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IN VESSEL CORE MELT PROGRESSION PHENOMENA

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O - INTRODUCTION

Safety improvements are an ongoing concern for the nuclear industry. For all light water reactor (LWR) accidents, including the so called severe accidents where core melt down can occur, it is necessary to determine the amount and characteristics of fission products released to the environment. For existing reactors this knowledge is used to evaluate the consequences and eventual emergency plans. But for future reactors safety authorities demand decrease risks and reactors designed in such a way that fission products are retained inside the containment, the last protective barrier.

This requires improved understanding and knowledge of all accident sequences, thus avoiding consideration of only enveloppe situations, which would tend to induce excessive conservatism and cause economic difficulties. In particular it is necessary to be able to describe the very complex phenomena occuring during in vessel core melt progression because they will determine the thermal and mechanical loads on the primary circuit and the timing of its rupture as well as the fission product source term. It could be a great benefit if the core melt could be kept inside the vessel as was the case in the TMI 2 accident.

On the other hand, in case of vessel failure, knowledge of the physical and chemical state of the core melt will provide the initial conditions for analysis of ex-vessel core melt progression and phenomena threatening the containment. Vessel failure modes, corium flow characteristics and hydrogen production will strongly affect core catcher and containment designs.

Finally a good understanding of in vessel phenomena will help to improve accident management procedures like Emergency Core Cooling System water injection, blowdown and flooding of the vessel well, with their possible adverse effects.

Research and Development work on this subject was initiated a long time ago and is still in progress [1] but now it must be intensified in order to meet the safety requirements of the next generation of reactors.

Experiments, limited in scale, analysis of the TMI 2 accident which is a unique source of global information and engineering judgment are used to establish and assess physical models that can be implemented in computer codes for reactor accident analysis.

Reactivity insertion accidents, such as the one at Tchernobyl, will not be treated in this paper.

1 - PHENOMENOLOGY DURING CORE MELT

a - General characteristics

Physical phenomena occuring during core melt down are very complex and coupled involving several fields of physics such as physicochemistry, metallurgy, thermal-hydraulics and mechanics. These have to be used with the same level of refinement.

The phenomena cover a wide range of temperatures up to extreme conditions (about 3000°C) and involve many materials with different physical properties such as silver, indium, cadmium and boron carbide for absorbers, Zircalloy and UO_2 for fuel, inconel, stainless and carbon steel for structures. These materials will melt, relocate, solidify, remelt and some of them will vaporize. They are thermodynamically unstable with each other and chemical interactions will occur that become significant at temperatures above 1000°C with the formation of eutectics which will exhibit melting temperatures lower than those of the elementary constituants.

Moreover the presence of water and steam will cause oxidation of metals with hydrogen release which is a major contributor to possible containment threats. During meltdown fission products will escape from the corium, modifying heat source distribution. They are transported throughout the primary circuit in aerosol form where they can redepose and revaporize with multiple chemical reactions.

All these processes will be, of course, strongly influenced by the cooling achieved through natural convection in frequently multidimensional configurations and an important contribution by radiative heat transfer .

b - Core degradation

In an unmitigated degraded-core accident that leads to fuel rod melting and failure of the reactor core, the following processes and chemical reactions can occur as the temperature rises (figure 1)[2]:

- plastic deformation and bursting or collapsing of the Zircaloy fuel rod cladding, depending on the differential pressure during a low or high-pressure accident scenario,
- melting of the (Ag, In, Cd) absorber alloy and, after failure of its stainless steel cladding, chemical interactions with Zircaloy,
- oxidation and embrittlement of the Zircaloy cladding by interactions with H_2O (steam) and UO_2 fuel which may result in rod fragmentation,
- oxidation of the stainless steel cladding and Inconel spacer grids by steam,
- melting of the metallic Zircaloy or the metallic oxygen-stabilized α-Zircaloy (α-Zr(O) phase),
- reduction of the UO_2 due to interactions with solid and/or molten metallic Zircaloy, with partial dissolution and disintegration of UO_2, forming a metallic Zr-U-O melt; as a result, liquefied fuel relocation can already take place below 2000°C,
- eutectic and monotectic reactions between α-Zr(O) and UO_2,
- melting of ZrO_2 and UO_2, forming a ceramic Zr-U-O melt,
- relocation of the solid and liquid materials into the lower reactor pressure vessel,
- interactions of the relocated solid and molten materials with water,
- and finally thermal and chemical attack of the reactor pressure wall.

