severe accident progression in the BWR lower plenum and the modes of vessel failure

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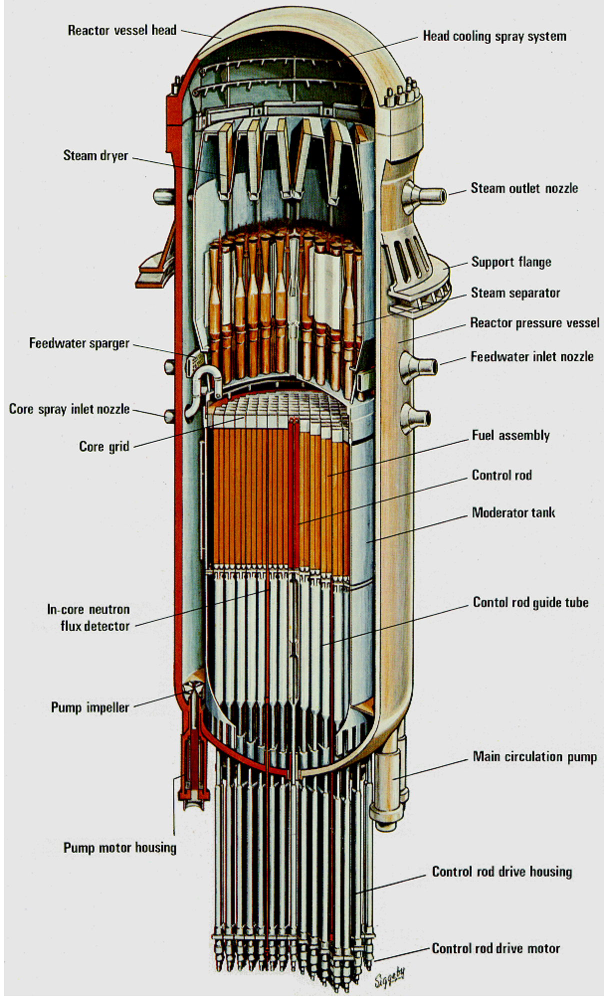
Introduction-1

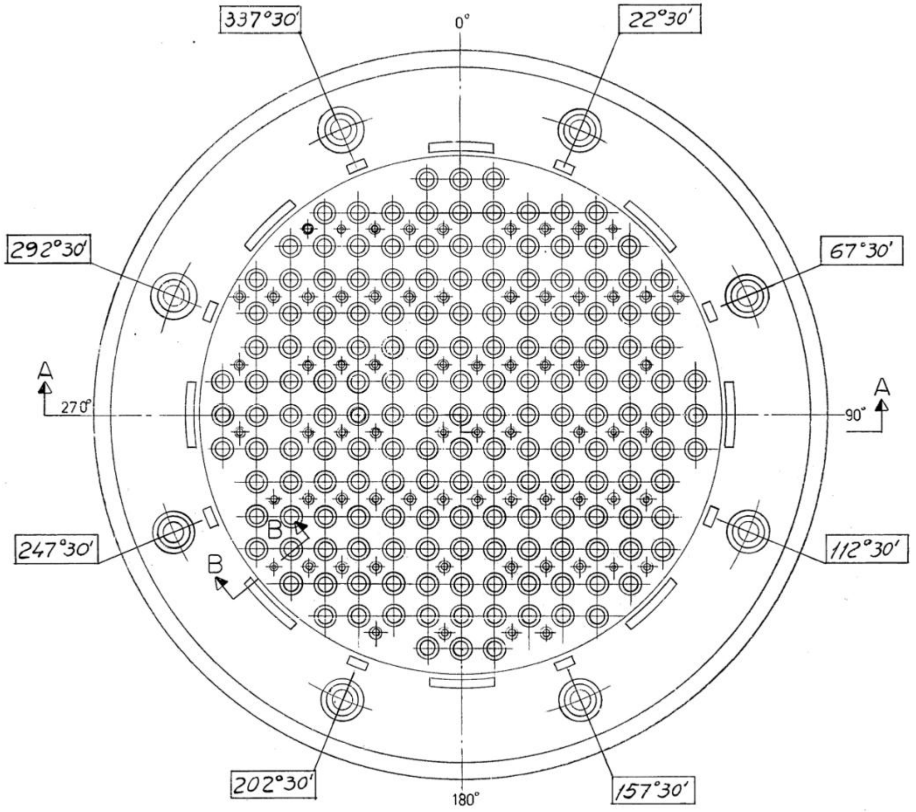
- This paper concerns the severe accident melt progression in a BWR. The BWR core and the plenum internals are very different than those of a PWR. These differences are bound to change the progression of the melt in the BWR vessel and the failure modes for the BWR vessel; compared to those in a PWR vessel.
- The BWR core has many more rod bundles than a PWR core, but each BWR bundle has fewer rods. Each rod bundle is enclosed in a zircaloy wrapper; thereby each rod bundle has its own thermal hydraulic conditions and the power level variations between the bundles is much greater than those in a PWR.
- The core is in a unit cell structure with a set of 4 rod bundles supported by the structure on top of a control rod guide tube (CRGT). Each bundle is plugged into a core plate at its bottom and water is delivered to the 4 bundles through a passage in the core plate, which may be orificed to tailor the flow to the power level in the 4 bundles.

