$

HEAT TRANSFER MECHANISMS IN THE CORIUM

The correlation (7), neglecting the term 0.825 and for *Pr=0.13*, becomes:

$$Nu = 0.076 Ra^{1/3} \qquad (8)$$

Theofanous Procedure for Calculating the Heat Flux at Core Catcher Internal Surface

On the basis of the previous correlations and using a global energy balance, Theofanous determined the heat flux q_{dn} and q_{up}, that the oxidic pool applies to the bottom head and the upper part.

Following Theofanous' schema, first we calculated the decay power partition between the core catcher and the metallic layer. Then we considered the vessel external wall as isothermal boundary, at a temperature T=400 K (temperature related to the water in the reactor cavity).

From an overall energy balance on a hemispherical oxidic pool (volume V and decay power Q (Mw/m^3)) we obtained:

$$QV = q_{up}S_{up} + q_{dn}S_{dn} = q_{dn}S_{dn}\left(1 + \frac{q_{up}S_{up}}{q_{dn}S_{dn}}\right) = q_{dn}2\pi R^2(1 + 0.5R')$$

HEAT TRANSFER MECHANISMS IN THE CORIUM

Therefore

$$q_{dn} = \frac{QR}{3(1+0.5R')} \qquad q_{up} = \frac{QR}{3(1/R'+0.5)}$$

where
the ratio R'= q_{up}/q_{dn} is in inverse proportion to the respective effective thermal resistance $S_{dn}=2\pi R^2$ and $S_{up}=\pi R^2$.
The decay heat power was estimated using the 19979 ANS 5.1 standard curve [5]: $P = 0.125 P_o t^{-0.28}$

Where P_o (Mw) is the nominal thermal power (3300 Mw) and t (sec) is the time elapsed after the scram.
We considered that:
- the decay heat is constant and equal to 12 MW and that this corresponds to the power two days after the scram
- only the 70% of this power is contained in the corium, because the 30% is the fraction associated with the gaseous fission products and therefore can be considered removed from the pressure vessel.

Assuming that the total volume of the corium is equal to 8.6 m^3, then Q is equal to 1.4 MW/m^3.

HEAT TRANSFER MECHANISMS IN THE CORIUM

Effective Thermal Resistance Along the Path Oxidic Pool-Core Catcher – Bottom Vessel

There are three thermal resistances in the path oxidic pool-core catcher – bottom vessel:

- resistance at the boundary layer between the oxidic pool and core catcher
- resistance due to the conduction in the wall of the core catcher
- resistance due to the radiation at the external surface of the core catcher

The heat transfer coefficient at the boundary layer between the oxidic pool and the core catcher is calculated using the correlation (2): $Nu_{dn}=0.55Ra'^{0.2}$

which becomes:

$$Nu_{dn}=\frac{h_{dn}H}{k}=0.55\left\{\frac{g\beta QH^5}{\nu\alpha k}\right\}^{0.2} \qquad h_{dn}=\frac{1}{R_{dn}}=0.55\left\{\frac{g\beta Qk^4}{\nu\alpha}\right\}^{0.2}=2375\cdot w/m^2K$$

The thermal resistance due to the conduction in the wall of core catcher is: $R_{cc}=s_{cc}/k_{cc}=5\ m^2K/W$

The heat transfer coefficient due to the radiation at the external surface of the core catcher can be estimated following McAdams [8]: the heat flux due to the radiation is

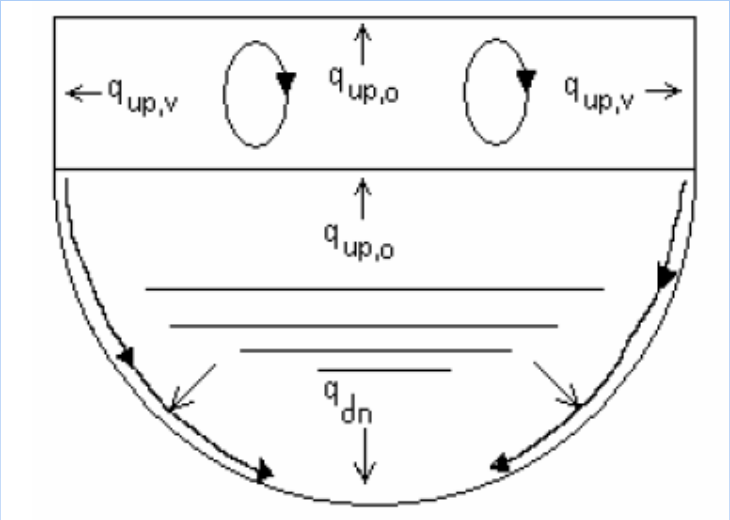
$$\sigma\varepsilon(T_{cc,dn}^4-T_w^4)=\sigma\varepsilon(4+n)\frac{(T_{cc,dn}+T_w)^3}{8}(T_{cc,dn}-T_w)$$

HEAT TRANSFER MECHANISMS IN THE CORIUM

Effective Thermal Resistance Along the Path Oxidic Pool-Core Catcher – Bottom Vessel

an effective heat transfer coefficient is:

$$h_r = \frac{1}{R_r} = \sigma\varepsilon(4+n)\frac{(T_{cc,dn}+T_w)^3}{8} = 6W/m^2K$$



assuming ε=0.4, $T_{cc,dn}$=410 K, T_w=400 K, n=0.5.

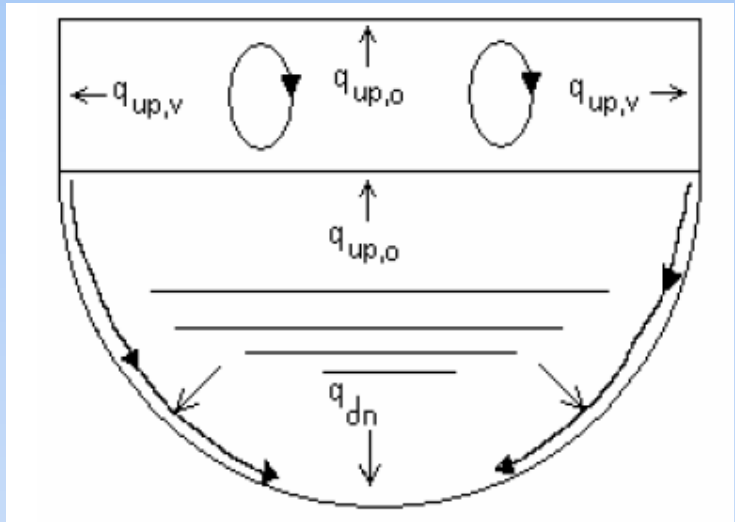
Therefore the effective resistance in the path oxidic pool-core catcher – bottom vessel is:

$$R_{e,dn}=R_{dn}+R_{cc}+R_r=5.1671\ m^2K/w$$

HEAT TRANSFER MECHANISMS IN THE CORIUM

- Effective Thermal resistance along the path oxidic pool-metallic layer –upper wall of the vessel