At temperatures above 1200°C, the rapid oxidation of Zircaloy and of stainless steel by steam are extremely important factors in a severe reactor accident because the heat generated by these exothermic chemical interactions results in local uncontrolled temperature escalations within the core with peak temperatures of 2000°C and higher. All

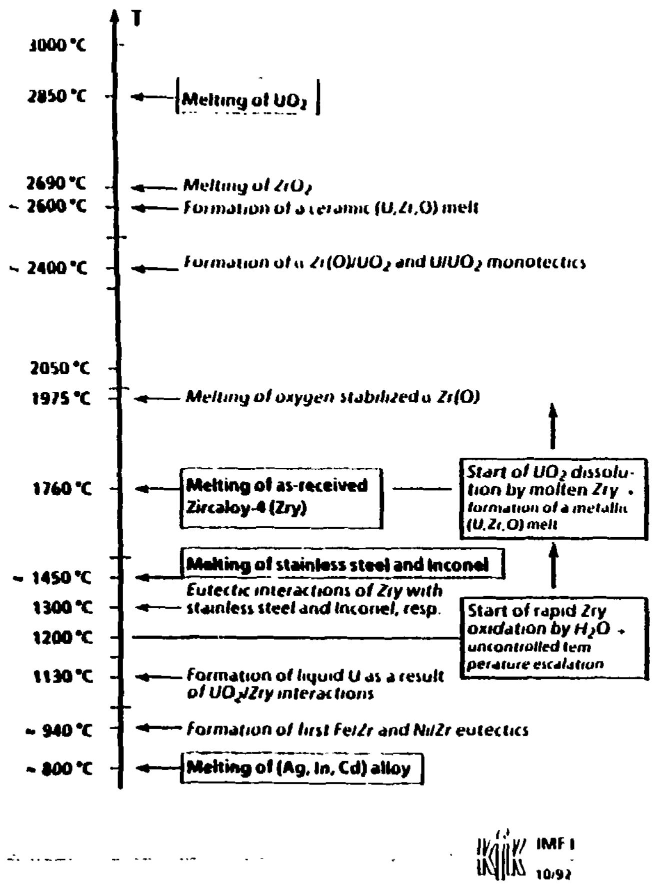

Fig. 1

Chemical interactions and formation of liquid phases in a PWR fuel rod bundle with increasing temperature

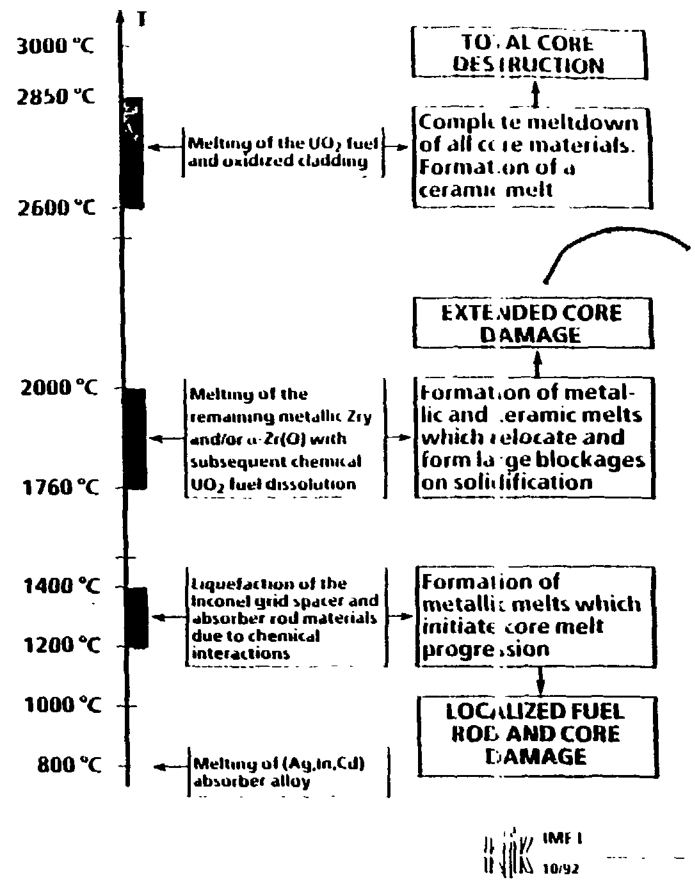

Fig. 2

TEMPERATURE REGIMES FOR LIQUID-PHASE FORMATION IN A SEVERE REACTOR ACCIDENT AND POSSIBLE CONSEQUENCES FOR REACTOR CORE DAMAGE

