

# SEVERE ACCIDENT PROGRESSION IN THE BWR LOWER PLENUM AND THE MODES OF VESSEL FAILURE

**B.R. Sehgal and S. Bechta**

Division of Nuclear Power Safety, Royal Institute of Technology (KTH)  
AlbaNova University Center, Roslagstullsbacken 21, 106 91 Stockholm, Sweden  
balraj@kth.se, bechta@safety.sci.kth.se

## ABSTRACT

Most of our knowledge base on the severe accident progression in the lower plenum of LWRs is based on the data obtained from the TMI-2 accident. It should be recognized that the lower plenum of a BWR is very different from that of a PWR. Unlike the PWR, the BWR plenum is full of control rod guide tubes (CRGTs) with their axial structural variations. These CRGTs are arranged in a cellular fashion with each CRGT supporting 4 rod bundles. There are also a large number of instrument guide tubes (IGTs), each generally placed in the middle of 4CRGTs. Both the CRGTs and IGTs traverse the thick vessel bottom wall and are welded to their extensions which come to bottom of the core. The core-melt progression in the lower plenum is controlled by the structures present and they, in turn, influence the timings and the modes of vessel failure for a BWR.

The Uranium oxide- Zirconium oxide core melt formed in the 4 fuel bundles is directed by the structure below towards the water regions in-between the 4 CRGTs. The FCI will take place in those water regions and some particulate debris will be created, although there is insufficient water for quenching the melt. A FCI may occur inside a CRGT if and when the melt breaches the wall of the CRGT.

The important issue is whether the welding holding the IGT inside the vessel will fail and the bottom part of the IGT falls out creating a hole in the vessel with release of melt/ particulate debris to the containment. Similarly the failure of CRGT could have melt/particulate debris coming out of the vessel. These modes of vessel failure appear to be credible and they could occur before any large-scale melting and melt pool convection takes place. These modes of vessel failure and the melt release to the containment will have very different consequences than those generated by the other modes of vessel failure.

Such BWR plenum melt progression scenarios have been considered in this paper. Some results of analyses performed at KTH have been described. We believe that the issues raised are important enough to consider a set of experiments for verification and validation of the melt progression in a BWR plenum. Such experiments are proposed.

## KEYWORDS

Severe accident, .

## 1. INTRODUCTION

The BWR core and internals in the BWR vessel lower plenum are quite different from those for a PWR. The BWR core has many more fuel bundles than those in a PWR. Each fuel bundle in a BWR contains far fewer fuel rods than those in a PWR bundle. The BWR fuel bundle is enclosed in a Zircaloy wrapper and each bundle has a separate thermal hydraulic flow profile, compared to an open lattice core of a PWR with an almost uniform flow field throughout the core. The BWR core contains much greater amount of zirconium than that in a PWR core. Thus, there is a potential for much greater quantity of hydrogen generation in a BWR.