There are two paths of the heat flux q_{up} that should be considered:
- from the oxidic pool to the cylindrical surface of the core catcher ($q_{up,v}$)
- from the oxidic pool to the upper surface of the metallic layer ($q_{up,o}$)



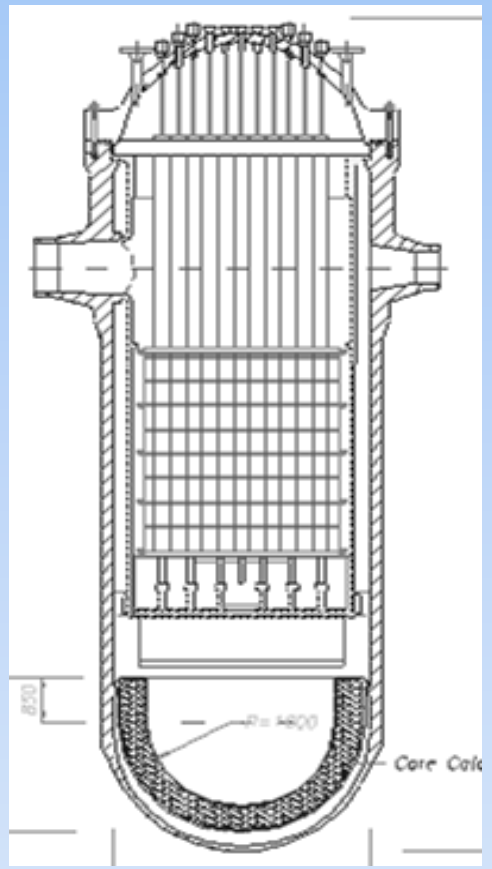
The heat flux $q_{up,v}$ has five thermal resistances:
- at the boundary layer between the oxidic pool and the metallic layer
- at the lower boundary of the metallic layer
- at the boundary of the cylindrical surface of the core catcher
-resistance due to the conduction in the wall of the core catcher
- resistance due to the radiation at the external surface of the core catcher

The heat transfer coefficient at the boundary layer between the oxidic pool and the metallic layer is given by eq. 1) , which can be written

$$Nu_{up} = \frac{h_{up}H}{k} = 0.345\left\{\frac{g\beta QH^5}{\nu\alpha k}\right\}^{0.233} \Longrightarrow h_{up} = \frac{1}{R_{up}} = 0.345\frac{k}{H}\left\{\frac{g\beta QH^5}{\nu\alpha k}\right\}^{0.233} = 4864 \cdot W/m^2K$$

HEAT TRANSFER MECHANISMS IN THE CORIUM

- Effective Thermal resistance along the path oxidic pool-metallic layer –upper wall of the vessel



The heat transfer coefficient at the lower boundary of the metallic layer is given by eq. 6)

$$Nu = 0.059 Ra^{1/3} \longrightarrow h_{l,i} = \frac{1}{R_{l,i}} = 0.059 k \left\{ \frac{g\beta\Delta T}{\nu\alpha} \right\}^{1/3} = 13875 W/m^2K$$

The heat transfer coefficient at the boundary of the cylindrical surface of core catcher is given by Eq. 8)

$$Nu = 0.076 Ra^{1/3} \longrightarrow h_{l,v} = \frac{1}{R_{l,v}} = 0.076 k \left\{ \frac{g\beta\Delta T_2}{\nu\alpha} \right\}^{1/3} = 9911 W/m^2K$$

The last two resistances are similar at those of the hemispherical core catcher . These are:

- The thermal resistance due to the conduction in the wall of core catcher:

$$R_{cc}=s_{cc}/k_{cc}=5\ m^2K/W$$

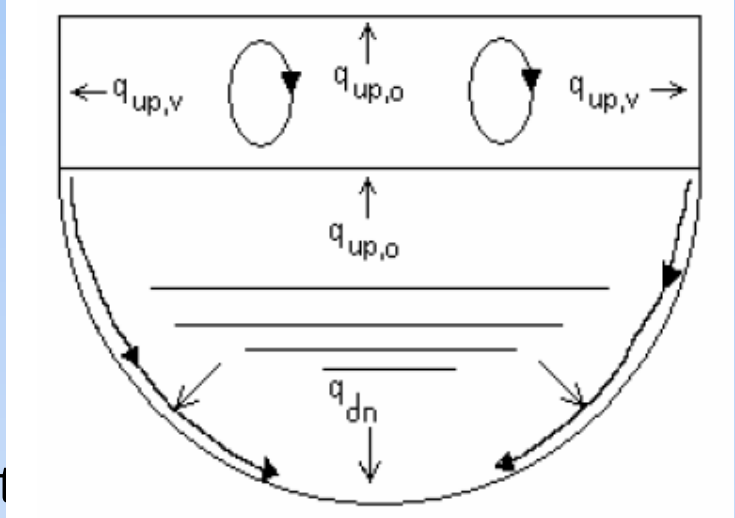
- The effective heat transfer coefficient for radiation: $h_r = \frac{1}{R_r} = 8 W/m^2K$

HEAT TRANSFER MECHANISMS IN THE CORIUM

- Effective Thermal resistance along the path oxidic pool-metallic layer –upper wall of the vessel

Therefore the effective resistance in the path 'oxidic pool-to the cylindrical surface of core catcher' is:

$$R_{e,up,v}=R_{up}+R_{l,i}+R_{l,v}+R_{cc}+R_r=5.1254\ m^2K/W$$



The heat flux $q_{up,o}$ has four thermal resistances .

a) at the boundary between the oxidic pool and the metallic layer

b) at the lower boundary of the metallic layer

c) at the upper boundary of the metallic layer

d) Resistance due to the radiation at the external surface of the core cat

The first two are the same resistances calculated for the heat flux $q_{up,v}$.

