Modelling of severe accident behaviour using the code ATHLET-CD

K. Trambauer, H. Austregesilo, C. Bals, A. Hora, G. Lerchl, J-D. Schubert

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Forschungsgelände, 85748 Garching, Germany

Abstract:

Thermal-hydraulic and core degradation phenomena play a decisive role for the course of severe accidents in light water reactors. Therefore, the simulation of such accidents with computer codes requires comprehensive and detailed modelling of these processes. The code ATHLET-CD is being developed for realistic simulation of accidents with core degradation and for evaluation of accident management measures. It makes use of the detailed and validated models of the thermal-hydraulic code ATHLET in an efficient coupling with models for core degradation and fission product behaviour. The capabilities of the coupled code are demonstrated by means of the calculation of the TMI-2 accident.

The first three phases of the accident were successfully simulated in a reasonable computing time. The calculated system pressure and pressurizer level after pump trip, during the pump restart, and until core slump are in acceptable agreement with the measured data. The calculated hydrogen generation before the pump restart is in accordance with the deduced value. Contrary to estimates based on the system behaviour, no significant hydrogen generation was calculated during the quench phase. Further model improvements regarding the quenching of degraded core material, fracture and relocation of solid fuel rods, as well as the simulation of debris bed behaviour are necessary for better simulation.

1 COMPUTER CODE ATHLET-CD

1.1 Objectives of code development

The system code ATHLET-CD (Analysis of Thermal-hydraulics of LEaks and Transients with Core Degradation) is designed to describe the reactor coolant system thermal-hydraulic response, core damage progression, fission product and aerosol behaviour during severe accidents, to calculate the source term for containment analyses, and to evaluate accident management measures. It is being developed since 1990 by GRS (Teschendorff, 1998, Trambauer, 1998, Trambauer, 2002) in cooperation with the Institut für Kernenergetik und Energiesysteme (IKE), University of Stuttgart. ATHLET-CD includes also the aerosol and fission product transport code SOPHAEROS which is being developed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN).
1.2 Model extent

The ATHLET-CD structure (figure 1) is highly modular in order to include a manifold spectrum of models and to offer an optimum basis for further development.

ATHLET-CD contains the original ATHLET models for comprehensive simulation of the thermo-fluid-dynamics in the coolant loops and in the core (Teschendorff, 1996). The ATHLET code comprises (1) thermo-fluid-dynamic module, (2) heat transfer and heat conduction module, (3) neutron kinetics module, (4) general control simulation module, and (5) differential equation system solver FEBE. The thermo-fluid-dynamic module has two different fluid-dynamics equation systems: (1) a six-equation model, with fully separated balance equations for liquid and vapour, complemented by mass conservation equations for up to 5 different non-condensable gases and by a boron tracking model (2) a five-equation model, with a mixture momentum equation and a full-range drift-flux formulation for the calculation of the relative velocity between phases. Specific models for pumps, valves, separators, mixture level tracking, critical flow etc. are also included in ATHLET.

The rod module ECORE consists of models for fuel rod, absorber rod (AIC and B4C) and the fuel assembly including BWR-canister and -absorber. The module describes the mechanical rod behaviour (ballooning), Arrhenius type rate equation for the oxidation of zirconium (figure 2) and boron carbide (figure 3), Zr-UO2 dissolution, as well as melting of metallic and ceramic components. The melt relocation (candling model) is simulated by rivulets with constant velocity and cross section, starting from the node of rod failure. The model allows oxidation, freezing, re-melting, re-freezing and melt accumulation due to blockage formation. The different modes are depicted in figure 4. The feedback to the thermal-hydraulics considers steam starvation and blockage formation (Trambauer, 1996). Besides the convective heat transfer, energy can also be exchanged by radiation between fuel rods and to surrounding core structures.