of these interactions are of concern in a severe accident because relocation and/or solidification of the resulting fragments or melts may result in local cooling channel blockages of different sizes and may cause further heatup of these core regions because cooling still can be inadequate, causing further melt progression and material relocation into lower regions of the reactor pressure vessel (RPV).

As the molten phases are formed at different temperatures during in-vessel core melt progression, they are formed in a complex pattern involving both spatial and temporal variations. As a result, the melt progression begins at different times at different places in the core. The various molten phases will solidify on cooldown at different temperatures and will therefore form blockages at different axial locations. All these processes have a significient influence on hydrogen generation, natural circulation, the chemical composition of the melt that finally reaches the lower RPV head and its temperatures.

The presence of water and/or the injection of water into an uncovered core due to safety devices or operator actions have an important effect on in-vessel core-melt progression. For example, if emergency core cooling water enters the RPV early during the meltdown process (early reflood), there will be only limited fragmentation and collapse of solid but embrittled material. However, quenching under these conditions will result in extended Zircaloy oxidation by steam with consiquently rapid heatup combined with a considerable hydrogen generation and localized melt formation and relocation. The longer the delay in establishing this water flow (late reflood) the greater will be the amount of both molten and embrittled materials. Ultimately, in-core configurations could be formed that are not coolable in place. This is thought to have caused the relocations of molten material into the RPV lower head in TMI 2. During the process of melt relocation, the grid structures can provide a major impediment to the downward movements of melts.

Three distinct temperature regimes exist forming liquid phases in large quantities during core heatup, either due to primarily eutectic chemical interactions or by reaching a melting point. These are indicated in figure 2 [3]

Above 1200°C, liquefaction of portions of the absorber rod fuel assemblies occurs as a result of Zircaloy/stainless steel and Zircaloy/(Ag, In, Cd) interactions.

Above 1400°C, the absorber rods and the Inconel spacer grids will be completely molten. The resulting metallic melt is able to dissolve the Zircaloy cladding of the fuel rods and the UO_2 fuel far below their melting points.

Between 1760 and 2000°C, the unoxidized portions of the Zircaloy cladding, which are still metallic, start to melt and can chemically dissolve the solid UO_2 fuel and the ZrO_2 surface layer that steam oxidation is producing on the cladding outer surface. The amount of unoxidized cladding depends on the heatup rate and steam availability. The molten metallic Zircaloy then relocates downward along the individual rods in a slow "candling" process or by a fast "slumping" and is thus removed from the higher temperature regions of the core where quicker oxidations prevails.

In areas of the core where temperatures between 2600 and 2850°C may be reached, the $(U,Zr)O_2$ solid solutions which form at lower temperatures start to melt and relocate. At temperatures >2850°C all components of the reactor core and chemically formed phase are molten.

The different temperature regimes result in different core damages. Regime 1 causes localized fuel rod and core damage and the blockages formed will probably be coolable. In temperature regime 2, much stronger melt formation occurs with extended core damage and the generation of core regions that can no longer be cooled. Regime 3 finally results in the complete meltdown of all materials and total destruction of these high temperature core regions. Evidence for all these molten phases and relocation processes has been seen in the various integral in-pile and out-of-pile experiments and in TMI 2 [4].

The extent of core damage depends on the initial heatup rate and the maximum temperature reached. Accident management measures, which delay core uncovery, result in a lower initial heatup rate of the core, hence, in a reduced formation of liquid phase up to about 2600°C, leaving more time for further operator actions [3].

c - Molten material relocation in- side the core

Another phenomenon encountered during core degradation is the formation of rubble beds.

The collapse of solid material onto the blockages (solidified materials and grid spacers) can form debris beds on top of the blockages. Continuous heatup of these debris beds can form molten pools, held in place by a solid crust, which acts as a crucible (as shown by TMI 2), with later crust collapse possibly influencing the late melt relocation stage.