The heat transfer coefficient at the upper boundary of the metallic layer is given by eq. 6) (considering a ΔT=154K, between the bulk of the metallic layer, assumed to be at 2950 K, and the upper boundary, assumed at 2800 K)

$$Nu = 0.059 Ra^{1/3} \longrightarrow h_{l,o} = \frac{1}{Ro} = 0.059k\left\{\frac{g\beta\Delta T}{\nu\alpha}\right\}^{1/3} = 7694 W/m^2K$$

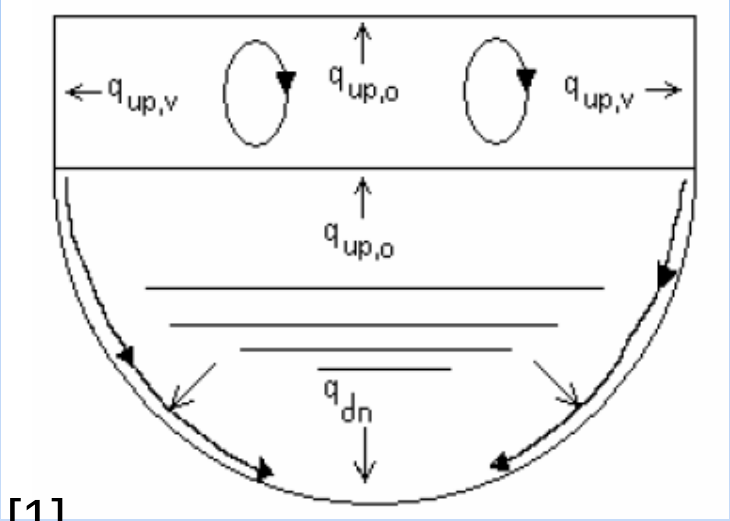
HEAT TRANSFER MECHANISMS IN THE CORIUM

- Effective Thermal resistance along the path oxidic pool-metallic layer –upper wall of the vessel

The effective heat transfer coefficient, due to the radiation at the upper surface of metallic layer can be estimated as :

$$h_r = \frac{1}{R_r} = 600 W / m^2 K$$

assuming that ε=0.4, $T_{l,o,up}$ =2800 K, T_w=400 K



A wall temperature of 400 K is a plausible temperature because the flux through the vessel wall is assumed to be lower than the critical heat flux [1].
The effective resistance in the path oxidic pool-core catcher – upper boundary of the metallic layer vessel is:

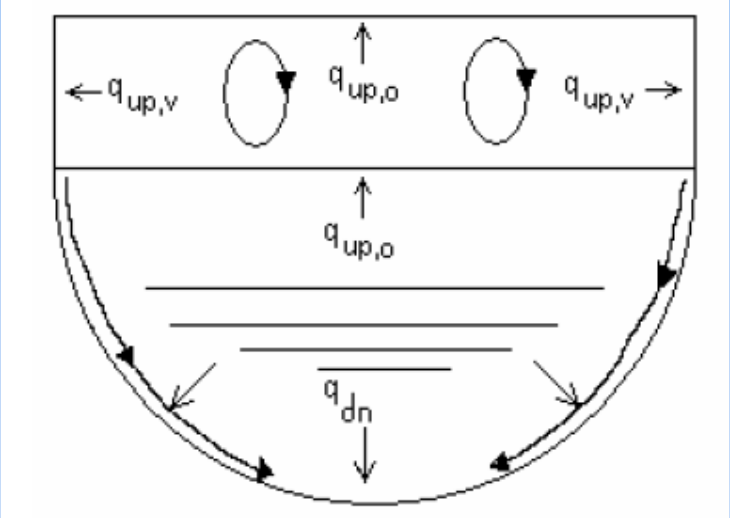
$$R_{e,up,o} = R_{up} + R_{l,i} + R_{l,o} + R_r = 0.0021\ m^2K/W$$

HEAT TRANSFER MECHANISMS IN THE CORIUM

- Effective Thermal resistance along the path oxidic pool-metallic layer –upper wall of the vessel

Therefore an energy balance, relative to the heat flux q_{up}, allows us to calculate the energy partition between the horizontal upper metallic boundary and the vertical one, adjacent to the core catcher wall:

$$q_{up}\pi R^2 = q_{up,o}\pi R^2 + q_{up,v}2\pi R H_1 = q_{up,o}\pi R^2\left(1+\frac{q_{up,v}2H_1}{q_{up,o}R}\right) = q_{up,o}\pi R^2(1+Q_r)$$



$$q_{up,o} = \frac{q_{up}}{(1+Q_r)} = 0.9996 q_{up} \quad \Rightarrow \quad q_{up,v} = \frac{Q_r q_{up}}{(1+Q_r)} = 0.0004 q_{up}$$

where $Q_r = q_{up,v} / q_{up,o} = R_{e,up,o} / R_{e,up,v} = 0.0004$

The total thermal resistance relative to the heat flux q_{up} is obtained by the rule of composition of parallel thermal resistances:

$$\frac{1}{R_{e,up}} = \frac{1}{R_{e,up,o}} + \frac{1}{R_{e,up,v}}$$

thus $\boldsymbol{R_{e,up,} = 0.0021\ m^2K/w}$

HEAT TRANSFER MECHANISMS IN THE CORIUM

-Energy Partition Between the Upper and Lower Parts of the Oxidic Pool

The energy partition between the upper and lower parts of the oxidic pool can be calculated once the respective thermal resistances have been determined, that is