The differential equation system of the thermo-fluid-dynamics is solved implicitly (Hofer, 1981). The integration scheme is laid out in figure 5. At the begin of the time step, the time derivatives (function call f(t)), the Jacobian matrix, and the partial time derivatives over the whole time step are evaluated. After that the integration is performed in one step, two sub-steps, and (if necessary) in three sub-steps, and then the final solution is extrapolated. The modules with strong feedback (ECORE, HECU) are integrated accordingly to provide the thermal-hydraulic equation system with the correct data at the beginning of each sub-step and to support the proper extrapolation.

The release of fission products is modeled by rate equations or by a diffusion model. The release of aerosols is described by rate equations. The release of control rod material (Ag, In, Cd) is based on temperature functions. The transport and retention of aerosols and fission products in the coolant system are simulated by the code SOPHAEROS.

For the simulation of debris bed a specific model MESOCO is implemented with its own fluiddynamic equation system, coupled to the ATHLET-thermo-fluid-dynamics on the outer boundaries of the debris bed (figure 6). The transition of the simulation of the core zones from ECORE to MESOCO depends on the degree of degradation in the zone.

The code system ATHLET/ATHLET-CD is coupled to the containment code system COCOSYS. Both code systems are the main process models within the German nuclear plant analyzer ATLAS. The ATLAS environment allows not only a graphical visualisation of the calculated results but also an interactive control of the calculation.
In the continued developmental planning it is foreseen to implement the 2D/3D fluid module FLUBOX for an improved thermal-hydraulic simulation in the RPV as well as models for the simulation of melt slumping into lower plenum (figure 7) and melt retention in the RPV (figure 8).

1.3 Validation

The code validation is based on integral tests and separate effect tests, proposed by the CSNI validation matrices, and covers thermal-hydraulics, bundle degradation as well as release and transport of fission products and aerosols. Recent post-test calculations have been performed for the out-of pile bundle experiments CORA-13, CORA-W2, QUENCH-03, QUENCH-05, QUENCH-06 (Erdmann, 2001), QUENCH-07, and QUENCH-09 as well as for the in-pile experiments Phébus FPT0, Phébus FPT1 (Erdmann, 2002, Klein-Heßling, 2002), and Phébus FPT2 (see figure 9 with the final mass distribution). The TMI-2 accident is used to assess the code for reactor application.

2 TMI-2 ANALYSIS

The analysis and evaluation of the accident at Three Mile Islands Unit 2 (TMI-2) in 1979 (Tolman, 1988, Moore, 1989) have been a challenge to all computer codes intending to simulate severe accidents. The main events during the first four hours of the accident and the final state of the core materials are depicted in figure 10. It provides not only a unique opportunity to compare calculations with an event in a real plant but it also demonstrates the importance of reliable thermal-hydraulic models. The accident has been thoroughly analysed in the frame of international activities (OECD, 1992, OECD, 1994). A new international activity to identify the progress made since 1990 in the simulation of severe accidents by benchmarking different codes to the TMI-2 accident has been initiated recently by CSNI (Royen, 2003).

2.1 Input model for TMI-2 analysis

The nodalization adopted for the ATHLET-CD analysis of the TMI-2 accident is shown in figure 35. It consists of the reactor pressure vessel (RPV), the two coolant loops A and B with the once-through steam generators (OTSG), four cold legs with main coolant pumps (MCP), four high pressure safety injections (HPSI) in the cold legs and one let-down in loop A1, and the pressurizer with surge-line (connected to the hot leg of loop A), spray, and pilot operated relief valve (PORV). The RPV comprises the downcomer, lower and upper plenum, upper head, and core bypass as well as five parallel channels in the core with 22 axial nodes and with cross flow connections to allow flow deflection due to fuel rod deformation and blockage formation caused by refreezing of molten material.

The simplified model of the secondary system consists of two components (loop A and B), simulating the riser (16 axial volumes) and steam dome as well as the boundary conditions for feed water injection and steam pressure to control the water inventory and steam exit flow. In total, the nodalisation comprises 280 control volumes and 400 flow paths.

The core is modeled by four rings with 22 axial nodes. The three inner rings include control rods (Ag, In, Cd). The fourth ring contains only fuel rods. The fifth channel is without rods to avoid complete core blockage. The geometrical data, material properties, power distribution
and boundary conditions are based on TMI-2 data reports (Golden, 1986, McCormick, 1987) and former ATHLET analyses (Wahba, 1990).