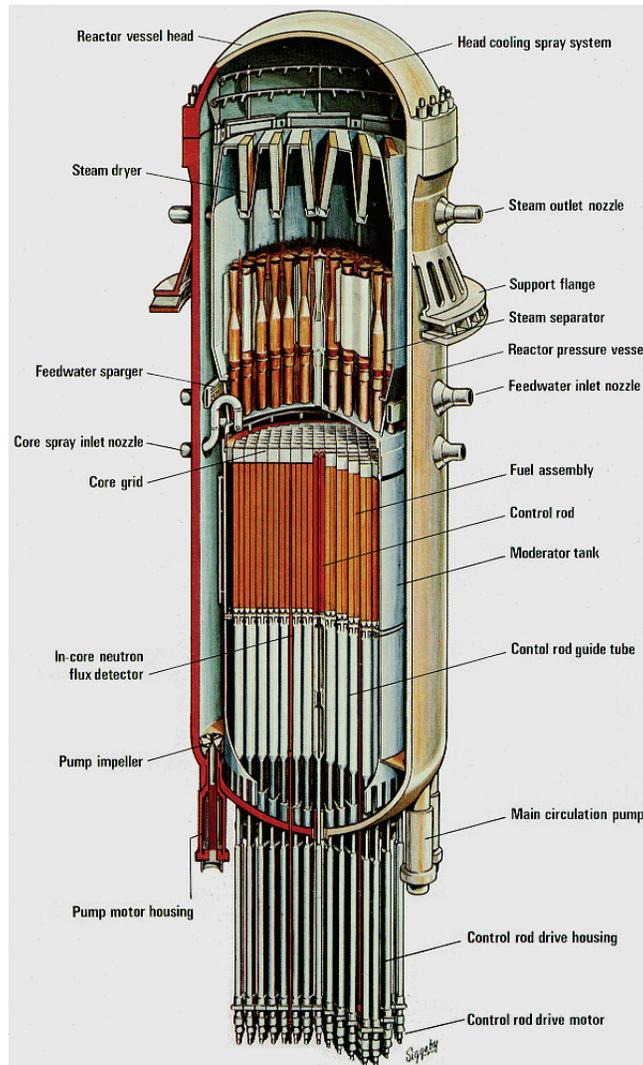


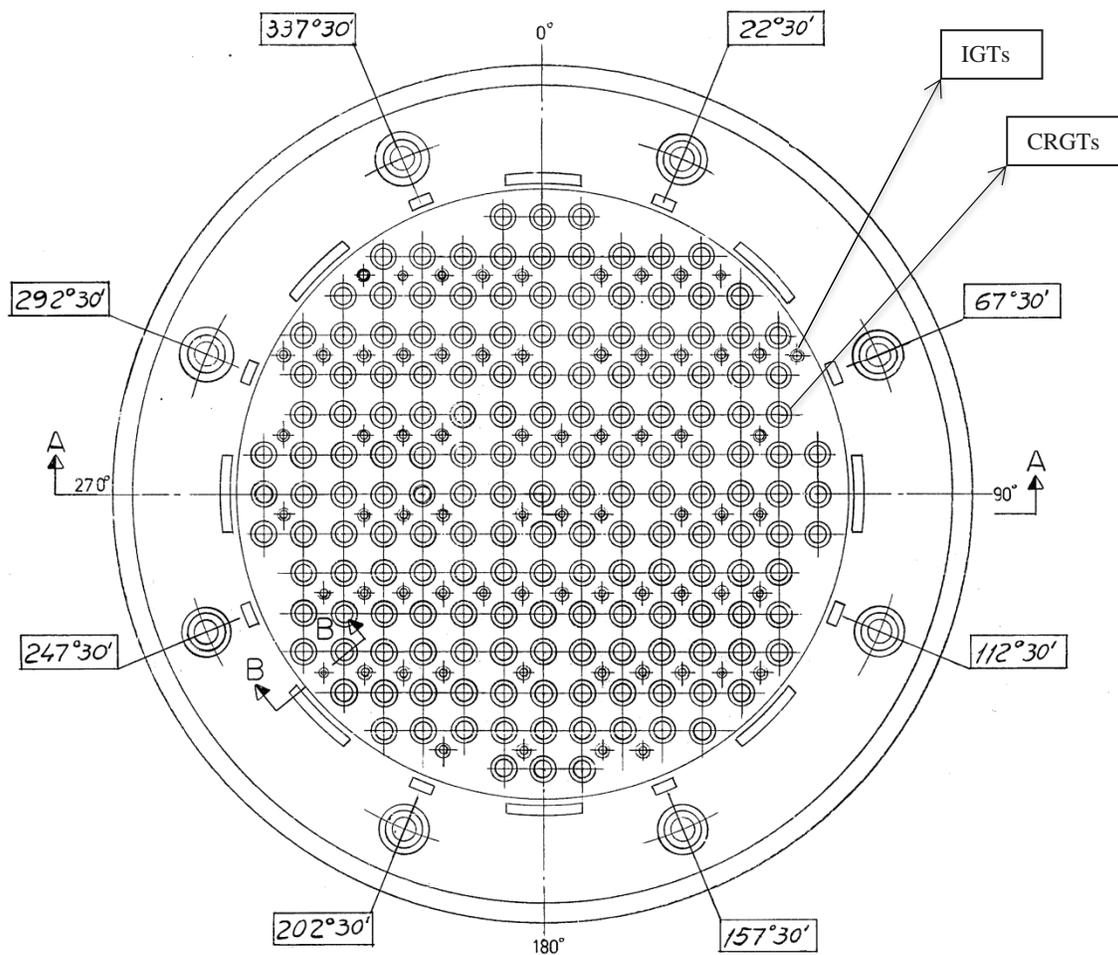
Figure 1. Nordic-BWR internal design.

