CANDU SEVERE ACCIDENT ANALYSIS

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Romania is now a UE member since January first 2007. New challenges are for our country that includes, also, their nuclear power reactors. Romania operates since 1996 a CANDU nuclear power reactor and soon will start up a second unit. In EU are operated PWR reactors, so, ours have to meet UE standards. Safety analysis guidelines require to model severe accidents for these types of reactors. Starting from previous studies a CANDU degraded core thermal-hydraulic model was developed. The initiating event is a LOCA with simultaneous loss of moderator cooling and the loss of emergency core cooling system (ECCS). This type of accident is likely to modify the reactor geometry and will lead to a severe accident development. When the coolant temperatures inside a pressure tube reaches 1000 C, a contact between pressure tube and calandria tube occurs and the decay heat is transferred to the moderator. Due to the lack of cooling, the moderator eventually begins to boil and is expelled, through the calandria vessel relief ducts, into the containment. Therefore the calandria tubes (fuel channels) uncover, then disintegrate and fall down to the calandria vessel bottom. All the quantity of calandria moderator is vaporized and expelled, the debris will heat up and eventually boil. The heat accumulated in the molten debris will be transferred through the calandria vessel wall to the shield tank water, which surrounds the calandria vessel. The thermal hydraulics phenomena described above are modeled, analyzed and compared with the existing data.

Keywords: CANDU, reactor, severe accidents, thermal hydraulics, debris.

1. Introduction

After the major events as Three Miles Island and especially Chernobyl, accidents beyond design basis, these types of accidents called severe accidents which lead to a core degradation and reactor geometry modification are intensely scrutinized and analyzed. Computer codes which analyze severe accidents were developed. For LWRs: US MELCOR, MAAP4, RELAP5-SCDAP, German ATHLET and the European Union code ASTEC are available. For CANDU severe accidents only MAAP4 CANDU is available. Romania as CANDU owner

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is interested to have CANDU severe accidents analysis available. ASTEC UE code should have a CANDU module in order to analyze this new type of PHWR nuclear reactors, besides the LWRs European reactors.

The paper presents a simple model to analyze severe accident development, given the special features of the CANDU reactor, horizontal core, fuel channels in the pressure tubes, etc.

The CANDU reactor has moderator calandria vessel as ultimate heat sink during severe accident development, which acts also as a core debris catcher.

2. CANDU severe accidents analysis

Nuclear reactor severe accidents are important in terms of consequences: radioactive releases and the public perception.

CANDU reactor is provided with safety features for severe accidents mitigation: two independent shutdown systems, moderator system and the shield tank to remove the reactor decay heat in case of unavailability of other heat sinks.

It is needed to define plant damage categories for severe accident consequence assessment. AECL considers four CANDU reactor fuel damage categories [1]: Local Fuel Damage; Widespread Fuel Damage; In Vessel Core Damage; Ex Vessel Core Damage.

Local fuel damage can happen in case of a LOCA with ECCS available, and only a limited part of fuel channels are affected.

Widespread fuel damage can take place in case of a LOCA with ECCS unavailable. In this case more fuel channels are affected and an important quantity of fission products is released in the primary heat transport system. These fuel damage categories can be considered within the design base accident criteria.

The damage of all fuel channels due to core degraded cooling or in vessel core damage takes place in case of a LOCA, with ECCS and calandria moderator cooling unavailable. This is a development for severe accidents with significant fission releases into containment and core geometry changing. In this case, primary heat system depressurizes, the fuel channels cooling is reduced. The fuel heats up, deforms sags onto pressure tube bottom. The pressure tubes will heat up till 1000 C, when contact the calandria tubes. So, the most part of decay heat is transferred to the calandria moderator. Unless cooling, the moderator begins to heat up causing the pressure inside calandria vessel to increase, as the D2O vapour pressure increases and the calandria moderator begins to swell. This leads to compression of the calandria helium cover gas in the relief ducts. The rupture disks of the pressure relief ducts burst and the D2O moderator overflows into the containment. The moderator is initially in a sub-cooled boiling regime and eventually starts to boil. The moderator is expelled through the relief ducts outside the calandria vessel as a mixture of liquid and vapour. The moderator void