$$R' = q_{up} / q_{dn} = R_{e,dn} / R_{e,up,} \quad = 2461$$

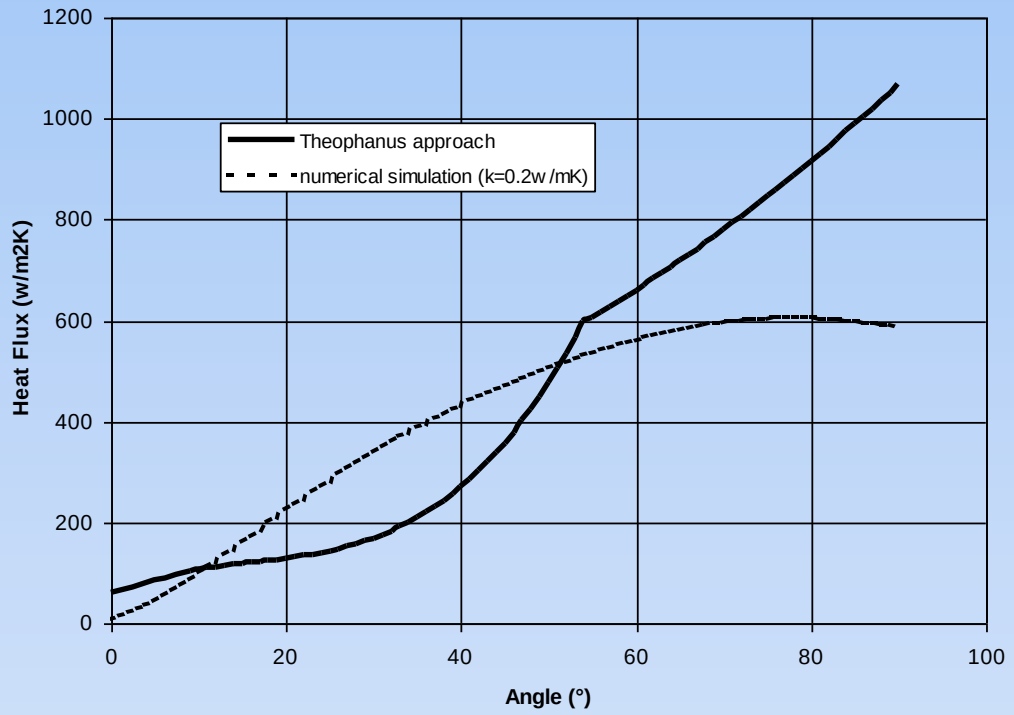
and the energy partition is:

$$q_{dn} = \frac{QR}{3(1+0.5R')} = 2.71 \cdot 10^{-4} QR = 606 W/m^2$$

$$q_{up} = \frac{QR}{3(1/R'+0.5)} = 0.66613 QR = 1.492 MW/m^2$$

MAIN RESULTS : the high thermal resistance of core catcher forces the transfer of all the power of the Corium toward the upper surface.

If the thermal resistance of the core catcher is reduced by one order of magnitude, there is no appreciable variation in the energy partition.



distribution of the heat flux along the angular position of the core catcher (relations 4a) and 4b)

HEAT TRANSFER MECHANISMS IN THE CORIUM

The maximum temperature of the oxidic pool strongly depends on the effective heat transfer coefficient at the horizontal upper part.

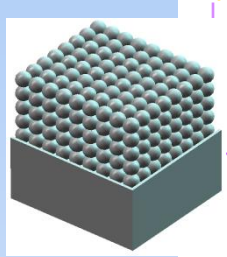
In the examined case: the vessel wall temperature is assumed to be $T_w=400\ K$, and the maximum temperature of the Corium is $T_{max}=3533\ K$.

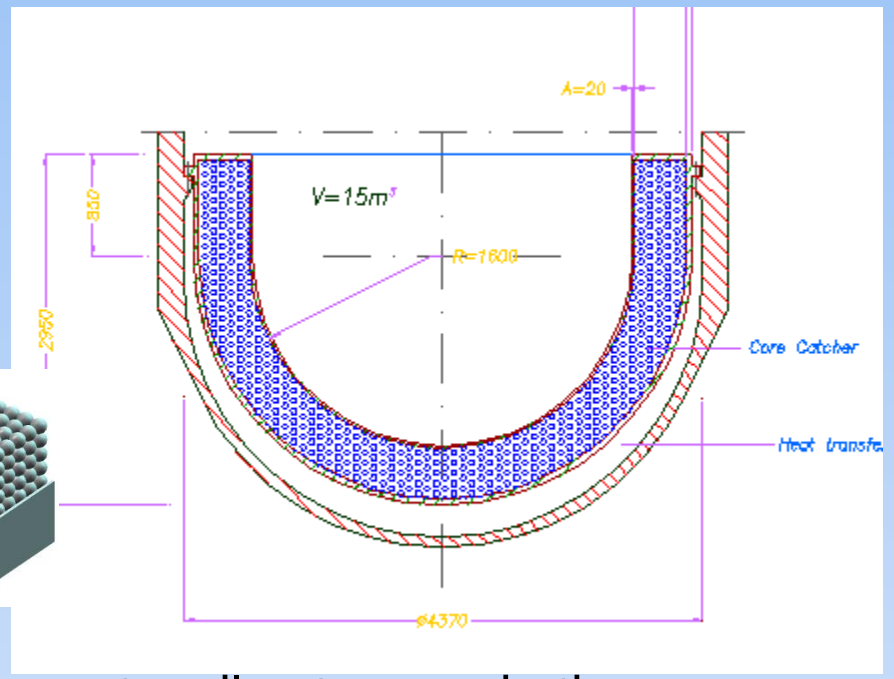
If the effective heat transfer coefficient at the horizontal upper part doubles (from 600 to 1200 w/m2K), the effective thermal resistance becomes $R_{e,up}=0.00127\ m^2K/w$.

This value does not produce any variation in the energy partition, but the maximum Corium temperature becomes $T_{max}=2290\ K$.
This results highlight that the Corium may be safely contained in a core catcher which works as a crucible as long as it is guaranteed an adequate cooling of the upper part of the metallic layer.

CORE CATCHER DESIGN

- The high thermal resistance of the core catcher is due to the alumina pebble bed located inside boxes made of alumina sheets (2 mm thick).
- The pebble bed reduces the conductivity of the material by one order of magnitude and it allows the material to expand without producing thermal stresses.





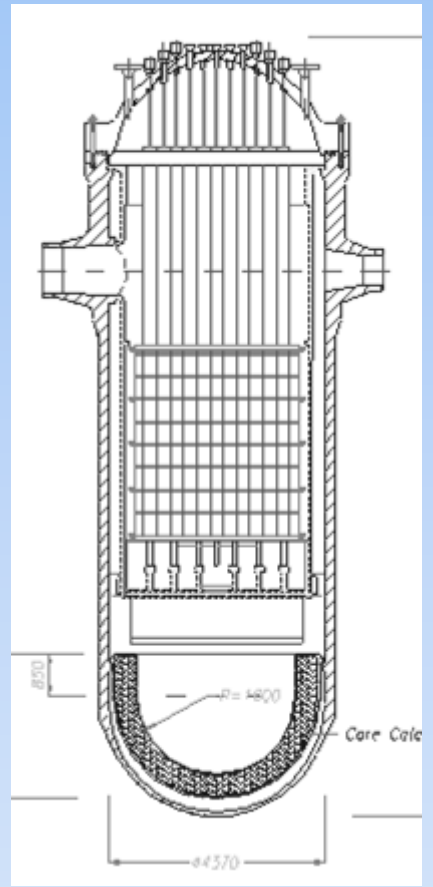
The high temperature gradient in a monolithic structure causes tensile stresses in the colder zone, which could lead at cracking and at the consequent failure of the structure.