The gravity-driven relocation of molten and liquefied materials and their solidification in the cooler core regions involves many complex thermal-hydraulic phenomena. The velocity and layer thickness of the flowing mixture and the continued oxidation and chemical reactions are the major factors determining the relocation rate and solidification process. Melt relocation was found to occur mostly by non-coherent, non-coplanar rivulet flow [3]. The relocated melts in the TMI 2 accident formed an extended solidified crust above the water level in the core [4]. Failure of the crust would allow the molten interior to relocate into the lower region of the RPV. Potential crust failure mechanisms are thermal melt-through of the crust by natural convective heat transfer due to temperature and pressure differences across the crust layer and eutectic interactions between the crust and interior material. In the TMI 2 accident, it has been assumed that melt-through caused crust failure high up on one side of the molten pool [4].

d - Molten material relocation into the vessel lower head

A global failure of the crust supporting a molten pool within the core or of the core support structures that could induce a massive molten material relocation into the lower plenum does not appear to be very probable. Much more likely, corium relocation will be rate limited through local breaches in the crust and downstream through the holes of the different support plates and flow distributors which will be destroyed gradually. Moreover, the presence of internal structures forming flow paths of different sizes may intercept and redirect the melt forming streams and rivulets.

Jets of corium will fall into water and after some length of penetration will break into droplets which will reach the vessel bottom in liquid or quenched conditions according to jet velocity, droplet sizes and height of water crossed and will form a debris bed [5].Oxidation, steam and hydrogen production and pressure increase are likely to occur during this phase. The debris size can also be significantly affected by the possible occurrence of fuel coolant interaction or steam explosions which will divide the corium into very small fragments. All these phenomena are partly plant design dependant.

Depending on to the amount of water available and the debris size, the bed can be coolable or not. Anyway, if no more water is added, the debris bed will dry out and progressively remelt. A pool of several metallic and oxidic liquefied components which can separate under gravity forces will finally form and will be animated by natural convection movements.The natural convection flow will then determine the heat flux transferred to the vessel.

Part of the heat will be also transferred from the upper surface to the structures by radiation depending on the emissivity of the different facing surfaces and the absorption by the in vessel atmosphere that is composed of gas, steam and aerosols.

e - Vessel failure

Several vessel failure modes can occur under the action of molten materials:

- Jet impingement: A jet of molten material can impinge the vessel wall and attack it locally.

  This situation is very unlikely due to the presence of water.

- Failure of a lower head penetration:

  The tubes inside the vessel can be melted and corium will progress inside the tubes and freeze outside the vessel causing plugging of the tubes. At high pressure the tube could also be ejected.

- Global creep rupture

  The debris bed and the molten pool can chemically and thermally attack the vessel wall, either directly and rapidly by the metals if they are separated or more slowly by the ceramic crust

The thinning of vessel walls, coupled with temperature conditions, pressure loadings and corium weight, can induce a global creep rupture of the vessel.

This phenomenon might be avoided by an efficient cooling of the external surface of the vessel. Flooding of the vessel well or spraying of water can be foreseen. The amount of heat to be removed will very much depend on the decay heat and the quantity of corium relocated in the lower head . The efficiency of cooling will be limited by the boiling crisis.

f - Steam explosion

Contact of core melt at nearly 3000°K and water can cause non-energetic rapid vaporization (steam spike) or it can - in the other extreme - lead to an energetic steam explosion, i.e. a violent vaporization that is accompanied by high sustained pressures, typically of the order of 100 to 1000 bar. A steam spike can lead to some additional hydrogen release. But a steam explosion might release several gigajoules (GJ) of mechanical energy and so do significant damage to the reactor pressure vessel. It could even lead to early containment failure with its catastrophic radiological consequences. Steam explosions of a sufficient magnitude to break the containment are currently considered to have a low probability [6] [7] but the data base for such a conclusion is poor. There are two main reasons for this. First, all experiments available until now (or conceivable) involve melt masses that are smaller than those possibly available in a core melt accident by orders of magnitude [8]. Secondly, the complex processes involved in steam explosions are neither sufficiently understood nor amenable to modelling for it to be possible to make reliable extrapolations from small-scale experiments to the case of a reactor accident [9.] The following discussion will concentrate on the low pressure case as this is better understood and probably more relevant .