The main input data relevant for the degradation are:

- Start of fuel dissolution by Zirconium: 2030 K
- Clad failure temperature ($\delta_{\text{ox}} < 0.3$ mm): 2250 K
- Clad failure temperature ($\delta_{\text{ox}} \geq 0.3$ mm): 2450 K
- Start of fuel melting: 2600 K
- Ceramic melt enthalpy / specific heat capacity: 200 K
- Relocation velocity: 6 - 3 cm/s
- Upper limit for steam starvation $p_{\text{steam}}/p_{\text{total}}$: 0.1
- Correlation for cladding oxidation: Cathcart - Urbanic - Heidrick

3 DISCUSSION OF RESULTS

The aim of the calculation was to assess the core degradation models and the quenching during the pump restart (174 min). Therefore, special attention has been given to the time from 100 to 220 min, i.e. the accident phases two, three and the beginning of phase four up to the time of core slumping into lower plenum. The objectives of the phase one simulation was to provide the correct water and energy distribution in the system at time 100 min, i.e. the time as the coolant pumps in loop A have been stopped.

3.1 Performance of calculation

The calculation over the whole transient time of 220 min (13200 s) took about 2420 min (145000 s) on a DEC-ALPHA workstation and made 97000 time steps. This results in an average time step size of 0.14 s and a run time to real time ratio of 11. The first 140 min took only 330 min with a run time ratio of 2.4 and an average time step size of 1.67 s. In the remaining 80 min up to the end of the calculation, the run time ratio increased to 27 and the average time step size decreased to 0.06 s. This indicates a rather good and robust code performance under consideration of the two phase flow thermal-hydraulics, presence of one non-condensable gas, and core degradation processes, and it is a proof of the coupling technique between the thermal-hydraulics and core degradation models.

3.2 Comparison of global system parameters

Figure 11 shows that the calculated primary system pressure (solid line) reached the measured value (dashed line) at 105 min. Calculated and measured data agree up to 150 min. After that time the calculated pressure rises faster than the measured data, indicating a too high makeup flow (4 kg/s) during this time, which results in more hydrogen and heat generation due to the higher steam availability. The calculated pressure meets the measured value again just before the pump restart (loop B2) at time 174 min. Subsequently, the calculated pressure increase is overestimated during the quench phase. 10 min later (184 min) the pressure remains higher than the measured data with approximately the same deviation as 2 min before the pump restart. After 190 min the calculated and measured
pressure drop in three steps due to twice short opening of the block valve at the pressurizer and due to the injection of cold water (60 kg/s) into the cold legs after the start of HPSI.

The hydrogen generation is shown in figure 12. The beginning of the oxidation at about 130 min agrees well with the pressure stabilization at this time, short before the pressurizer valve has been closed. From the plant data a total mass of about 300 kg has been estimated before the quench phase and 400 to 500 kg after it. The calculation results in 380 kg before and 400 kg after the quench phase, i.e. some over-estimation before and a high under-estimation during the quench phase. The pressure increase and hydrogen generation before the quench phase could be brought to better agreement to the plant data by either adapting the makeup flow or by improved cladding failure criteria. The low hydrogen generation of 22 kg during the quench phase will be discussed later. During the first opening of the pressurizer block valve at time 192 min, 23 kg hydrogen are released to the containment. During the main oxidation phase (145 - 165 min) an average hydrogen generation rate of 0.25 kg/s is calculated. This corresponds to a steam consumption of 2.25 kg/s and a heat generation by oxidation of 34 MW, which is equal to the decay heat at this time. It is also remarkable that the total hydrogen generation of 400 kg is equivalent to about 40 % consumption of zirconium inventory.