The rod bundles in a BWR are supported by Control Rod Guide Tubes (CRGTs), in a unit cell structure with 4 bundles supported by one CRGT. The CRGT incorporates a 5 meter long stainless steel tube at the top of which is fixed a cruciform structure, containing the  $B_4C$  absorbers. The cruciform structure moves up and down in the space between the wrappers of the 4 rod bundles. The control rods move up and down to adjust the power level in BWR. In addition, they provide a SCRAM function for a complete shutdown

of the plant. The control rods operate under hydraulic pressure for a fast shutdown, but control rods can be moved with a screw action into the core for adjustment of core power level.

The lower plenum of BWR is almost full of structures unlike that of a PWR.

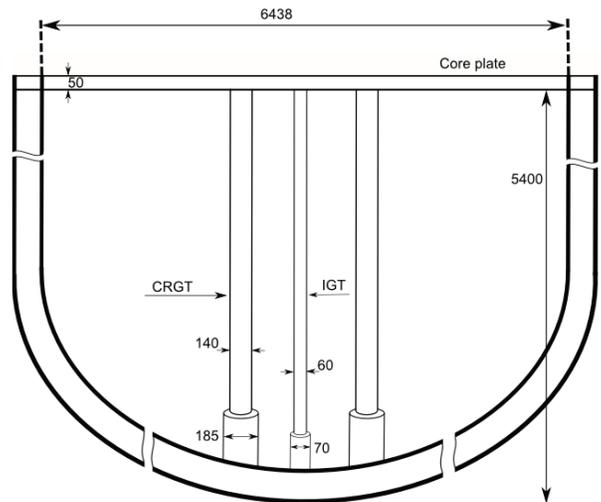
Figure 1, shows how crowded and full of the structures of CRGTs and the in core instrument tubes (IGTs) is the lower plenum of a BWR. These are shown in Figure 2. In a typical Swedish BWR there are as many as 169 CRGTs, 66 IGTs and up to almost 800 rod bundles, including the rod bundles in the space at the periphery of the vessel, where there are very few CRGTs. There are 169 cruciform B4C control rods, one per CRGT. The fuel rod bundles are plugged into the core plate which contains one passage for each 4 bundles, through which the main flow of water enters the 4 bundles. This passage may have an orifice according to the position of the 4 bundles in the core. For example, bundles in the middle of the core require greater water flow, since they are the higher power bundles. The bundles at the core periphery, in general, needs less flow of the coolant.



**Figure 2. Cross-section of BWR Vessel Lower Head with CRGTs and IGTs.**

The CRGT tubes below the core have water flowing inside in a separate water circuit with a pump. The flow is small: 65 grams/sec for each CRGT. However, it is possible to remove the long term decay heat from the core with the flow in the 169 CRGTs. This is what was done when the normal feed water circuits were lost for the Browns Ferry BWR in USA, due to the fire in the electric cable trays.

The construction of a CRGT involves two sections with the lower section of 185 mm. diameter and a long upper section of 140 mm. diameter with a welding joint between them at about 40 cm above the wall of the vessel lower head. This is shown in Figure 3. A structural failure of the stainless steel tube of the CRGT is possible at the welding joint, or even at the wall if attacked thermally by the melt discharged from the rod bundles above.



Not to scale

Figure 3. Configuration of the CRGTs and an IGT in BWR Lower Plenum

The IGTs are of much smaller diameter than that of the CRGTs, as seen in Figure 3. The IGTs are also made of 2 sections i.e. a 70 mm. diameter short section at the bottom welded to a tall 60 mm. diameter section. The IGT weld is also vulnerable to thermal attack during melt progression in the lower plenum. The bottom portion of IGT can be ejected out of the vessel bottom, creating a vessel failure location. In fact, it is possible, that with weld failures several IGT bottom sections fall off outside of the vessel leading to a substantial failure of the vessel. It should be noted that the CRGTs are located in a periodic fashion at the pitch of 310 mm, as indicated in Figure 4.