Introduction-2

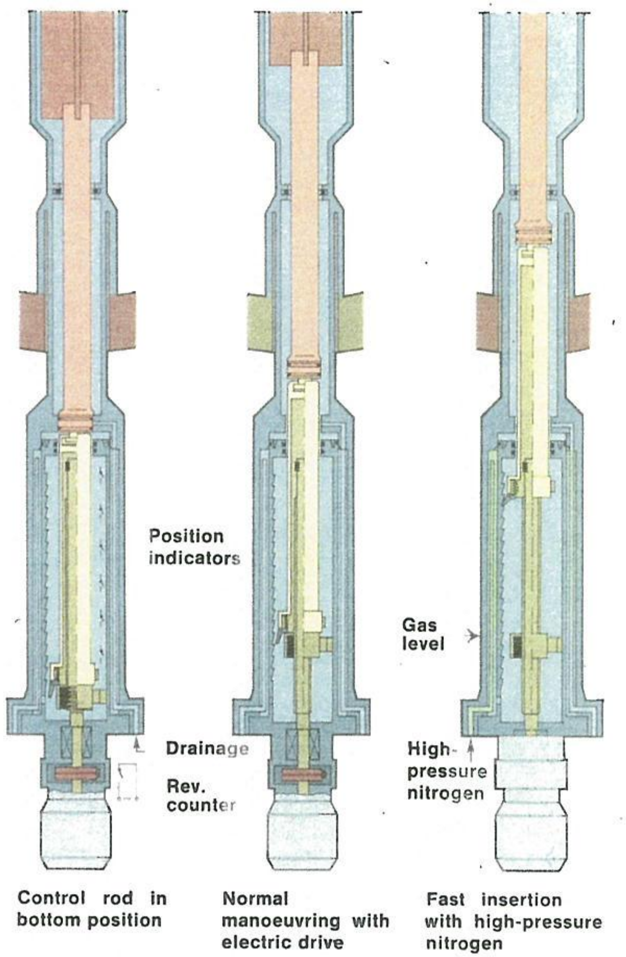
- The CRGT also incorporates a 5 meter long tube which supports a cruciform structure containing the B_4C absorber control rods used for shut-down as well as for power regulation. The cruciform moves up and down in the space between the 4 bundle wrappers.
- The BWR has much greater content of zirconium; therefore, potential for much greater hydrogen generation.
- The largest difference between the PWR and BWR is in the lower plenum. The BWR is full of the CRGT structures, while the PWR is relatively empty. In a typical Nordic BWR, there may be 169 CRGTs arranged in a unit cell structure, except in the outer reaches of the BWR vessel lower head. The CRGTs are full of water and there is a water flow at the rate of 65 gram/sec/CRGT, which is sufficient for removal of long term decay heat.
- Besides the 169 CRGTs there may be up to 66 instrumentation guide tubes (IGTs), inserted between the CRGTs. The construction involves welding joints between larger dia., lower and smaller dia., upper tubes for both CRGTs and IGTs. The welds are vulnerable to thermal attack during melt progression and the lower IGT tube can be ejected out leaving a 7 cm hole in the BWR vessel.

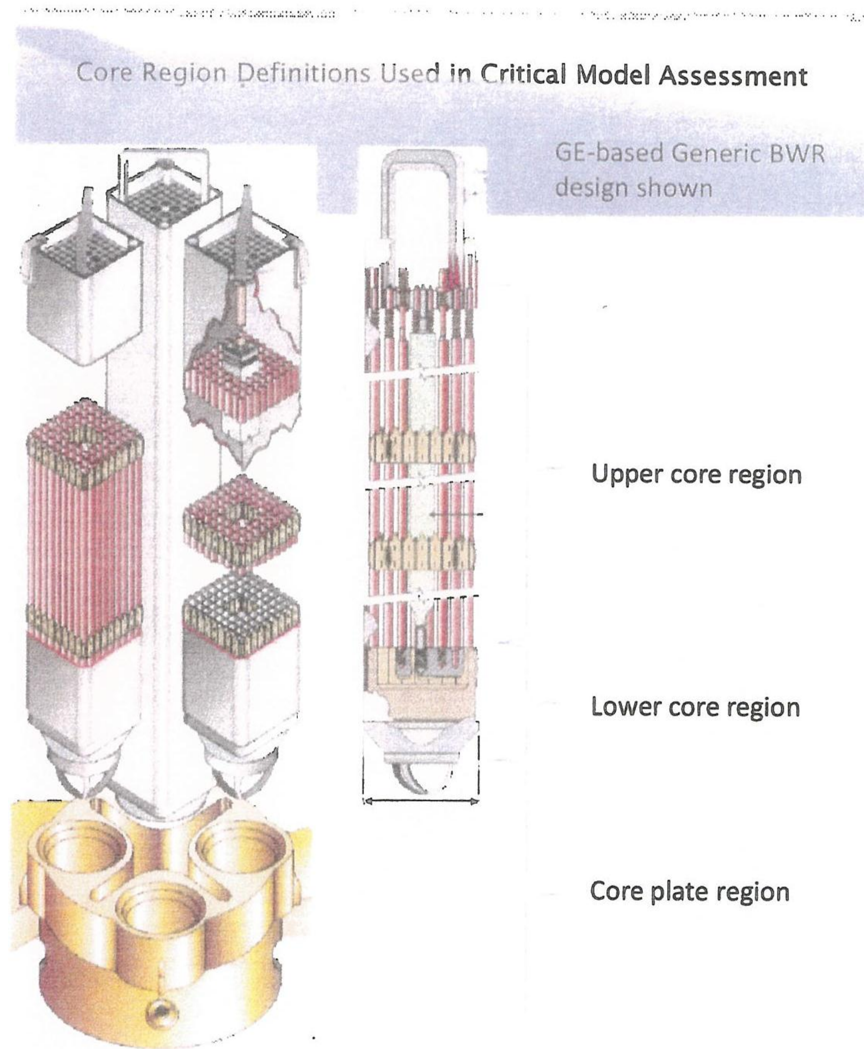


Nordic-BWR internal design



Cross-section of BWR Vessel Lower Head with CRGTs and IGTs.