The collapsed level in the core and reflector bypass are depicted in figure 13. After the pump stop at 100 min the two-phase mixture collapses and the water is accumulated in the lower plenum and lower core region. Continuous loss of coolant results in a slow level drop up to 140 min. The level is 1.1 m high at this time and the temperature escalation has started due to the oxidation. The sudden level drop at ROD1 indicates the first absorber melt relocation and blockage formation (level 1.189 m). After this the levels in the five parallel channel develop differently according to the blockage formation. The lowest level height of approximately 0.75 m is in agreement with the estimated plant data at this time. The pump restart at 174 min results in a sharp level rise, more pronounced in the outer rings than in the inner rings. In the following time, after 180 min, the core dries out again. At time 200 min core reflooding starts due to the high pressure injection.

In figure 14 the calculated mixture and collapsed level in the pressurizer are compared with the signal of the level measurement. This signal is affected with large uncertainties due to the operation beyond design limits. The difference between measured and calculated collapsed level is nearly constant in the time between 120 and 200 min. The calculated mixture and collapsed level are equal as long as the pressurizer block valve is closed. They are different during the time of the valve leakage (before 140 min) and during the block valve operation after 190 min. These observations indicate that the pressurizer behaviour and the sealing effect of the surge line are well captured.

The melt and crust masses are depicted in figures 15 and 16. The metallic melt consists of molten cladding and dissolved fuel, and candles down after clad failure. The ceramic melt includes molten fuel and molten zirconia from the cladding that relocate after reaching the rod failure temperature and complete melting. The metallic melting and crust formation start at 145 min. The sum of melt and crust reaches 16 Mg and the amount of melt stays mostly below 4 Mg. The metallic melt mass remains unchanged with the beginning of the second quench phase. The ceramic melting starts at 152 min. The sum of melt and crust approaches 10 Mg before the first quench phase and 11.5 Mg before the second phase. The ceramic melt mass decreases after the first quench phase, which is in contradiction to the observations made in the plant.
3.3 Fuel temperature and cladding oxidation

More detailed information regarding the fuel temperature and cladding oxidation is collected in figures 17 to 28 over the time from 100 to 220 min for the core region between 1 and 3 m elevation. Below 1 m elevation the rods remain at saturation temperature (< 600 K) except in the innermost ring (ROD1) where absorber melt candles downwards to the bottom of heated core (183 min) and metallic melt (zirconium and fuel) relocation to the axial level just below 1 m (177 min). Also clad oxidation is observed in the innermost ring below 1 m after 183 min but not in the other rings. The thermal behaviour in the upper core region above 3 m is similar. The temperature exceeds the saturation temperature after the collapse of mixture level in the core at 103 min. In each individual ring, the temperature escalation is equal along the rods and the claddings fail at 2450 K with oxide layer thicknesses of more than 0.4 mm. Ceramic melting takes place only in the innermost ring at about 160 min after reaching the melting or relocation temperature of 2600 K.

Figures 17 and 18 show the fuel temperature and clad oxide layer thickness at level 2.836 m. In the following the general degradation process is described on the basis of ROD1 (red line). The temperature raise starts with the collapse of the steam water mixture at time 103 min with a heat-up rate of 0.6 K/s, in the inner ring (ROD1) slightly faster than in the outer ring (ROD4). The heat-up rate decreases to 0.2 K/s at about 1100 K (125 min). At this temperature the oxidation becomes more important and the temperature gradient increases again. At 1500 K (140 min) the oxidation power reaches the decay power and the temperature escalation commences. The heat-up rate increases up to 4 K/s due to heat generation by the oxidation. 270 s later (144.5 min) the temperature increase is additionally accelerated by metallic (Zr-UO₂) melt relocating from the elevations 3.202 and 3.385 m. Further 30 s later (145 min) the oxidation is limited due to the steam consumption at lower elevation. This can be seen by constant oxide layer growth rate and reduced temperature increase. Additional 100 s later the cladding reaches the failure temperature of 2450 K while the fuel temperature is about 100 K below clad temperature.