The core catcher is 500 mm thick and is externally lined by high alloy steel plates (internal and external liners 20mm and 50mm thick, respectively). The internal cavity is filled with the pebble bed boxes (about 100x100x100mm).

CORE CATCHER DESIGN

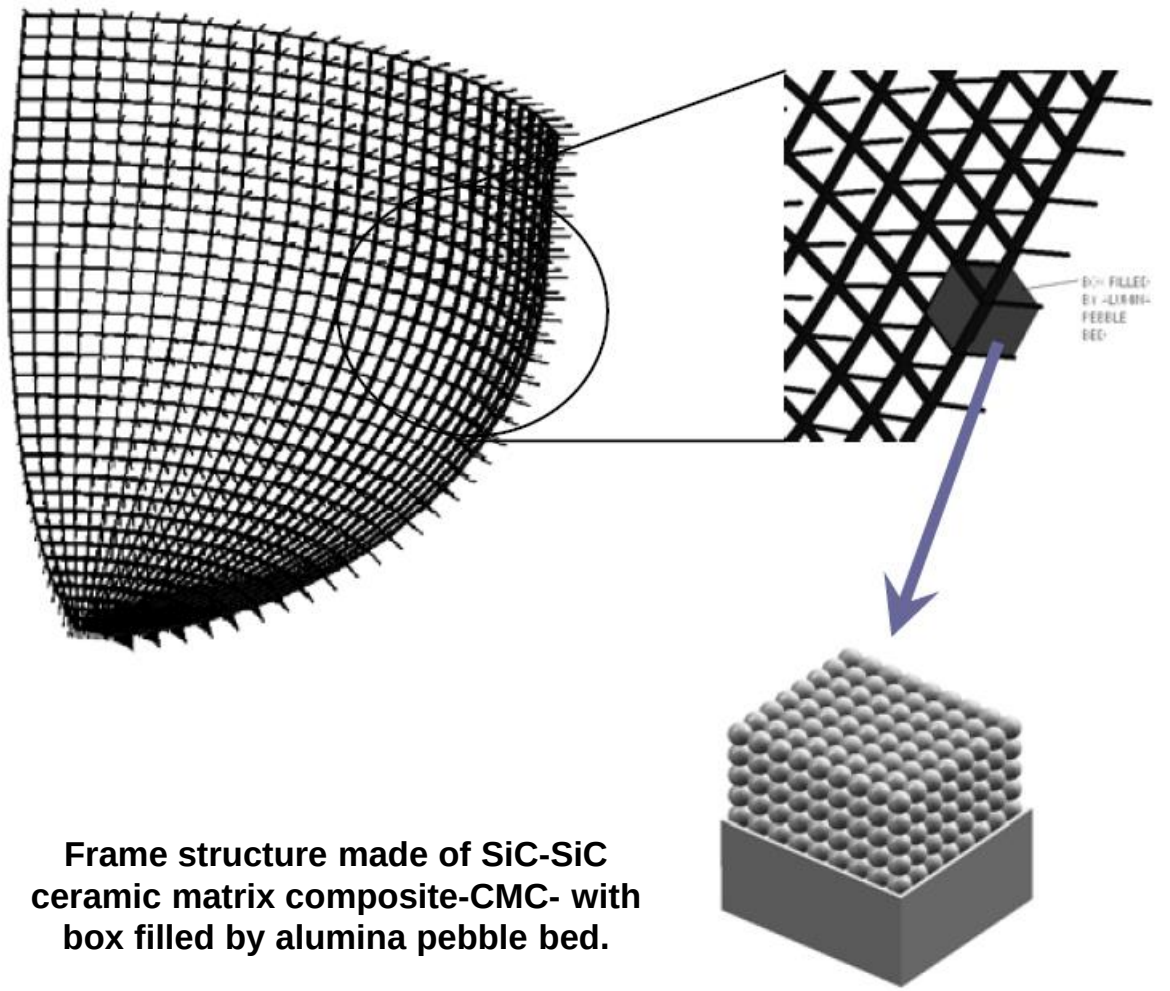
- The amount of corium has been determined for a complete meltdown of 1000 MWe PWR core.

- For a core catcher with a net volume of 15m^3, the height of the pressure vessel can be increased by about 2.5m while the diameter remains unchanged.



CORE CATCHER DESIGN

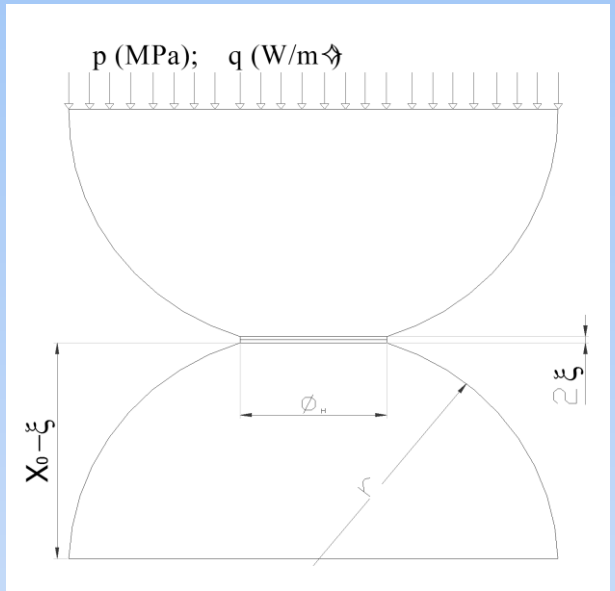
- The boxes are supported by SiC-SiC frameworks
- These frameworks are designed to give the core catcher a structural resistance until the fusion temperature of alumina is reached.
- This ceramic matrix composite is a new material so its possible use in the nuclear field should be analyzed from a nuclear and chemical point of view.
- The interaction between Corium and alumina should be studied in detail in order to assess their chemical compatibility.



Frame structure made of SiC-SiC ceramic matrix composite-CMC- with box filled by alumina pebble bed.