Position indicators
Drainage
Rev. counter
Gas level
High-pressure nitrogen
Control rod in bottom position
Normal manoeuvring with electric drive
Fast insertion with high-pressure nitrogen

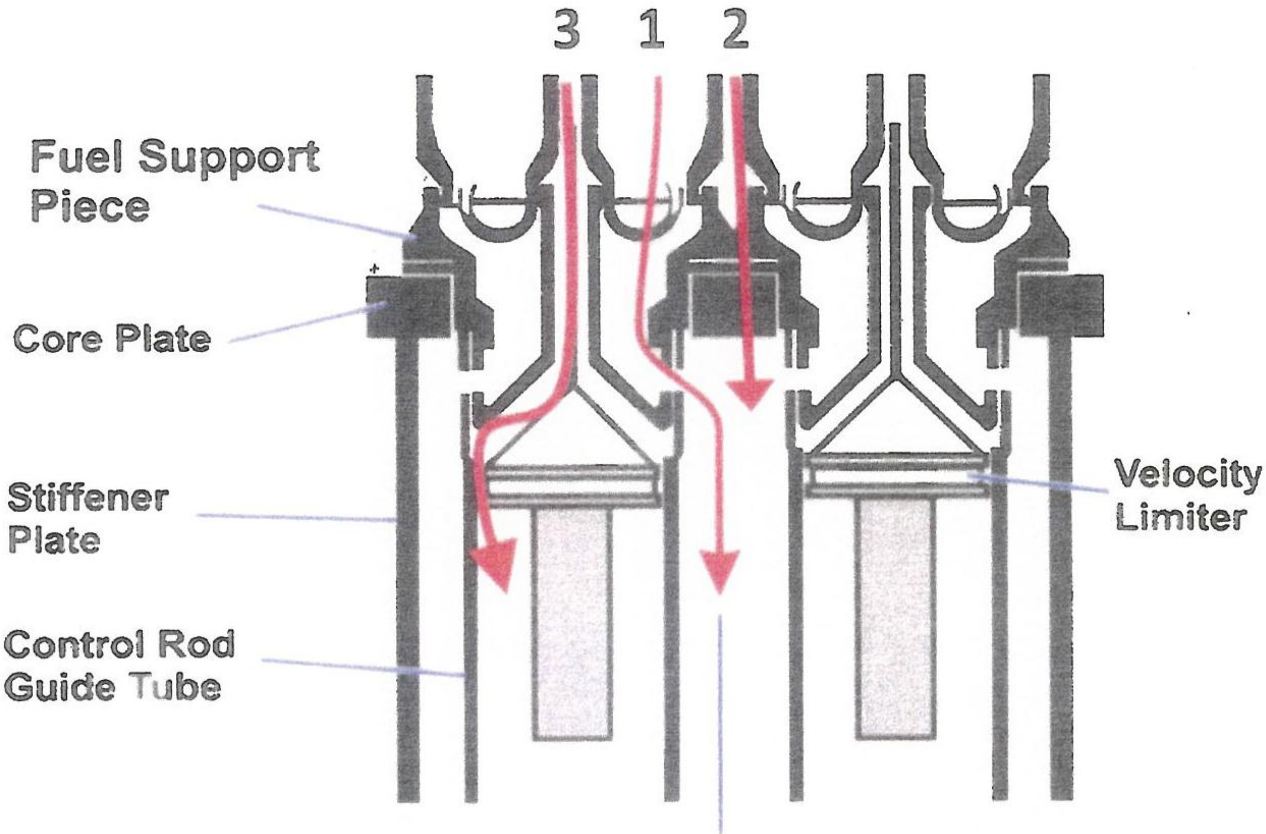

Core Region Definitions Used in Critical Model Assessment
GE-based Generic BWR design shown
Upper core region
Lower core region
Core plate region