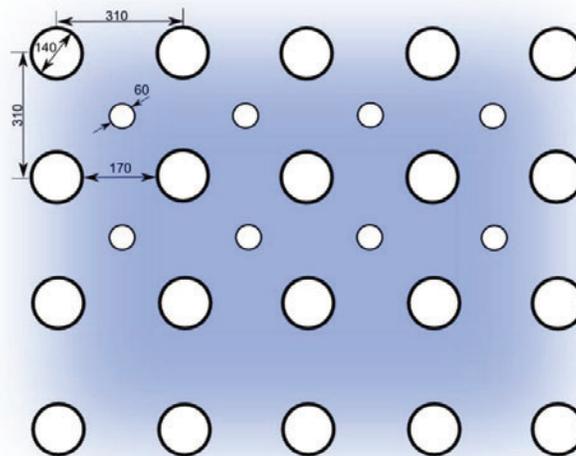
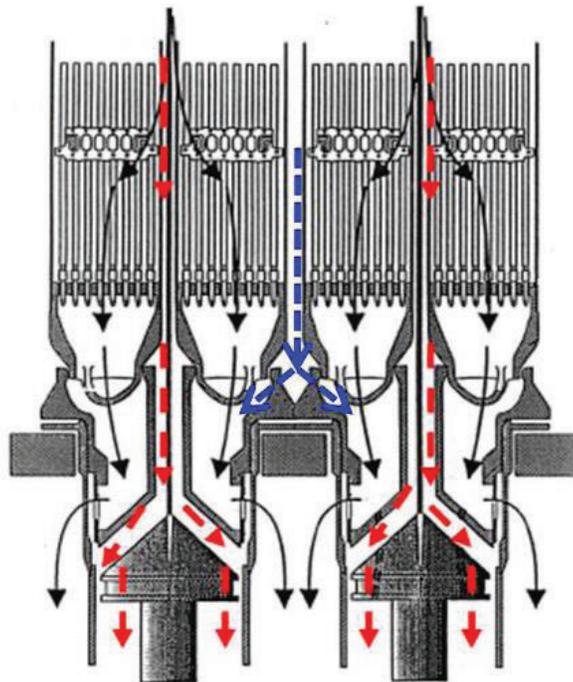


Figure 4. Periodic (cellular) structure of CRGTs and IGTs in BWR Lower Plenum

## 2. BWR SEVERE ACCIDENT MELT PROGRESSION

The postulated severe accident in a BWR starts almost as it does in a PWR, i.e. with the fuel heat-up from the decay heat, in the absence of any cooling; the B<sub>4</sub>C in the control blades makes an eutectic with stainless steel clad which melts at about 1200°C and the eutectic dribbles down along the structure of the control blade to the core support plate where it may freeze. Further heat up results in the formation of zirconium-uranium eutectic at about 1900°C. This cattles down along the fuel rods to freeze near the bottom of the fuel rods, close to core plate. If the severe accident involves automatic depressurization, it is possible that the water level in the lower plenum is below the core plate and the core plate could start heating up, in particular when the uranium-zirconium eutectic imparts the decay heat to the fuel bundle plug-in region of core plate. This could lead to the creep rupture of the core plate. If the severe accident results in the water level in the lower plenum, touching the core plate, the heat removal is sufficient to keep the core plate cool enough not to suffer creep rupture.



**Figure 5. Possible main material relocation paths: red: Melt within the FE bypass and flow down into CRGT, blue: melt within the bypass and flow down between CRGT after failure of FE foot/canister, black: melt with FE channel and flow between CRGT.**

The details of the movement of various melt streams are depicted in Fig.5. The boron carbide-steel eutectic melt is formed in the bypass region between the fuel bundle wrappers and this could be migrating to the CRGTs, where it would interact with the water and structure in the CRGTs. The uranium and Zirconium melt formed in the rod bundles would follow the pathway of the water and will flow down into the water pool between the 4 CRGTs. The melt formed from the Zirconium wrappers could also be following the same route as the melt from the rod bundles.

Considering the scenario in which the core plate is touching the water in the lower plenum in the BWR, the melt formed during heat up process will eventually liquefy the deposited- freshly-frozen melt near the bottom of the rod bundles and the melt streams from the 16 bundles will go down the pathways depicted in Fig.5. Clearly, the largest fraction of the melt generated, i.e. the Zirconium and Uranium in the 16 rod

bundles would follow the pathway of the water entry into the core plate and land into the water region between the 4 CRGTs.

At this moment it should be recognized that the BWR configuration in the core and in the lower plenum is a set of repeating unit cells and analysis of melt progression in one unit cell could represent the action in the whole lower plenum. But, it also must be realized that the core melt scenario will not be uniform over the whole core, since there are regions of unequal power generation in the core. In fact, BWR power generation is much more spatially inhomogeneous than that in a PWR. Nevertheless, analysis of the melt progression in one unit cell and its interaction with the structures in the BWR lower plenum is entirely appropriate to obtain the average behavior of the melt-water-structure interactions in the lower plenum of the BWR.