The reactor pressure vessel provides a strong barrier against damage to the containment. Thus only really large steam explosions involving e.g. tens of tons of core melt can threaten containment integrity. Such large-scale steam explosions are generally expected to develop (if at all) through four stages: quiescent coarse intermixing (premixing), triggering, propagation, and expansion. The basic idea behind this scheme is that the high heat transfer rates required in steam explosions require a sudden development of a large contact surface between melt and liquid coolant together with a very effective heat transfer mechanism such as heat conduction in (essentially) liquid-liquid contact.

It is the role of premixing to bring any mass element of the initially separated melt and water into close proximity with the other medium while preserving the explosive potential, i.e. the heat stored in the core melt. This requires coarse fragmentation of the melt into droplets of about one centimeter size and film boiling, which, however, is clearly present in the case of core melt in water. Quite obviously, premixing is much easier to obtain if melt flows from the core area into a water filled lower plenum than if water should be poured on core melt that has previously relocated into a dry lower plenum. But even with melt pouring into water, premixing can be expected to be a self-limiting process. The high melt temperature will cause a high radiative heat flux into the already saturated water.

So a large amount of steam will be created which will tend to remove the liquid water from volumes that contain melt. In this way, melt tends to keep itself separated from liquid water. What is certain is that the degree of effectiveness of the mechanism, by itself, and the possibility of rapid intermixing during the expansion phase (see below) have yet to be assessed.

The trigger is some pressure event (e.g. flashing of some entrapped and thus superheated water) which causes a propagation wave to run through the whole mixing zone, disturb film boiling, and cause or at least initiate fine-scale fragmentation of the melt to submillimeter sizes so that the required large melt surface is created. This causes a rapid pressure increase. The most popular example of a propagation wave is the shock wave in the thermal detonation model (for references see [9] [10]) which causes hydrodynamic shock fragmentation owing to large velocity differences between melt and water. But other propagation mechanisms and fragmentation mechanisms are under discussion as well and may be relevant in practical situations [10].

During the expansion phase, finally, the high pressure causes expansion, exerting strains on surrounding structures and mobile materials. But of course, mixing and fine scale fragmentation may continue during this phase and add to the violence of the explosion. Therefore, the duration of this phase is of great importance and makes an important difference between small scale interactions in which the high pressure phase may last for a fraction of, or at best, a few milliseconds and the reactor accident case in which it may last for tens or even a hundred milliseconds (for references see [9]). Thus even multiple explosions might become possible in which the requirement of premixing is partly removed.

Besides the immediate consequences on the spatial distribution of the core debris within the reactor vessel, and their coolability, there are two potentially dangerous mechanical consequences of the steam explosion. The first is a failure of the lower vessel head directly under the action of the high pressure. The second is the accumulation of large amounts of kinetic energy (of order 1 GJ) in core debris and possibly water that are accelerated towards the upper vessel head. If the impact of these materials on the upper head should cause a separation of the head from the vessel (failure of the vessel head bolts), containment integrity would seriously be threatened.

g - <u>Fission product release and transport</u>

During the whole course of a severe accident, fission products will escape from fuel and corium. This release is influenced by all parameters which can modify the fuel structure (temperature, kinetics of temperature transients, burn up, etc) and by the chemical environment (oxidizing or reducing conditions).

In addition, low boiling point materials can vaporize and form aerosols which will strongly influence fission product transport. They will settle on surfaces, heat up, revaporize and settle again in colder places, a process governed by multidimensional natural circulation gas flows.

Knowledge of all the phenomenology is very important to compute the source term able to escape from the primary system and also the thermal loadings applied to the circuit and especially to steam generator tubes.

2 - IN VESSEL CORE MELT COMPUTER CODE

a - A strategy based on a two-tier approach [11]

Two groups of codes have been developed:

- Integrated codes, characterized by simple engineering models covering all the phenomena occuring during a severe accident. They are especially designed for plant evaluation. Simplifying assumptions are used to provide fast running codes which can perform numerous parametric studies at low cost in order to compensate for the weakness of physical models. The main code in this category is STCP (USA). More detailed models have been introduced in the later codes together with improved numerical efficiency and flexibility. These codes are for example ESCADRE (France), MAAP (USA), THALES (Japan) and the more complicated MELCOR (USA).
- Detailed mechanistic codes, with sophisticated physical models, whose initial aim has been the description of special parts of the accident. They have often been developed for designing and analyzing experiments and are used as a benchmark for validating integrated codes. Three main groups of codes are now in this category: ATHLET (Germany), CATHARE/ICARE (France), RELAP 5/SCDAP (USA).