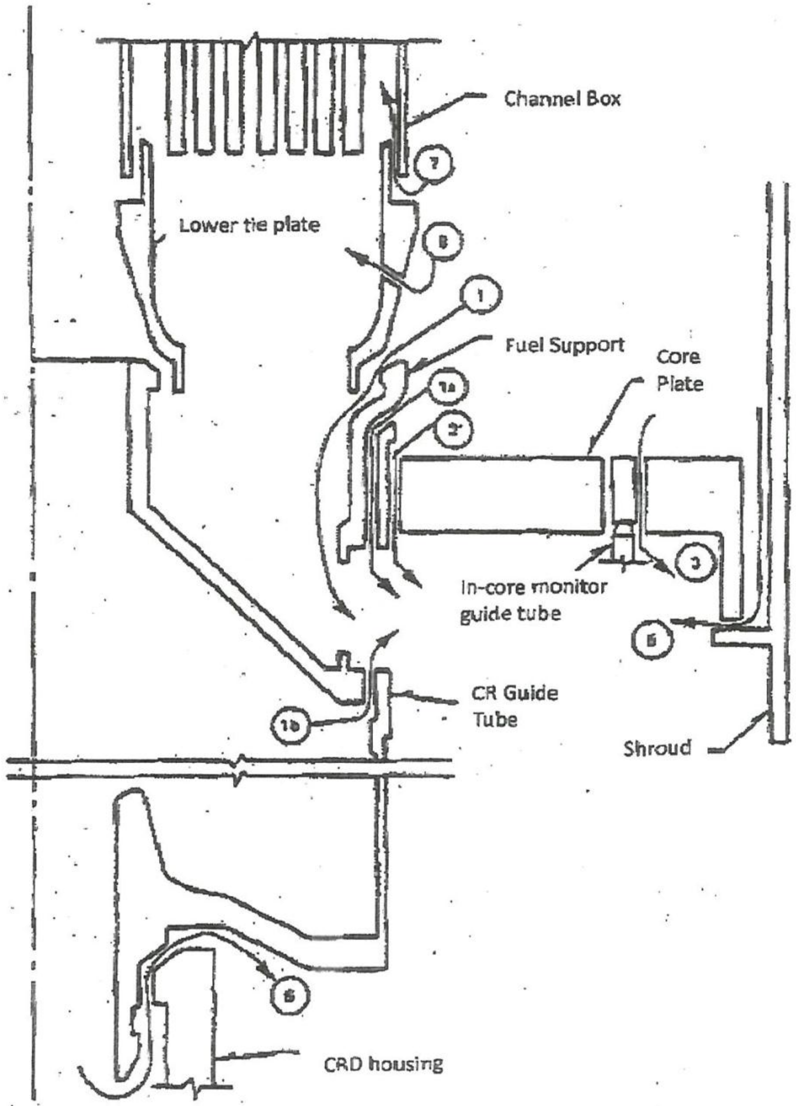
BWR Severe Accident Melt Progression-1

- The BWR severe accident starts like that in a PWR, i.e., heat-up of fuel due to lack of cooling. The B_4C in control blades makes a eutectic with stainless steel clad which melts at about 1000ºC. This melt candles down to the core support plate, where it freezes.
- Further heat up results in formation of U-Zr eutectic which melts at 1900ºC, candling down to the bottom of the fuel rods, close to core support plate. It freezes if the lower plenum water level touches the core plate.
- More melt joins the frozen melt and eventually the frozen melt liquefies and heads towards the water below the core plate.
- The molten zircaloy wrappers also candle down to the core plate which heats up as well. Its creep failure can be an issue, if there is no heat transported to water in the plenum of BWR.

BWR Severe Accident Melt Progression-2

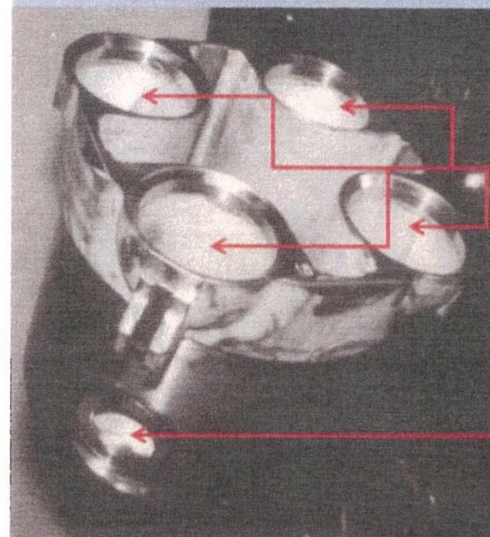
- The major flow of the melted core fuel is through the passage leading from the rod bundles to the water region between the 4 CRGTs. Some of the melted Zr and control rod material could also go along with the molten fuel.
- The conservative assumption would be that all the melt from 4 fuel bundles would descend into the water region between 4 CRGTs.
- It should be recognized that the BWR configuration in the lower plenum and in the core is a set of repeating unit cells and the analysis of melt progression in one cell could represent the consequence of melt progression in the whole lower plenum.


3
1
2
Fuel Support Piece
Core Plate
Stiffener Plate
Control Rod Guide Tube
Velocity Limiter



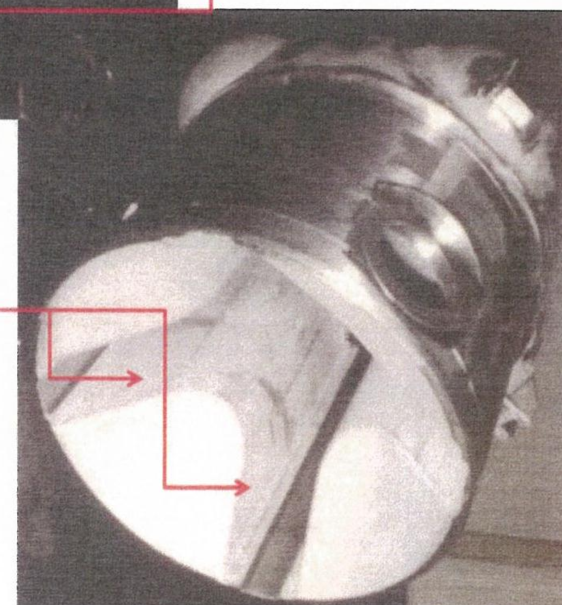
Current Investigation of Melt Relocation in Lower Core Non-Fuel Nodes