Here, we must make some conservative assumptions. In this context, it is entirely appropriate to assume that all of the 16 fuel bundles supported by the 4 CRGTs are involved simultaneously in core heat up and the melt progression process. With this assumption the melt amount to consider for a water cell between the 4 CRGTs would be approximately:

$$\frac{4}{800} \cdot (1.58 \cdot 10^5 \text{UO}_2 + 7.2 \cdot 10^4 \text{Zr}) \text{kg} = (790 + 360) = 1150 \text{ kg} = 1.15 \text{ tons of U - Zr melt}$$

A similar calculation for the boron carbide-steel eutectic melt entering the CRGT indicates that approximately 150 Kg of this melt would interact with the water and structure contained in each of the four CRGTs. It should be noted that this melt will not be generating decay heat and it would be at a much lower temperature than the U-Zr melt from the fuel bundles, which is discharged to the water volume between the 4 CRGTs. It certainly will evaporate some of the water in the CRGTs but will, probably not fail the CRGT wall.

Considering the water available in the unit cell, between the 4 CRGTs, heat balance gives that only ~560 kg of melt can be quenched. The melt deposited could be in liquid and particulate form and being heavy, would descend to the vicinity of weldings of both the CRGTs and any IGT that are present in the unit cell under consideration. The questions to ask are: "What are subsequent events?" and "What are the timings of their occurrence?"

### **3. THE INTERACTION OF MELT WITH WATER AND THE STRUCTURES OF CRGT, IGT AND THE VESSEL IN THE UNIT CELL.**

The interaction of about 1.15 tons of melt with water in the unit cell between the 4 CRGTs would be a highly transient process. Most probably the water in the unit cell under consideration will be displaced to the neighboring cells due to pressure generated, caused by the high heat transfer provided by the high temperature of the melt and of the particulate debris formed. We believe there will be an exit of water and steam from the unit cell in which the drop of the melt occurred and simultaneously a difficulty for water from other cells to enter into the subject cell due to the maintenance of pressure generated in it.

The collection of the melt in the form of liquid or particles near the bottom of the unit cell is problematic for the structures, since the melt is still generating decay heat at a relatively high level (~1-2 % of the nominal power level). The exit of water may provide time periods when the melt or debris comes in direct contact with the welds on the CRGT and IGT tubes. In addition, the melt/debris may thermally attack the walls of the stainless steel CRGT tubes and could ingress in the tube itself. It should be realized that any left-over water in the unit cell would be evaporating away, and with no additional supply of water to the CRGTs the inside of the CRGTs would be dry very soon.

The attack of melt/debris on the IGT weld is of relatively high consequence, since the 70 mm diameter tube coming inside the vessel from below the vessel could drop out and create a 70 mm hole in the vessel. This may occur readily if the vessel pressure is elevated, as it was in the Fukushima accident scenarios. This fall-off of the IGT may be repeated in neighboring locations, or even in locations farther away to create a series of holes in the vessel which are initially of 70 mm in diameter. These holes could increase in size as the melt/debris flows through them due to ablation of the vessel material.

The interaction of the melt/debris with the CRGT tube walls could have melt flowing inside the tubes to the regions of tubes below the vessel. The CRGT tubes are rather large (185 mm diameter) however they contain the tube propelling the cruciform control blades. There certainly will be crust formation from the melt/debris flowing inside these tubes; however, the large size of the tubes may not permit formation of a blockage in the whole diameter of the tube and there could be a rather low melt flow to the lower structure of the CRGT. Similar wall attack of an IGT, leading to melt flow within the IGT could heat up any fastening connection of the IGT to the vessel wall and causing its creep rupture.

The vessel failure as a series of rather small holes is envisioned in this scenario. However, currently it is a conjecture and there is no experimental evidence to support the above conjectured progression of the melt in the lower plenum, from the currently accepted melt progression and vessel failure as modeled in the severe accident codes, e.g. MELCOR and MAAP.

The implications of this proposed melt progression process in the BWR lower plenum on the consequences of a severe accident in a BWR, however, will be substantially different from those predicted with the MELCOR and MAAP codes. In this context, it should be pointed out that the MELCOR code follows the melt progression as described above, but later in the melt progression scenario, it fails the core plate resulting from creep-rupture which discharges a large quantity of melt of fuel rods and control rods in the lower head. The lower head fails subsequent to the drop of a large quantity of melt (after it quenches, evaporates the water in lower plenum, and the dry debris bed re-melts from the decay heat). There may be some facility provided to the user for input of failure temperatures which could lead to an alternate progression of the melt and the vessel failure, somewhat like that depicted in this paper, however, in general a large failure of the BWR vessel results from the conventional MAAP and MELCOR analyses. The MAAP code is currently being changed for the melt progression in the lower plenum of a BWR.