fraction inside the calandria increases and the upper rows of the pressure tubes start to uncover. After calandria tubes (including pressure tubes and fuel bundles) are uncovered, they overheat and calandria tubes may disintegrate and melt. Disintegrated and/or melted components of fuel channels fall into the remaining moderator at the calandria bottom as in the Figure 1 [1].
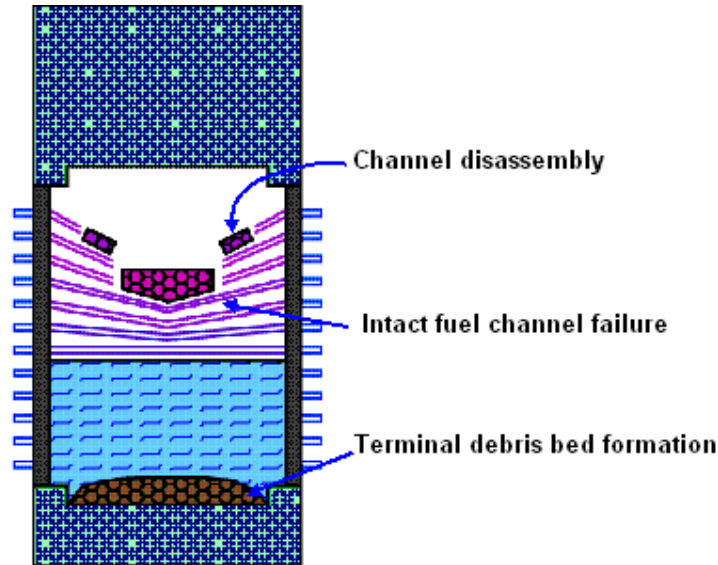

Fig. 1. CANDU core during a severe accident.

As more fuel channels will disintegrate and accumulation of the debris will proceed at the calandria bottom, and as a result, eventually, the entire moderator will be lost from the calandria vessel.

The debris accumulated at the calandria bottom is formed by the Zircaloy pressure tubes, calandria tubes, Zircaloy fuel clad and fuel pellets. Due to the concentrated residual heat the debris this will heat up, melt and eventually reach excessively high temperatures as high as $4000^{0}C$ at which the melted debris will boil. The molten pool is supported by the calandria wall which is cooled externally by the water from the shield tank. The heat from the molten debris pool will be transferred to the water in the shield.

Ex-vessel fuel core damage is in case of a LOCA with ECCS unavailable and calandria and shield tank loss of cooling.

The severe accident scenario is similar with above scenario, completed by the calandria wall melt and break, shield tank water boil off due to the molten debris bed escaped from calandria and, eventually, interaction between debris and concrete vault will take place.

3. CANDU severe accident debris bed thermal hydraulic model RELAP-SCDAP COUPLE module

After the complete disintegration of all the tube rows ends up, there is no more moderator left in the calandria to cool down the debris, which is accumulated at the calandria bottom. The debris temperature begins to rise by the heat generated due to the remaining fission products. Debris temperature can reach the melting temperature of ZrO2 and UO2. Debris will then form a molten pool with the materials fallen down at the calandria bottom. This pool may, eventually, reach the boiling point. The final debris configuration is subdivided in ten equal layers and their temperatures are predicted. At the same time it is examined whether the calandria wall melts down during the process of heat transfer to the shield tank water. It is assumed that the shield tank water cooling is still functioning [2].

These phenomena are modelled by the DEBRIS subroutine.

For comparison reasons, a debris bed model for CANDU 600 transient was developed [3]. This model represents behavior of the calandria vessel bottom where the debris bed is formed after all CANDU channels disintegration. Three volumes of calandria vessel and one volume for the shield tank were used to model the core catcher and the cooling means. The debris and the calandria wall were modeled using COUPLE module of RELAP5 SCDAP. The debris is shared in the finite elements mesh in order to perform the debris heat up and heat transfer to the shield tank water. The COUPLE input data are the debris inventories and residual heat resulted from the CANDU fuel channels disintegration model, above presented.

3. Results and discussion

Severe accident progression evaluation, with the model presented above, needs as input the reactor decay heat power.