CORE CATCHER DESIGN: THEORETICAL MODEL

The core catcher behaviour during corium relocation depends on the effective thermal conductivity (λ_{eq}) and stiffness (K_{eq}) of the pebble bed.
The authors have developed an elastic plastic model which allows to determine the stiffness and conductivity versus the strain of the generic pebble bed. [9,10]



Two spheres in contact under pressure (P) and heat flux (q)

The effective thermal resistance, R_{eq}, and the effective conductivity, λ_{eq},of two half spheres are given by:

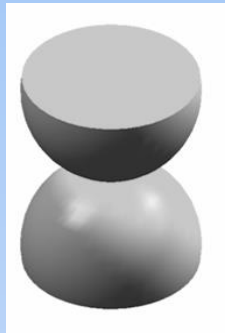
$$R_{eq} = \frac{2\pi}{3x_o} \cdot \frac{2\xi}{\lambda} \sqrt[3]{\frac{0.06E^2r^7}{P^2}} + \frac{2r^2}{3x_o\lambda} \ln\left(\frac{1+\left(\frac{x_o-\xi}{r}\right)^2}{1-\left(\frac{x_o-\xi}{r}\right)^2} \right)$$

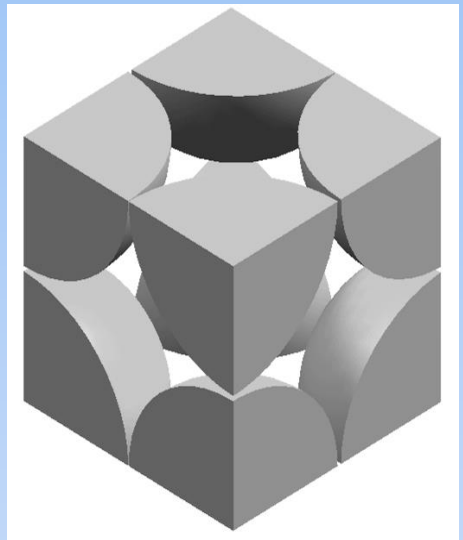
$$\lambda_{eq} = \frac{2x_o}{R_{eq}} \cdot = \frac{2x_o}{\frac{2\pi}{3x_o} \cdot \frac{2\xi}{\lambda} \sqrt[3]{\frac{0.06E^2r^7}{P^2}} + \frac{2r^2}{3x_o\lambda} \ln\left(\frac{1+((x_o-\xi)/r)^2}{1-((x_o-\xi)/r)^2} \right)}$$

- R_{eq}: effective thermal resistance; • x_o: height of compressed half sphere ; • E: alumina Young modulus;
- λ: thermal conductivity of sphere;

NUMERICAL ANALYSIS: CORE CATCHER MODELLING

Effective thermal resistance of a simple cubic lattice





Geometrical equivalence between two half spheres in contact and a simple cubic lattice (packing factor γ =0.5236)

From the rules of the thermal resistances connected in series or parallel, it is possible to extend the previous results to a pebble bed characterized by different values of the packing factor γ.

A pebble bed can be considered as being made of a mixture of regular lattices (simple cubic, cubic centred body, cubic centred face).

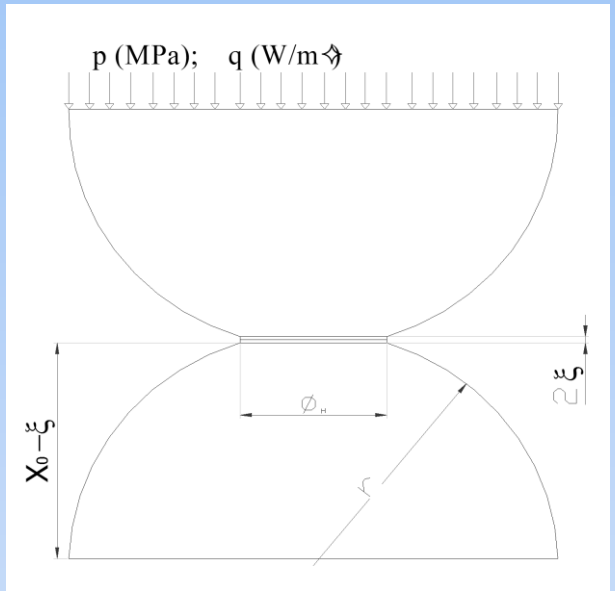
In the following example we consider a bed made only of a simple cubic lattice, the packing factor of which is =0.5236.

$$\lambda_{eq}^{sc} = \frac{2x_o}{R_{eq}}\frac{\pi}{6}\cdot = \frac{2x_o}{\frac{4}{x_o}\cdot\frac{2\xi}{\lambda}\sqrt[3]{\frac{0.015\cdot E^2 r^7}{P^2}} + \frac{4r^2}{\pi x_o \lambda}\ln\left(\frac{1+((x_o-\xi)/r)^2}{1-((x_o-\xi)/r)^2}\right)}$$

CORE CATCHER DESIGN: THEORETICAL MODEL

Effective stiffness of the assembly of two half spheres compressed by a load P in elastic regimen

The stresses and the area of contact between the spheres are calculated on the basis of the Hertz theory. The elastic phase ends when the contact stress reaches the yielding stress.
By calculating the stress and strain distribution of spheres, we can obtain the equivalent stiffness of spheres:



Two spheres in contact under pressure (P) and heat flux (q)

$$Keq = P / 2u_{\max} = \frac{P}{2(r - x_o) + \sigma_0 r \ln\left((1 + x/r)/(1 - x/r)\right)/E}$$

The effective stiffness of a simple cubic lattice is reduced by the factor $\pi/6$ in order to take into account the presence of the void space.

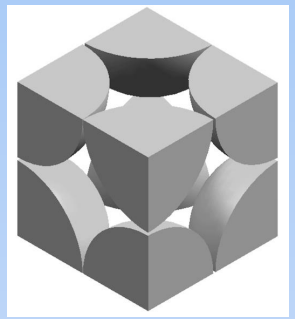
NUMERICAL ANALYSIS: THERMAL ANALYSIS OF THE CORE CATCHER

The pebble bed core catcher has been analysed using an FEM code considering the scenario called ‘first configuration’ which represents the final state of Corium relocation.