In the following, the review of these codes will be focused on the in vessel core melt part and it should be borne in mind that comments will be related only to this part.

b- Integrated codes

These codes are above all intended to be simple and fast running.

The circuit is often described by a limited number of volumes connected by flow paths. Stratification is assumed within all volumes (STCP, MELCOR) or in specific or groups of volumes (ESCADRE, MAAP). More detailed nodalization is used for the core region in order to take account of radial and axial effects. However the general pattern described in the core is based on a partition into a "covered" and an "uncovered" zone.

These two zones which are defined by the overall mass balance in the circuit, will determine the heat transfer mode. In the covered zone, decay heat is transmitted to water using general heat transfer packages. In the uncovered zone, convective heat transfer is complemented with radiative heat transfer. Axial radiative heat transfer (especially to upper structure) is accounted for in almost every code but radiative absorption by the gas and-droplets of the coolant is calculated only by two of them (ESCADRE and MELCOR).

Core degradation starts with clad ballooning and rod rupture which are described mechanistically in ESCADRE and MAAP and which are evaluated with user-defined criteria in the other codes. The core melting and relocation descriptions are based on highly user dependent models. Melting starts when some threshold temperatures are reached (clad melting point in ESCADRE, some user-specified eutectic temperature in MAAP). Relocation is evaluated using many user options (input controlled blockages in ESCADRE and STCP, three different meltdown models in STCP, control of the process through user-specified melting temperatures and user specified latent heat in MAAP, more mechanistic models in MELCOR).

Later in the transient, debris bed formation and behaviour are at best "described" via user-specified parameters (input porosity in MAAP, user-specified heat transfer and conduction areas in MELCOR, choice between three models in STCP, currently no model in ESCADRE).

Concerning the chemical reactions, the oxidation processes by steam are modelled in all the codes. However there are currently no models for interactions between materials such as UO_2/Zr, ZrO_2/Zr,(Ag, In, Cd)/Zr, stainless steel/Zr... (except UO_2/Zr interaction in ESCADRE). Quench (flooding) phenomena and the resulting H_2 generation are also not yet considered.

Models for vessel rupture and ejection of materials have been developed for all of these codes. After the slumping of corium into the lower head, some codes (STCP, ESCADRE) calculate wall heat up and tensile stresses which allow the determination of the rupture. Other codes (MAAP and MELCOR) use different types of failure modes (failure related to penetration failure in MAAP with a number of affected penetrations given by input-specified parameters, failure related to user-specified critical temperature in MELCOR).

Among the integrated codes, the models describing interactions between molten fuel and coolant are quite diverse. Till now in ESCADRE, no model has been developed, as most of the situations which are described correspond to simple boil off transients. In STCP there is a model for the drop of molten core material into the bottom head; this model is based on equivalent spherical particles to which mechanistic models of oxidation and heat transfer are applied. The MAAP code has special quenching models : top quench limited by countercurrent flow, bottom flooding based on film boiling heat transfer with an input coefficient. In the bottom head a melt pool model gives the thermal behaviour including heat transfer to the overlying water and crust formation. For MELCOR only the preximing phase is calculated prior to an eventual steam explosion.

Fission product release from core fuel is modelled using CORSOR-M or models derived from CORSOR except for MAAP which has its own specified models. Each code has its own vapor and aerosol module which calculates vapour condensation, and aerosol transport and deposition in the primary circuit.

c - <u>The detailed mechanistic codes</u>

The main codes in this category are often the combination of core degradation modules with large thermalhyraulics codes.

The thermalhydraulic models have the full capabilities of the original thermalhydraulic code i.e. ATHLET, CATHARE or RELAP 5. The standard versions of these codes however generally require extensions of their domain of validity especially with respect to high temperatures.

Heat transfer by convection is based on the heat transfer packages of the main thermalhydraulic codes which are able to take all hydraulic situations into account. Detailed radiative heat transfer models are added which take account of the core and structure geometrical specificities and changes in different ways. Radiation absorption by steam is calculated only by SCDAP and ICARE.