The oxide layer thickness has increased to 0.39 mm and remains constant up to 158 min. At this time the rod has reached the rod failure temperature (2600 K at 152 min) and has been completely molten at the level of 2.836 m. ROD2 behaves similar as ROD1 but it is delayed up to 10 min. The oxide layer reaches 0.66 mm thickness due to the higher steam flow in the second ring. The clad failures of ROD3 and ROD4 are delayed by 13 and 17 min relative to ROD1 with oxide layer thicknesses of 0.88 and 1.06 mm respectively.

This illustrates that the degree of oxidation in the upper core region depends on the steam availability, flow conditions, and the heat-up rate. A lower heat-up rate generally results in more oxidation before clad failure. The same behaviour can be seen in figures 19 and 20 for the elevation 2.470 m. At this elevation the two inner rods reach the rod failure temperature, but only ROD1 melts completely and fails at 153 min, 5 min earlier than at 2.836 m elevation. At both elevations the temperature of the two outer rods decrease with approximately 1.2 K/s after the end of the clad oxidation. The intermediate temperature increase of ROD4 between 164 and 168 min is caused by accumulation of metallic melt relocating from higher elevations.

The next figures 21 and 22 show the situation at 2.104 m elevation. The sharp temperature ramps, starting from temperatures below 1500 K, are caused by melt relocation. Likewise at level 2.470 m the clad failure temperatures are reached by ROD1, ROD2, and ROD3 but only ROD1 meet the rod failure criteria. For all rods, except ROD3, melt accumulation and blockage formation can be observed, for ROD1 and ROD2 due to ceramic melt, for ROD4 due to metallic melt at level 2.470 m. Loss of flow and high fuel mass lead to superheating of
the ceramic melt for ROD1. For this level it is remarkable that during the second dry-out phase ROD1 and ROD2 experience a significant heat-up before 200 min.

The next figures 23 to 28 depict the rod behaviour for the level 1.739, 1.372, and 1.007 m, i.e. the core region below the core mid-plane. For the upper two elevations dry-out takes place at time 106 and 126 min. Due to sufficient cooling the temperature rise above saturation is limited to 400 and 200 K respectively. Therefore, the clad oxidation is very limited and is only significant if melt relocation results in temperatures higher than 1500 K and steam has access to the cladding (ROD3 at level 1.739 m, ROD1 at level 1.372 m, and during the quench phase ROD1 at level 1.007 m). In this core region only the crust and melt oxidation contributes essentially to the total hydrogen generation.

The resume of the description of the last 12 figures is, that the oxidation after 168 min is limited due to three reasons:

1. In the upper, hot core region most metallic zirconium has been lost due to clad failure and melt relocation.
2. The steam has no access to the metallic melt due to blockage formation.
3. In the lower core region the temperatures are too low for significant oxidation.

3.4 Pump behaviour and global parameters during the quench phase

The figures 29 to 34 cover the time from 170 to 210 min, i.e. the time between the restart of the main coolant pump in loop B2 (MCP-B2) at 174 min and the beginning of the high pressure injection with 60 kg/s at 200 min.

Figures 29 to 32 show the pump pressure difference, the density at the pump inlet and outlet as well as the mass flow into the two hot legs and out of the four cold legs, respectively. The pump head during normal operation is 0.67 MPa. The MCP-B2 reaches the nominal revolution speed in 120 s after restart. During this time, the density on the suction side first decreases from 200 to 60 kg/m$^3$ and then increases steeply to 540 kg/m$^3$ at 95 s after pump start. At this time the liquid mass flow has been increased from zero up to the maximum value of 1200 kg/s and the pump head reaches 0.1 MPa. Further 10 s later the pump head reaches the maximum value of 0.15 MPa, approximately 20000 kg water have been brought into the pressure vessel, and the water inventory in the core has been increased by 2700 kg. About 3700 kg steam and 1700 kg water have left the pressure vessel via the two hot legs and the three cold legs, respectively. 250 s after the pump restart the collapsed level in the core reaches its maximum value. At this time the water inventory in the core has been increased by 5000 kg, the liquid and vapour mass flow in the cold legs A1, A2, and B2 are about zero, counter-current flow with negative vapour flow (5 kg/s) and positive liquid flow (9 kg/s) takes place in cold leg B1 due to the makeup flow. The vapour flow in the hot legs A and B dropped from the maximum of 110 and 180 kg/s down to 15 and 9 kg/s. This steam flow is directed to the pressurizer or condenses in the steam generators. The pump head is 0.032 MPa and the pump mass flow is negligible, i.e. the pressure difference imposed by the pump is compensated by the different liquid level heights in the loop seal of the cold legs B1 and B2.