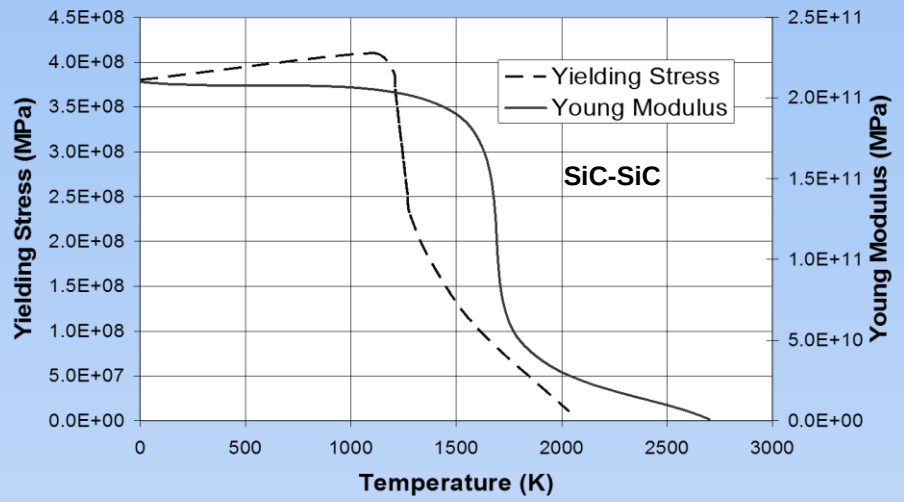
The analyzed simulations concern the most severe conditions which consist of:

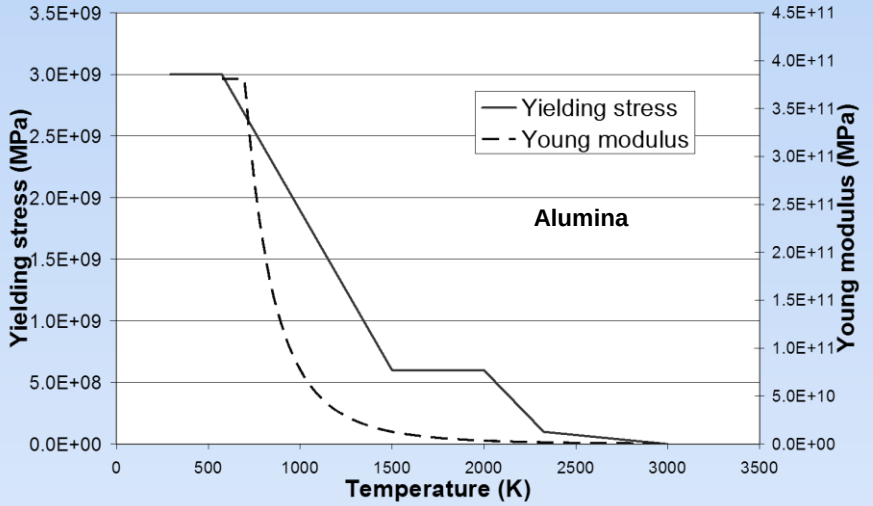
- Heat flux on the internal hemispherical surface calculated by means of a heat transfer coefficient of 2375 W/m^{2}K and a bulk oxidic pool temperature of 3500 K
- Heat flux on the internal cylindrical surface calculated using a heat transfer coefficient of 9911 W/m^{2}K and a bulk metallic layer temperature of 2954 K;
- Core catcher cooling on the external hemispherical surface obtained using a heat transfer coefficient of 6 W/m^{2}K and a bulk coolant temperature of 400 K
- Core catcher cooling on the external cylindrical surface obtained by means of a heat transfer coefficient of 8 W/m^{2}K and a bulk coolant temperature of 400 K.

NUMERICAL ANALYSIS: CORE CATCHER MODELLING



Property	Material		
	Alumina pebble bed	SiC-SiC	High alloy steel
Density, ρ	3970 Kg/m^3	2900 Kg/m^3	7800 Kg/m^3
Specific heat, c_p	1560 J/Kg K	2100 J/Kg K	514 J/Kg K
Fusion temperature, T_f	2318 K		
Conductivity, λ	0.5-0.25 w/mK	10 w/mK	30 W/mK
latent fusion heat, h	3577 KJ/Kg		
Young Modulus, E	380000 MPa	210000 MPa	196500 MPa
Shear Modulus, G		80000 MPa	
Comp.yielding strength, σ_y	3000 MPa	300 MPa	173 MPa