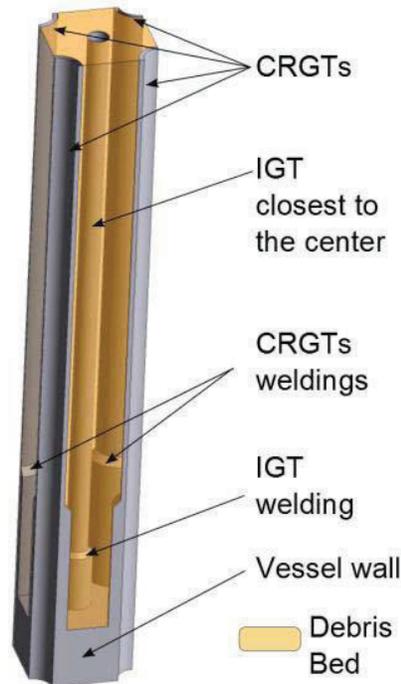
Coming back to the implications of the proposed melt/debris progression in the lower plenum of the BWR, it is clear that it leads to a vessel failure consequence quite different from those predicted by MELCOR and MAAP codes. A series of 70 mm (initially) diameter holes discharging corium melt/debris into a containment cavity full of 9 to 12 meter deep water, as provided in the Nordic BWRs, could be of much lower risk potential than the discharge from a large melt pool from the lower head into the water-filled cavity. In the Nordic BWRs, the discharge of melt/debris from a 70 mm hole would be in the form of a small diameter jet which would break up by the time its leading edge reaches the surface of the pool water. The melt jet will fragment into small-size particles, which will not agglomerate and would be coolable. The steam explosion threat could also be smaller, since the simultaneous melt discharge from a large number of holes in the vessel, formed by the IGT tubes drop-off, may not be very probable. The debris bed could also be coolable in the long term, since (a) not the whole core melt will be received in one drop, (b) the several particulate beds formed will not be very deep and (c) it could be a gradual cool down of the whole core/melt-debris.

The consequences of the above vessel failure scenario for the General Electric MARK-1, MARK-2 and MARK-3 BWRs may depend upon the extent of water injected in their dry wells. Certainly the consequences of a series of small to moderate melt/ particulate debris discharges in the General Electric BWRs will be less severe than those for a large (100 tons or more) drop of melt/ particulate debris.

### 3.1. Results of Analyses for the Temperatures in the Unit Cell.

Some analyses were performed for the configuration of the unit cell identified in the previous sections with the space between the CRGTs filled with a debris bed of certain height **Error! Reference source not found.** The objective was to determine the temperatures at the locations where the IGT and CRGT welds are located. Another objective was to predict timings of the wall melting of the IGT and CRGT.

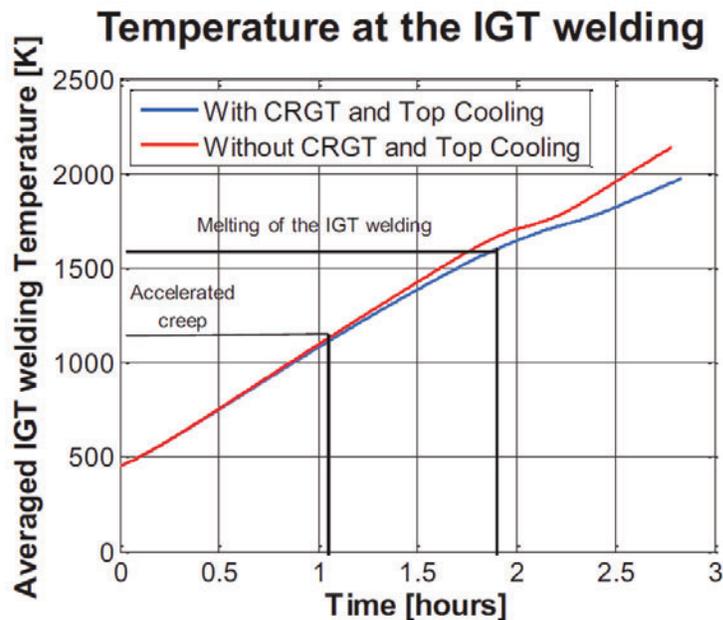
It was assumed that the melt discharged into the unit cell fragments on its interaction with the water in the cell. The debris bed formed is assumed to be uniform with the porosity of about 0.4, i.e., the scenario is a standard one. The heat transfer problem is solved with this scenario without CRGT cooling and top cooling. It is also assumed that all the water in the space between 4 CRGTs has been displaced or evaporated and that debris bed is dry and is heating up with the decay heat according to the ANS recommendation [2].