Full Support Piece: Top View

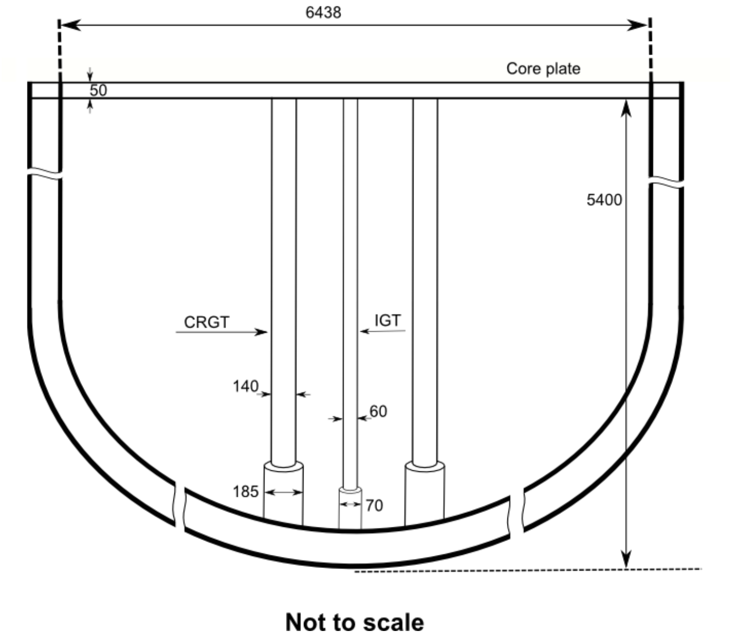


Path 1:
If molten debris accumulates in inlet nozzle (Path 1), the nozzle holes are large so freezing and plugging is not a probable event.

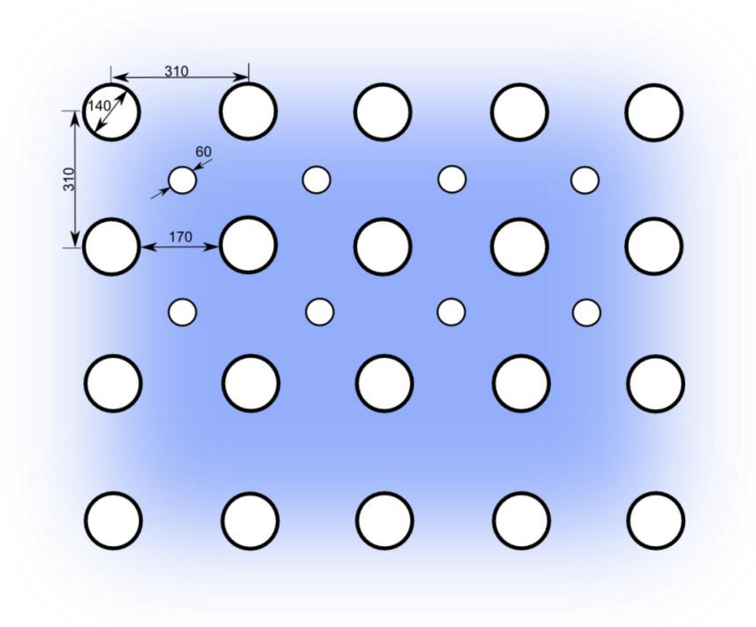
Full Support Piece: Bottom View



Path 3:
If molten debris accumulates, the travel distances are relatively short, so freezing and plugging is <u>not</u> certain.



Configuration of the CRGTs and IGT in BWR Lower Plenum



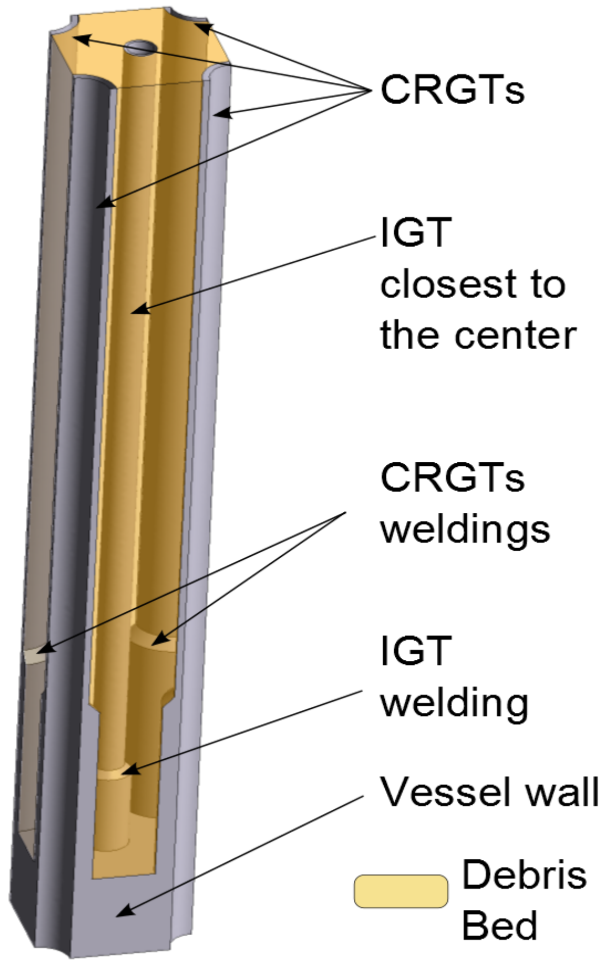
Periodic (cellular) structure of CRGTs and IGTs in BWR Lower Plenum

BWR Severe Accident Melt Progression-3

- It should also be recognized that the core melt progression will not be the same in all the cells, since the core power generation in a BWR is quite non-uniform (contrary to that in a PWR) from bundle to bundle.
- On the basis of conservatism it should be assumed that the 4 rod bundles supported by one CRGT are together in the melt progression process and contribute all of their molten material together to the 5 meter deep water region between 4 CRGTs.
- Accepting this scenario, the melt amount to consider for a water cell between 4 CRGTs is approximately 1300 kg.
- Considering the water available in the unit cell, heat balance gives that only about 560 kg can be quenched. The debris formed may be agglomerated and difficult to quench.
- The questions to ask are: “what are the subsequent events?” and “what are the timings of their occurrence?”