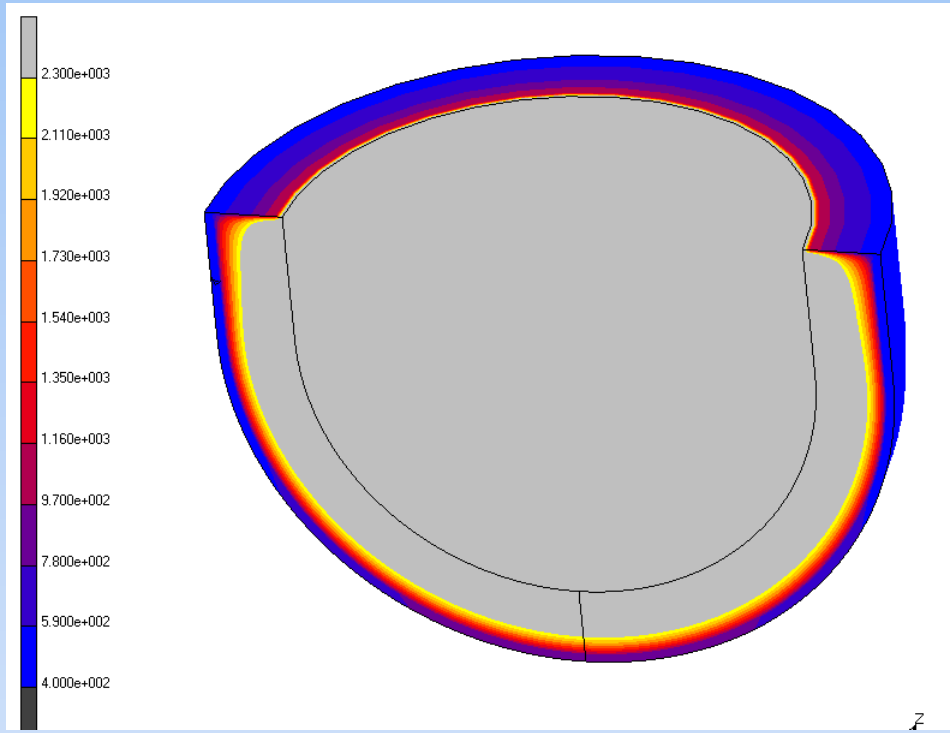




Pebble radius r=0.5 mm

NUMERICAL ANALYSIS: CORE CATCHER MODELLING

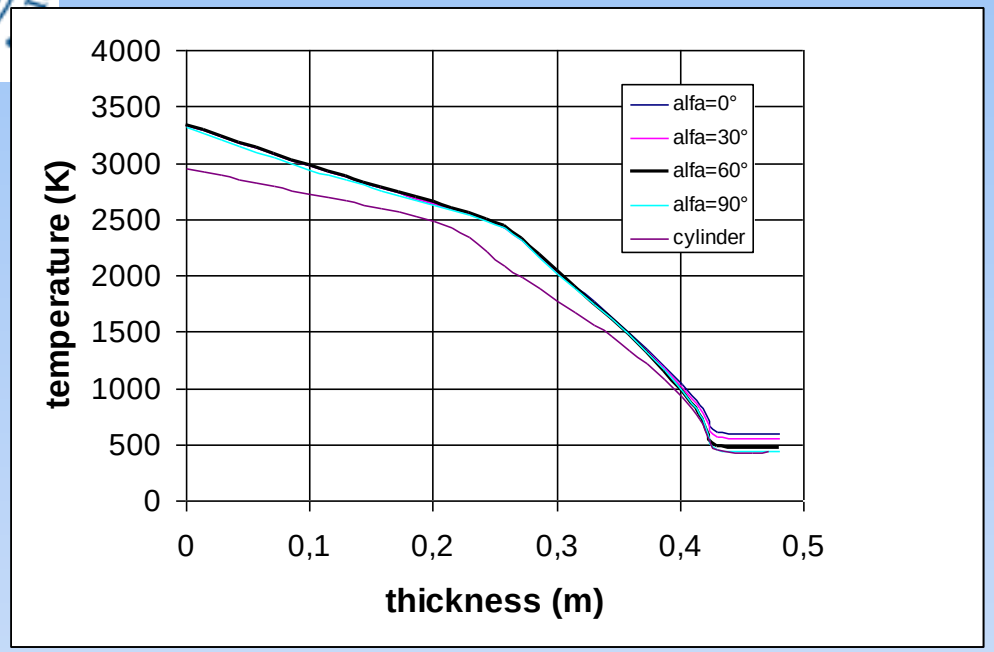
The performed simulations consist in coupled thermal mechanical analyses, assuming that the core catcher was loaded by the hydrostatic pressure of liquid Corium.
The steady state solutions were obtained as the limit configuration of a transient analysis.
An incremental analysis was required because the conductivity of the pebble bed is a function of the pressure and the temperature.
When the temperature of the alumina reached the fusion temperature (2318 K), the pebble bed was assumed to be molten and the conductivity was set equal to that of alumina.



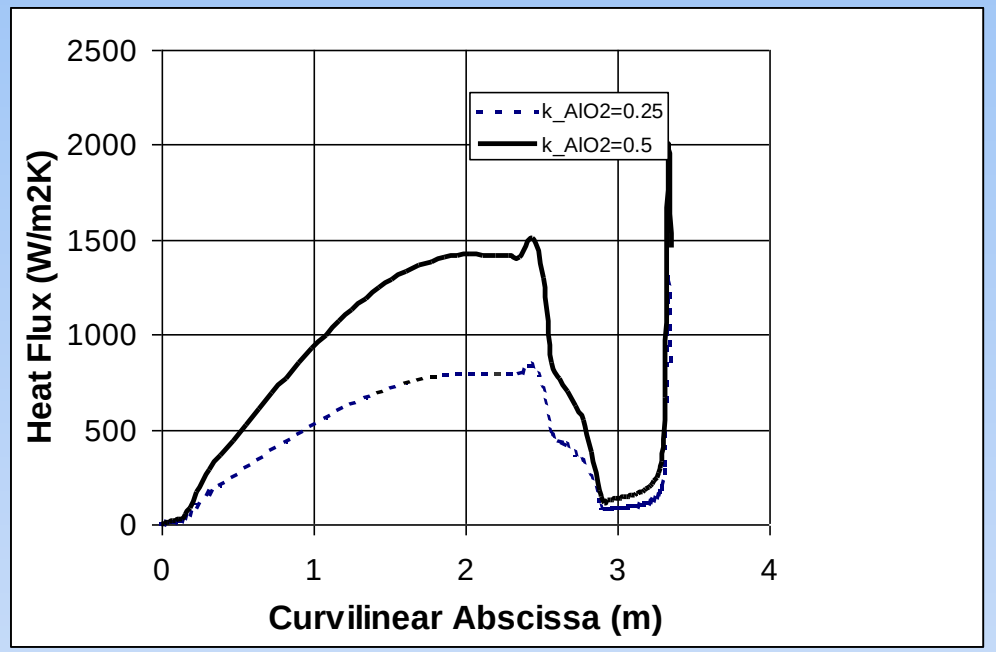
temperature distribution throughout the thickness of the core catcher,
thermal conductivity of alumina equal to k=0.5 W/mK.

About half the thickness is molten, but the external temperature ranges between 500 and 900 K

NUMERICAL ANALYSIS: CORE CATCHER MODELLING



Temperature diagrams versus the thickness
(AlO_2 conductivity k=0.25 w/mK)



Heat flux in correspondence to the internal surface of the core catcher versus the curvilinear abscissa
(from the symmetry axis to the cylindrical part)

The particular trend of the heat flux in the cylindrical zone (between 2.5m and 3.5 m) is due to extremely reduced conductivity of the pebble bed in this zone which produces a negligeable value of the heat flux. The ensuing increase depends on the cooling of the upper part next to the external surface.

SUMMARY

A core catcher located inside a PWR pressure vessel is designed to manage the in-vessel retention of the corium in the accidental event of the core meltdown.

This solution consists of a ceramic multilayered structure, filled with alumina pebbles .

The main aim of this solution is to protect the bottom head of the vessel from the heat flux caused by the Corium decay power.

The cooling of the Corium can occur through the upper surface of the Corium by means of radiation and convection with a coolant flowing into the vessel. The core catcher has to contain the Corium for a time interval as large as possible.

The alumina pebble bed has a low conductivity and a high loading carrying capability.
A theoretical model of the thermal mechanical behaviour of pebble bed has been illustrated.

NUMERICAL ANALYSIS: RESULTS

A numerical model of the core catcher has been implemented in order to determine its resistance under severe loading conditions.

The results of the analyses show that the core catcher, under the most conservative scenario, could resist indefinitely if the Corium was guaranteed to be cooled from the upper surface.

Moreover the results show that the conductivity of the pebble bed is strongly related to the temperature (through the Young modulus and yielding stress).

The exact dependence of these quantities on the temperature thus needs to be known in order to apply the illustrated method reliably.

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