Core degradation is described by mechanistic models based on the physical "conservation principles" allowing materials to melt and relocate with relatively few user specified parameters.

Quite detailed modelling of debris beds is available in SCDAP and KESS whereas they have still to be introduced in ICARE and ATHLET.

Specific calculations of molten pool behavior are made using computer codes describing natural convection in 2D or 3D. A 3D multicomponent code describing the behavior of metallic and oxide species is being developed in France: TOLBIAC.

The chemical reactions included in the codes are, at first, the different oxidation processes. Other chemical reactions include interactions between Zr and UO2 which are modelled in ICARE, KESS and SCDAP. ICARE is the only code taking into account UO2 interaction with solid Zr.

Vessel rupture and ejection of materials is described in SCDAP only. The corresponding module is based on creep rupture and melting models. Again SCDAP only calculates fuel coolant interaction but uses a simplified model which has to be specified by the user. For the description of the premixing phase and possibly later phases of steam explosions specific multi-component, multi-phase and multi-dimensional multi-field codes are being developed, e.g. IVA3 in Germany and TRIO-MC in France. The mechanical loads on structure following a steam explosion are described using specific codes such as PLEXUS developed in CEA, or general purpose structural mechanics codes.

For fission product release and transport CORSOR or CORSOR derived models are used in ICARE, ATHLET and KESS. Specific modelling based on some theoretical developments together with models from FASTGRASS and CORSOR is used in SCDAP. All these codes use TRAPMELT or similar models for the fission product transport.

d - Discussion and trends

At first sight this review seems to show that the objectives of the two-tier approach are quite fulfilled. The integrated codes are able to predict the whole accident sequence. But they include several user specified options and thus, the plant studies which can be made with them are mostly parametric studies. On the contrary, detailed mechanistic codes provide more complicated but also more physically-based modelling which satisfies the foreseen objectives.

Code development must be linked with code validation. Here again, a two-tier approach is claimed: direct validation on experiments is performed with the detailed mechanistic codes and the integrated codes are validated with reference to calculations provided by the detailed ones.

In a sense these approaches appear to be complementary and well adapted. In fact if in-depth analysis is made, it is found that their complementary aspects do not compensate their drawbacks at all:

- In the case of integrated codes, one often wonders which physical basis the user should take for his choice of options, when the code developer was unable to do so.
- Sensitivity studies of options are rarely referenced in plant calculations with integrated codes. These sensitivity studies may in many cases give a wide uncertainty range which raises the question of what is really "described" by the codes.
- As detailed codes are based on an approach which does not integrate user input option, the parts of the sequence where the physical knowledge is sparse are not yet described at all. These codes are then incomplete and this is especially true in the domains where user options of the integrated codes raise the most difficult choices.
- The two-tier validation process also raises more fundamental questions: first it has to our knowledge not often been applied, even for phases where both integrated and detailed codes exist. Moreover it is not sure at all that the crude simplified models of the integrated codes can be "adjusted" to reference results. This dead end situation is well known to physicists carrying out physical modelling.
- The last argument is the fast running objective of the integrated codes in order to make numerous calculations for risk studies. This argument is less valid when one takes into account the improvements in computer capabilities. Moreover, numerical optimization,

which is necessary for complicated models, often leads to performances "equivalent" to the ones of the integrated codes where such optimization was not really mandatory.

The code of the future will probably overcome the distinction between integrated and detailed mechanistic codes. A trend in this direction can already be observed with the most recent integrated codes which use mechanistic models more and more and with the beginning of use of detailed codes for reactor calculations. In order to progress in that direction, increased efforts are required in the areas not yet covered and especially in the late phase of in vessel melt progression. Thought should also be devoted to finding which additional experimental information will be required for developing and validating the new models needed to get a complete physical description of severe accidents.

3 -EXPERIMENTAL BASIS FOR MODELLING AND CODE ASSESSMENT

A lot of experimental programs have been performed and are underway [1] or planned [12] and in a very brief review we shall indicate the domains they are covering in the field of in vessel core melt.