**Figure 6. Unit Cell Water Volume with IGT surrounded by 4 CRGTs.**

The configuration of the unit cell for the analysis is shown in Fig.6. The analysis concentrates on the temperatures of the locations of the IGT and the CRGT welds and the temperature of the CRGT tube. Fig. 7 shows the average temperature of IGT weld with time. It is found that the welding material reaches the temperature of accelerated creep in about 1 hour and the melting temperature of the welding material is reached in 1.6 to 1.8 hours. The debris height assumed was 1.9 m and the debris bed particle size distribution assumed is like that observed in the FARO tests [2]. It is also found that the debris itself has not reached its melting temperature, before the melting of IGT occurs between 1.6 and 1.8 hours. The melting of CRGT occurs in about 3.1 hours as seen in Fig. 8. The particulate debris itself has not melted yet.

The IGT tube may be ejected from the vessel if the weld fails. The melt ejection mode will be in the form of a 7 cm jet. It could be a mixture of particulate material with some molten corium. In terms of IGT ejection, two locations were considered: (1) an IGT close to the center of the vessel bottom; (2) an IGT farthest away from the vessel center. Clamping of IGT was studied by considering the thermal expansion of the vessel material around the 7 cm hole. It was found that the IGT near the vessel bottom center will not be clamped and IGT ejection is possible between 1 and 1.9 hours after dry out of the particulate melt in the core unit cell. The CRGT failure would be the next event. It was calculated that the CRGT would fail in about ~3.1 hours (see Fig.8).



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

Figure 7. IGT welding temperature transient.

Calculations were performed with a debris bed height 0.7 m, which will correspond to an accident in which melting of a partial core is involved. When there is no cooling of the CRGT, the results for the modes of vessel failure (through IGT ejection and CRGT penetration failure) are quite similar between 0.7 m debris bed and 1.9 m debris bed.

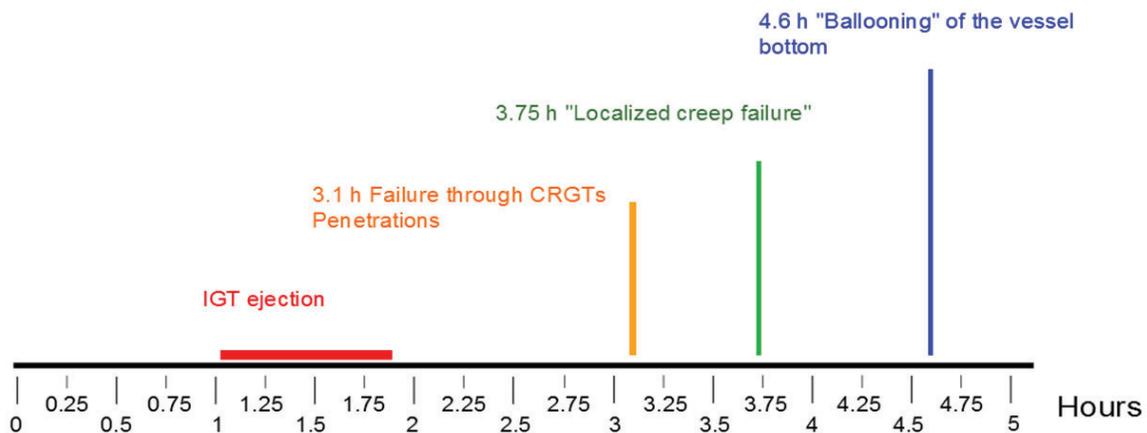


Figure 8. Four different failure modes are identified and the possible timing of their occurrence.