The Interaction of Melt with Water and Structures in the Unit Cell-1

- The interaction of about 1300kg of melt with the water in the unit cell between the 4 CRGTs would be a highly transient process.
- The pressure generated, caused by the high heat transfer will displace the water to the neighboring unit cells, which will have difficulty in returning water to the unit cell in which the melt was dropped.
- The melt accumulated near the bottom of the unit cell in the form of liquid or particles could be in direct contact with the welds on the CRGT and IGT tubes. If there was any water left in the unit cell, it would evaporate readily.
- The attack of the melt/debris on the IGT weld is of high consequence, since the bottom part of the IGT could drop-off from the vessel and create a hole of 70 mm initial radius.



Unit Cell Volume with IGT surrounded by 4 CRGTs.

The Interaction of Melt with Water and Structures in the Unit Cell-2

- This could be repeated in the neighboring unit cells or unit cells farther away. There could be a series of holes, initially of 70 mm dia, but increasing in size as the melt/debris flows through them to regions below the vessel.
- The melt/debris, generating decay heat, will also attack the outer walls of the 4 CRGTs. After some time, the water inside the CRGTs will evaporate and the outer walls of the 4 CRGTs could be breached, providing another pathway for the melt/debris to exit from the vessel. Crusts could be formed, however, a complete blocking of the CRGT is not expected due to its large diameter (185 mm) and the short traverse length (≤ 150 mm) inside the vessel wall.
- The above scenario of melt progression in the lower plenum of a BWR is presently a conjecture, perhaps a knowledgeable one; but it needs experimental configuration.

The Interaction of Melt with Water and Structures in the Unit Cell-3

- The mode of vessel failure in this “conjectured-scenario” is a series of small holes, with small amounts of melt/debris discharged through each hole, simultaneously or in succession.
- This scenario of melt discharge is very different from the predictions of the MAAP and the MELCOR codes.
- The implications of such a scenario on the containment loadings are also very different from those predicted by MAAP and MELCOR codes.

Implications of the “Conjectured” Melt Progression Scenario on the BWR Containment Loadings

- Clearly the melt released from the BWR vessel in the form of several non-simultaneous, melt/debris jets of ≈ 70 mm initial dia. will have much different consequences for the BWR containments.
- For the Nordic BWRs, the containment cavity is filled with water with depths of 9-12 meters. The melt discharge from small holes in the vessel would be of much smaller consequence, in particular, when the melt/debris jets are already fragmented by the time they hit water in the containment cavity.
- For the containments of the G.E. design with a dry well full of water, there is again much lower probability of containment failure, due to the small loadings of the melt itself, and also perhaps of the intermittent nature of the melt delivery to containment.

Results for Analysis for Temperature in the Unit Cell-1

- Some analyses were performed for the unit cell filled with a debris bed of certain height for the temperatures of the IGT and CRGT welds. It was assumed that the debris bed is dry with porosity of 0.4. The configuration is shown in the slide.

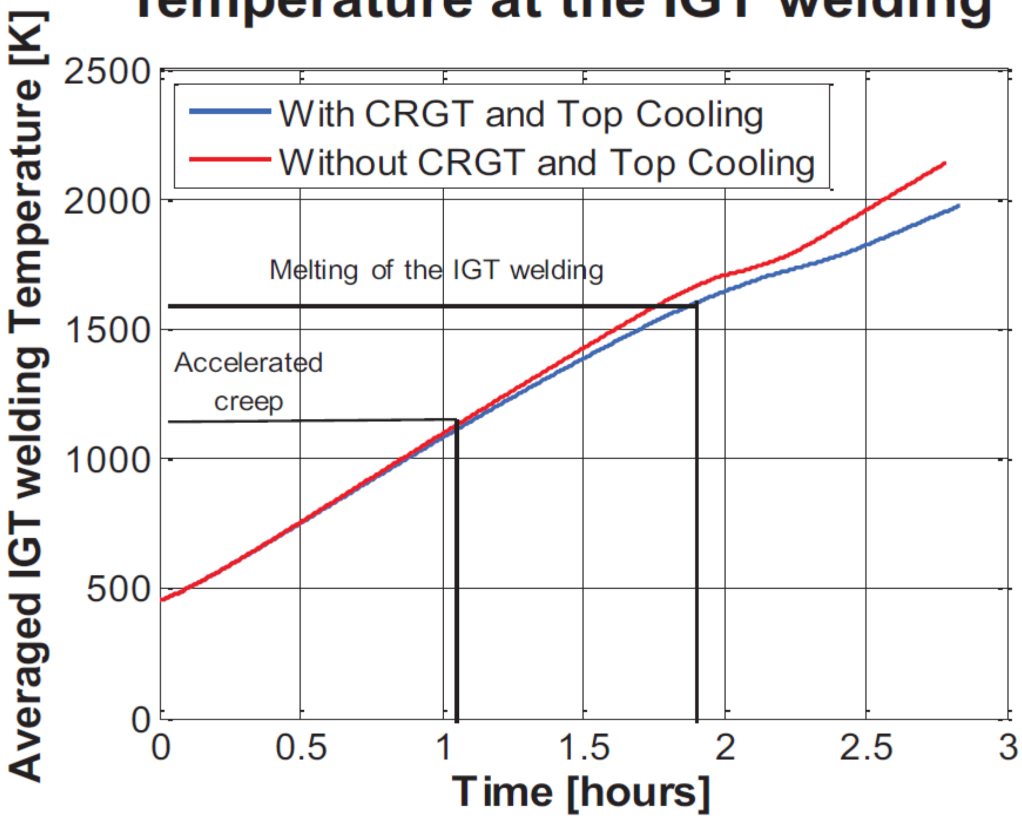
- The IGT weld is shown to reach the temperature of ≈ 1100 K in approximately 1 hour and melting temperature in 1.85 hours. The CRGT reaches melting temperature in about 3.1 hours. Localized creep temp. is reached in about 3.75 hours and later vessel bottom could baloon at 4.6 hours. All of these results are derived with only decay heating, i.e. without sensible heat of core melt.