- Thermophysical properties of materials, chemical interactions, oxidation process have been extensively studied on analytical separate effect tests. However there is still a lack of knowledge concerning the complex mixtures of corium
- Integral tests with bundles of limited size already provide a good data base for the early phase of core degradation until relocation into the lower part of the bundle
  The in pile test PBF (32 rods 0.9 m long) PHEBUS SFD (25 rods 0.8 m long)
  ACRR (9-12 rods 0.5 m long) NRU FLHT (12 rods .3.7 m long)
  LOFT (24 -100 rods 2 m long) and the out of pile CORA test (25-60 rods 2 m long) provide a lot of data for various accident scenarii, and different types of fuel including different control rods and spacer grids.
- For large scale situations involving radial melt progression only TMI 2 is available. A similar situation exists for the late phase of core degradation i.e. core melt relocation into the lower vessel head through cracks in the crust of the in core melt pool and lower internal structures.
- A lot of experiments have been performed related to fuel coolant interaction (FCI) problems [8,12] to determine the probability and efficiency of steam explosions but always at small scale and extrapolation to large scales is still a problem. It has been shown that one of the governing phenomena was the premixing phase and analytical experiments involving the pouring of hot solid spheres (2500 °K) in water are being prepared (Billeau at CEA, France, and PWI at KfK, Germany) in order to assess the constitutive laws of the 3D multicomponent computer codes TRIO MC and IVA3 under development in CEA and KfK. Further information will become available from more integral experiments using actual melt, already perfomed like, MIXA (AEA, UK), in progress, FARO (JRC ISPRA), ALPHA (JAERI, Japan), or in preparation: like LSCM for premixing and SEEC for energy conversion (KfK, Germany). European activities in the field of FCI are coordinated in a CEC Reinforced Concerted Action
- Many data are also available concerning the problem of dry out and cooling of debris beds of various sizes but there is a lack of knowledge concerning the heat transfer of these debris beds to walls

Concerning the behaviour of molten corium pools in the lower vessel head, experiments BALI, scale 1, (CEA, France) and COPPO, scale 1/2, (Finland) using water as a simulating material will make it possible to determine heat transfer coefficients at the realistic Raleigh numbers characteristic of natural convection. This simple situation would have to be completed by experiments with actual materials including mixtures of metals and oxides. The behaviour of vessel walls and penetrations under attack by a molten material (thermite) is being studied in the CORVIS facility (PSI, Switzerland)

- Heat transfer by radiation from a corium surface in the presence of aerosols will be studied in AEROSTAT (CEA, France).

The ex-vessel heat transfer coefficients in the case of external cooling of the vessel by water are measured in the SULTAN facility (CEA France)

In order to compensate for the lack of data concerning the late phase of the accident the VULCANO (CEA France) experiment is planned where 500 kg of UO2 or UO2 Zr O2 mixture could be molten and poured into a 0.5m diameter lower vessel head. Feasability studies for melting and keeping power in these large corium quantities are underway.

- Fission product release has been studied in many separate effect tests and an integral experiment is starting at CEA with international funding: the PHEBUS PF program where the release and transport of fission products in a simulated primary circuit and containment is studied.

4 - CONCLUSION

An important research and development effort has already been performed and engaged to be able to improve the description of very complex in-vessel core melt phenomena.

If the early phase of core degradation is relativitely well understood there is still a need to develop the codes to bring them up to date with the experimental data base, especially concerning the low temperature liquefaction processes and quench phenomena.

With respect to the following sequences where core melt progresses radially up to or possibly through the baffles of the core or axially through the core support structures and relocates into the lower vessel head, the situation is less comfortable and no code has a reliable model. For these situations there are no relevant available experiments except the TMI 2 accident, which is characterized by a rather peculiar senario, and the only codes describing this late phase need "user inputs" to overcome the shortcomings of modelling.

As one advances through the accident sequence the uncertainties become more and more important. Parametric studies are currently the only way to bound with quite wide ranges the real physical responses.

The reduction of these uncertainties is the first goal of the research and development program underway and major efforts should be focussed on the late phase in the experimental domain research on molten pool for example, as well as in code area.

Thanks to a reduction of uncertainty one may hope to obtain a better description of accident sequence timing, clearer definition of injected water cooling efficiency and an improved assessment of the risk of steam explosions, thus contributing to significant improvements in accident management procedures.

More accurate quantification of the probability of keeping the corium within the vessel will also be obtained, thanks to which it will be possible to optimize future designs as regards the consequences of severe accidents.

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