Figures 33 and 34 illustrate the energy distribution in the system. At time 174 min the decay power is 25 MW, the oxidation power is negligible, heat addition to the fluid is 34 MW, the stored energy in the core is decreasing with 8 MW, and the heat flows to the two steam generators A and B are 3 MW and 1.5 MW. 100 s after the pump restart the maximum values of heat flows are reached: the heat addition to the fluid and the energy release of the core
are 400 MW, and the heat flows to the two steam generators are 150 MW (at 106 s) and 400 MW (at 90 s). The high heat addition to the steam generators results in a sharp pressure increase on the secondary side. 250 s after the pump restart the heat flows have considerably declined: to 80 MW for the heat addition to the fluid, 60 MW for the energy release of the core, 32 and 16 MW for the heat flows to the steam generators (loop A and B). About 500 s later the quenching is finished, the heat to the fluid is equal to the decay heat and the energy release of the core approaches zero. The core dry-out continues. The steam flow in hot leg A drops to zero, about 6 kg/s steam flows in hot leg B, and the flow pattern in the cold legs remains the same as 250 s before. The MCP-B2 is switched off again at time 193 min and the pump head declines to zero in about 10 min.

At time 200 min the high pressure injection pumps are started and feed 60 kg/s cold water into the primary system. This results in condensation and subsequently in a steep pressure drop as well as a second quench phase but considerably milder than the first phase due to essentially lower temperatures in the core.

3.5 Rod temperature during the quench phase

At the outer rings, the temperatures are decreasing already before quenching with about 3 K/s. This indicates that in these nodes the steam flow is higher than in the inner rings. The slower cool down of ROD4 at level 2.104 m is due to the higher mass accumulation and less flow due to blockage formation. Blockage has been formed also in the two inner rings between 1 and 2 m, and in the third ring (ROD3) between 1 and 1.6 m. The characteristics of the mass and heat flow indicate that the fast quenching process takes place between 75 and 120 s after pump restart. During this time the rods cool down with 22 K/s in the unblocked zones. The water slug cannot penetrate the hot zones in the inner rings from below due to the blockage, which results in a delayed quenching and a lower cool-down rate of about 13 K/s. The quench process is practically completed at 180 min except for the zones with melt accumulation and flow blockage between 1.5 and 2 m and a small portion of metallic fuel melt and crust in the innermost ring between 0.7 and 1.5 m.

3.6 System behaviour during the quench phase

The spatial distribution of the water in the primary coolant system and of the rod temperatures and porosity in the core during the quenching are illustrated in the figures 35 to 46 for the time points 174, 175.5, 180, and 210 min. The colour scale for the water distribution goes from blue (only water) to white (no water) and for the fuel temperature from dark purple (500 K) to light yellow (3000 K). Dark blue (0 K) stands for 'no fuel present'. The porosity is defined by the ratio fluid volume to total volume of the mesh (structure and fluid) and varies between one (no structure present, light green) and zero (no fluid present, black).