Results for Analysis for Temperature in the Unit Cell-2

- What becomes clear from these analyses is that the IGT weld failure between 1 and 1.85 hours could preempt other failure modes by a large margin. The next failure would be the penetration of the CRGT and flow of melt/debris through the CRGT to the containment. Individual times for various failures are noted.

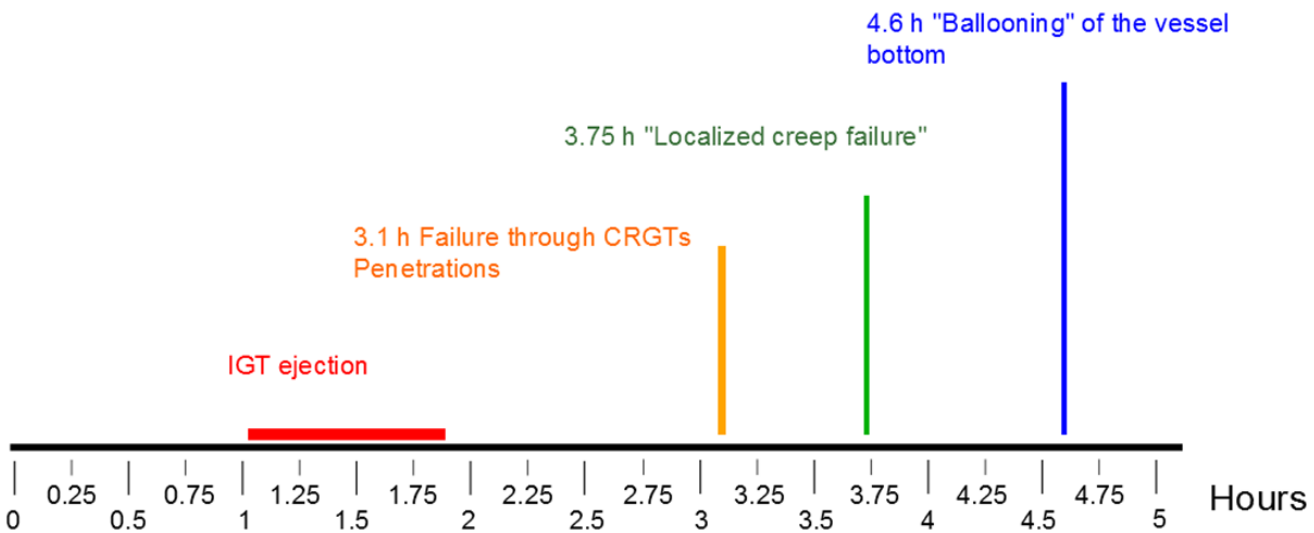
- Analyses were performed with a debris height of 1.9 m and of 0.7 m, signifying both a large scale accident involving the whole core and a partial core melt accident. It was found that there was not a large difference between the analyses results obtained.