#### 4. DESIGN OF AN EXPERIMENT ON BWR LOWER PLENUM MELT PROGRESSION

The objective of the experiment design is to investigate the interaction of the core melt with the water and the structure in the unit cell identified in sections 2 and 3 of this paper. In particular, the movement of water in the unit cell along with some water from the surrounding cells would be observed as a function of time. The unit cell to choose may be identified in Figs. 4 and 6. The radial extent of the cell will be 4 CRGTs and one IGT, surrounded by water thickness of one-half of the next water cell. The experiment could be performed at full scale, except that the full scale height is 5.4 m. The radial extent can be full scale i.e.  $310 + 185 + 310/2 = 650$  mm, which could be the diameter of the experimental vessel. The chosen height of the water tank could be equal to  $\frac{1}{2}$  scale, i.e. 2.7 m, which may be sufficient since the height determines the extent of the melt jet fragmentation and using Saito's correlation [2] provides that the melt jet diameter could be up to  $270/19 \sim 14$  cm, which is actually the equivalent diameter of water passage in the core plate which leads the water flow to the 4 fuel rod bundles in the G.E. design. The flow diameter could be different in the arrangement in the core plate in the Nordic reactors; however, we believe it could be quite similar to that found in the General Electric design.

The melt material could be the same which has been used at KTH i.e. a mixture of  $WO_3$ -CaO or  $WO_3$ - $ZrO_2$ . These melts would be at 1200- 1400 degrees Celsius, i.e. with a superheat of approximately 0- 200 degrees Celsius. The objective is that the material should fragment as the prototypic melt:  $UO_2$ - $ZrO_2$ , as found in the FARO tests [2]. There is sufficient confidence in the melts employed so far in the KTH laboratory in this respect.

The water temperature should be close to saturation at about 3 bar pressure. The water requirement would be  $\pi \cdot (325)^2 \cdot 2.7 = 0.896$  m<sup>3</sup>, which is a lot of water to heat up. However, the KTH laboratory has 2 large water heaters to supply water at  $\sim 3$  bar saturation temperature. Electric heaters would be needed to maintain the water in the tank at saturation temperature.

The construction of the CRGT and IGT should be as in the plant, except that the construction material could be lead, which provides in the proposed experiment the  $\Delta T$  that exists between prototypic corium melt temperature and the melting temperature of the stainless steel in the prototypic case. The tank itself could be stainless steel to preserve apparatus for further use. The CRGTs and IGTs could be made out of lead.

The tank bottom could be a heavy and thick piece of steel to represent the vessel wall. The construction of CRGTs and IGTs should be prototypic, including the welding at proper elevations.

The amount of melt to be discharged into the water tank cannot be prototypic, since the KTH furnace can probably prepare a melt discharge of only 12 liters. It is estimated that the melt mass in the prototypic case would be about 1.15 tons = 1150 kg/7500 kg/m<sup>3</sup> = 153 liters. So the scaling for the melt volume would not be possible and the observations obtained with  $\sim 12/153 \approx 1/13^{\text{th}}$  scale for melt volume would need to be scaled-up with the appropriate computation tools. The observations would be the temperatures at various locations on the CRGT and IGT.

Another experiment could be, in which the water volume (diameter and height) may be reduced and the water tank accommodates 4 CRGTs and 1 IGT with no additional water around and the height is reduced to 1.00 m. This would be a square water tank of approximately  $0.495$  m  $\cdot$   $0.495$  m  $\cdot$   $1.00$  m =  $0.245$  m<sup>3</sup> which is about 78 % smaller in volume. Again the melt volume of 12 liters would be insufficient; but an improvement from the water volume of  $0.896$  m<sup>3</sup>.

Extensive analysis would need to be performed to determine a good experimental scaling for the melt / water volume issue. What are presented here are very preliminary ideas on the design of the experiments. Much further work will be needed, in terms of assessments, in order to determine the experimental activities which would be most beneficial for clarification of the scenarios of melt interactions with water and structures in the BWR lower plenum.

## **5. CONCLUSIONS**

We believe that an experimental program like the one that has been described above is needed to develop the methodology for the accident progression in a BWR lower plenum. This progression determines the course of the BWR vessel failure and the character of the melt discharge from the vessel to the water pool in the Nordic BWRs; which in turn determines the long term melt coolability and the termination of a postulated core-melt accident.

The experimental program suggested above has been formulated for possible performance at the Nuclear Power Safety (NPS) laboratory at KTH; however it could be performed at other laboratories as well. This Program applies to all BWRs; it should be of interest to U.S. and Japan. In particular, at present, Japan is expressly interested in finding where the melt is in the containments of the Fukushima reactors. This experimental program should be of interest in this quest in Japan. A collaborative experimental test program could be the best outcome.

## **ACKNOWLEDGMENTS**

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