At the time of pump restart a clear separation of water and steam/hydrogen exists. The water level in the core is below 1.4 m and is in equilibrium with the level in the downcomer (figure 35). Loop A is nearly empty, only 6000 kg remained in the loop seal. The let-down (4 kg/s) is connected to the loop seal of this loop (cold leg A1), while the makeup flow feeds the same mass flow into loop B (cold leg B1) between pump and RPV. This flow goes into the RPV. The temperature and porosity distributions are depicted in figures 36 and 37. The next figures 38 to 40 show the situation 90 s later, the time with the maximum pump flow. The water from loop B is delivered to the RPV. The level rises in the outer core region, most rapidly in the small fifth ring without blockage. From this channel the water spreads radially to the inner rings which results in the fast cool-down of the upper core region. At time 180 s the dynamic process is over (figure 41 to 43). The liquid mass in loop A remains nearly
unchanged with 7000 kg, in loop B the liquid mass has been reduced by 20000 kg to 8000 kg. This mass was delivered into the RPV as described above. The water in the core has been spread out over the whole core and the levels are again in equilibrium. With the begin of the second core dry-out the temperatures of the uppermost core meshes increase again. The last three figures 44 to 46 show the situation at time 210 s. The RPV is refilled up to the loop connections, the pressurizer drains into the hot-leg in loop A. The major part of the core is quenched except the blocked region in the inner rings. The porosity distribution remains nearly unchanged.

4 CONCLUSION

The performance of the code ATHLET-CD has been demonstrated with this calculation. The first three phases and the beginning of the fourth phase of the accident (about 4 h) were successfully simulated in a reasonable computing time (40 h). This is a proof of the coupling technique between the thermal-hydraulics and core degradation processes. The calculated pressure history after pump trip, during the pump restart and until core slump is in good agreement with the measured data. The calculated hydrogen generation before the pump restart is in accordance with the deduced value. Contrary to estimates based on the system behaviour, no significant hydrogen generation was calculated during the quench phase. The debris bed and melt pool formation was underestimated due to the lack of a model for embrittlement and relocation of solid fuel fragments. Further model improvements regarding the quenching of degraded core material and the fracture and relocation of solid fuel rods are necessary for better simulation.

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REFERENCES


Figure 1: Modular structure of ATHLET-CD
Figure 2: Arrhenius correlation for cladding oxidation

Figure 3: Arrhenius correlation for B$_4$C oxidation

Figure 4: Modes of melt relocation, freezing, remelting, and blockage formation
Figure 5: Integration scheme for ATHLET-TFD and the modules ECORE and HECU

Figure 6: Simulation of core degradation in reactor pressure vessel
Figure 7: Simulation of relocation into lower plenum

ATHLET fluidodynamics

rod structure and cavity

debriis / water in core region

jet fragmentation

mixing zone

debriis / water in lower plenum

Figure 8: Simulation of melt retention in RPV

Modules AIDA (GRS), VECO (IKE)

- Heat transfer to water / particle bedflow
  - heat transfer coeff.
  - heat transfer particle bed

- molten core
  - thermal-hydraulic behavior
  - convection
  - stratification

- Deformation/failure RPV
  - symmetric/asymmetric
  - thermal load

- Gap flow

- Heat transfer melt <-> crust
  - heat transfer coeff.
  - crust dynamics
  - heat transfer crust
  - comparison to 3D models
Figure 9: Final mass distribution in Phébus FP Tests 0, 1, and 2, measured and calculated

Figure 10: TMI-2 accident progression, actions and final state

- 28.03.1979, 04:00:36
- Total loss of feed water 0 min
- Prizer PORV opened, SCRAM 0.1 min
- Relief tank burst disc opened 15 min
- MCP stop, Phase separation 100 min
- Begin of core heat-up 105 min
- Pressure stabilized 125 min
- Block valve closed 142 min
- Restart MCP B2 174 min
- 2 pumps of HPSI started 200 min
- Core slump into lower plenum 225 min
Figure 35: Void distribution at time 174 min

Figure 36: Fuel temperature distribution at time 174 min

Figure 37: Porosity distribution at time 174 min
Figure 38: Void distribution at time $175\frac{1}{2}$ min

Figure 39: Fuel temperature distribution at time $175\frac{1}{2}$ min

Figure 40: Porosity distribution at time $175\frac{1}{2}$ min
Figure 41: Void distribution at time 180 min

Figure 42: Fuel temperature distribution at time 180 min

Figure 43: Porosity distribution at time 180 min
Figure 44: Void distribution at time 210 min

Figure 45: Fuel temperature distribution at time 210 min

Figure 46: Porosity distribution at time 210 min