Temperature at the IGT welding



- IGT Welding accelerated creep: ~1 h
- IGT Welding melt temperature: ~1.9h

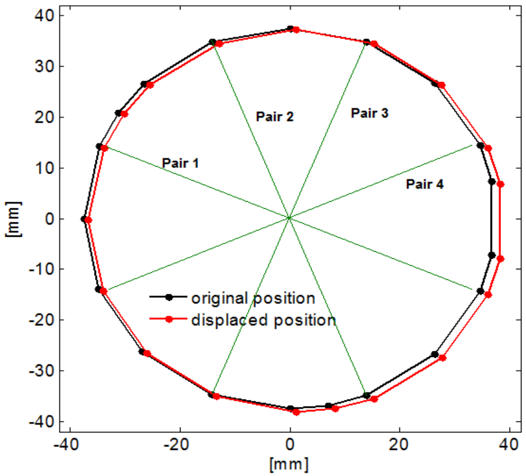
IGT welding temperature transient

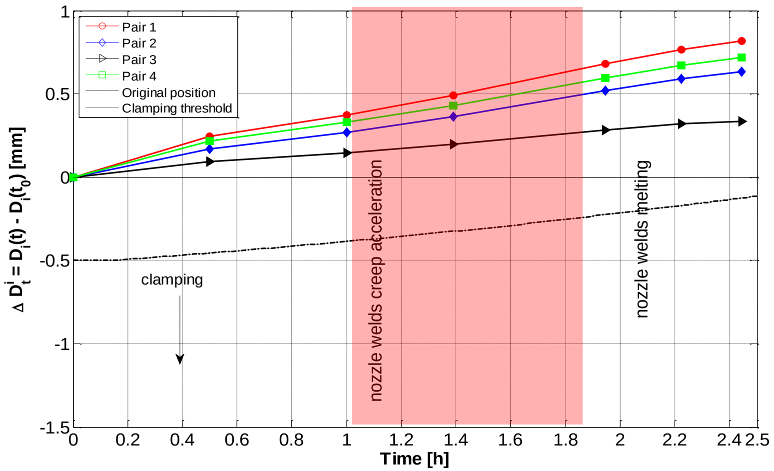


Four different failure modes are identified and the possible timing of their occurrence.

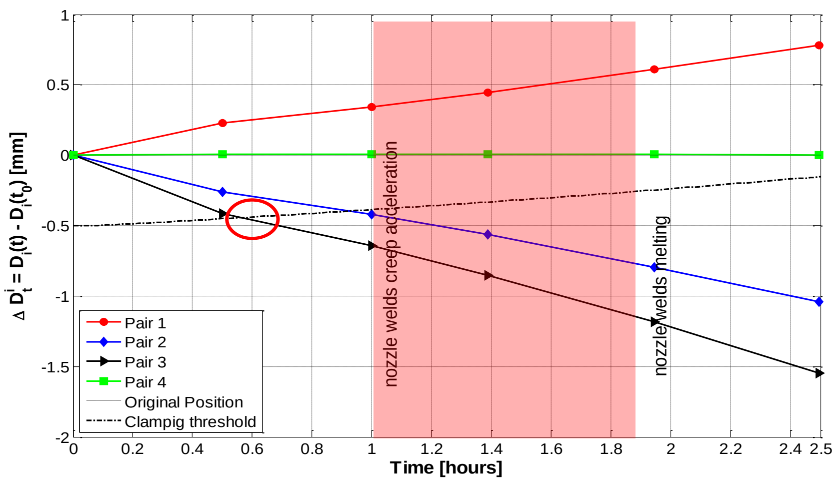
Analyses Results on Clamping of IGT Bottom Section

- Analyses were performed to determine if the vessel heating would result in clamping of the bottom section of the IGT inside the vessel wall. Two positions were considered: (1) one IGT closest from the center of the vessel bottom and (2) another IGT which is farthest.
- Clamping is assessed by changes in distances of diametrically opposite pairs of nodes.
- It was found that the IGTs close to the center of the vessel bottom do not suffer clamping. The clamping one farthest from the vessel bottom center could clamp.
- Thus, the ejection of IGTs near the bottom center of the vessel are possible between 1 and 1.85 hours.
- At that instant the melt/debris temperature is below the liquefaction temperature. Depending on the difference between the vessel pressure and the containment pressure, ejection of the melt/debris could occur immediately following the IGT ejection from the vessel to the containment.





- The closest IGT is not clamped
- IGT ejection is possible between 1 and 1.85 h



- Possibility of clamping of the farthest IGT
- No significant difference between cooling scenarios

Design of an Experiment on BWR Lower Plenum Melt Progression-1

- The BWR lower plenum melt progression scenario presented in this paper should be confirmed experimentally. Towards this purpose a unit cell design is proposed surrounded by some additional radial water volume to observe the disposition of water when a hot melt jet is delivered in the unit cell. The radial extent could be 60.5 cm. To represent 4 CRGTs and one IGT the radial geometry could be full scale.

- The axial height in the plant is 5.4 m. This could be reduced to lower values, since according to Saito's correlation, full fragmentation of a melt jet could be obtained with L/D of ≈19. Thus for a 5 cm melt jet, even 1 to 1.2 m height of the vessel could suffice.

Design of an Experiment on BWR Lower Plenum Melt Progression-2

- The melt volume in the prototypic case is ≈ 160 liters which for the 1 m high vessel instead of 5.4 m height in prototypic case, could be reduced to ≈ 30 liters, which is not easily achieved in most facilities in E.U.

- The melt employed could be a binary non-eutectic oxide mixture e.g. WO_2-ZrO_2 with temperature of ≈ 1600 K. The CRGTs and IGTs could be constructed out of lead to preserve the ΔT between corium and steel melting temperatures.

- These are preliminary ideas, which need backing with extensive analyses.

Conclusions-1

- The BWR severe accident melt progression in the lower plenum has been described with a focus on the mode of vessel failure.

- A knowledge-based scenario has been proposed in which the primary mode of vessel failure is the ejection of the several IGTs present in the BWR vessel. This mode of failure is not the predicted mode from the MAAP and MELCOR codes.

- This mode of vessel failure, if correct, will have quite positive implications for the stabilization and early termination of the severe accident, in particular for the Nordic BWRs. It would also be very beneficial for the termination of the accident in the G.E. designed BWRs.

Conclusion-2

- The proposed scenario and the mode of vessel failure need experimental confirmation. Towards this purpose an experimental approach is outlined, which needs much analysis support for the actual design of the experiment and the experimental program.

- It is suggested that a collaborative experimental research project be developed to obtain the benefits of the proposed severe accident scenario and the mode of vessel failure for the Gen-II BWRs currently operating in the world.