The previous assessment establishes that the pressure tube and calandria tube get in full contact in the 6 minutes from the start of severe accident development. In our prediction the rupture disks burst and contact between the calandria vessel and containment through the relief ducts takes place at 15 minutes compared with 9 minutes in the Rogers paper [2]. This is mainly due to lower energy transferred to the calandria moderator. This entire period time calandria moderator is in sub-cooled boiling mode. From this moment important quantities of moderator are expelled through the relief ducts to the containment. At 24 minutes starts transition from moderator sub-cooled boiling to the full saturated boiling mode. At 38 minutes all calandria inventory is in full saturated boiling. Rogers's paper shows that saturated boiling starts at 16 minutes and at 17

minutes all calandria moderator is in full saturated boiling. Important vapor quantities are produced in calandria.

The highest flow rate is reached before moderator generalized full saturated boiling. The first 3 rows uncover at 43 minutes and uncovering process continues up to complete moderator expulsion from calandria vessel. In the Figure 2 is presented the rows uncovering, rows disintegration and correlated with moderator level during boil off process. When fuel channels rows starts to uncover calandria tubes temperature rise sharply to 1500 C. Fuel channel starts to sag reach the lower ones and, eventually, disintegrate and fall dawn on calandria bottom as in Figure 1.
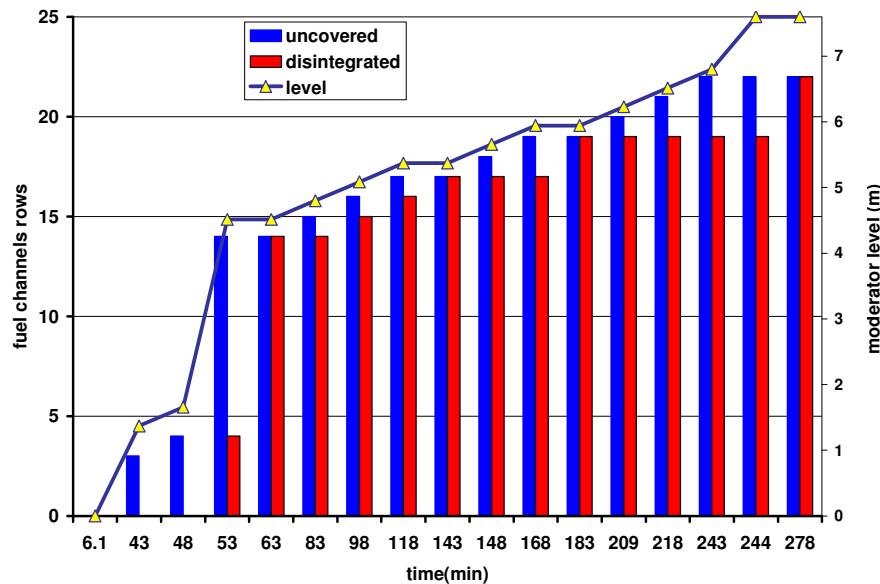

Fig. 2. Uncovered fuel channels rows and calandria level during severe accident
(0 level = maximum D2O level in calandria vessel, 7.6 m = minimum D2O level in calandria).

Our prediction is that the calandria moderator boils off finishes at 278 minutes. This time interval is longer that Rogers value [2] for Bruce reactor. Rogers [4], Meneley et al. [5] predicted for a CANDU 6 severe accident calandria moderator complete boil off a time of 300 minutes. So, our results are closed with that value. A study of AECB [5] gives complete boil off for 2 to 2½ hours, which is shorter than predicted by this paper.

The debris is formed by disintegrated fuel channels material which falls down on the calandria bottom. The solid debris bed begins to heat up, after the moderator is expelled completely from the calandria. Predicted upper debris crust temperature in contact with calandria atmosphere of moderator and fuel and

Zircaloy vapors, middle debris pool temperature, and lower debris crust temperature, in contact with calandria wall bottom obtained by DEBRIS subroutine and RELAP5 SCDAP COUPLE and are compared in the Figure 3 with temperatures from Rogers [5] and Meneley [6]. COUPLE temperatures distribution in the calandria wall and in the debris resulted from fuel channels disintegration is presented in Figure 4.
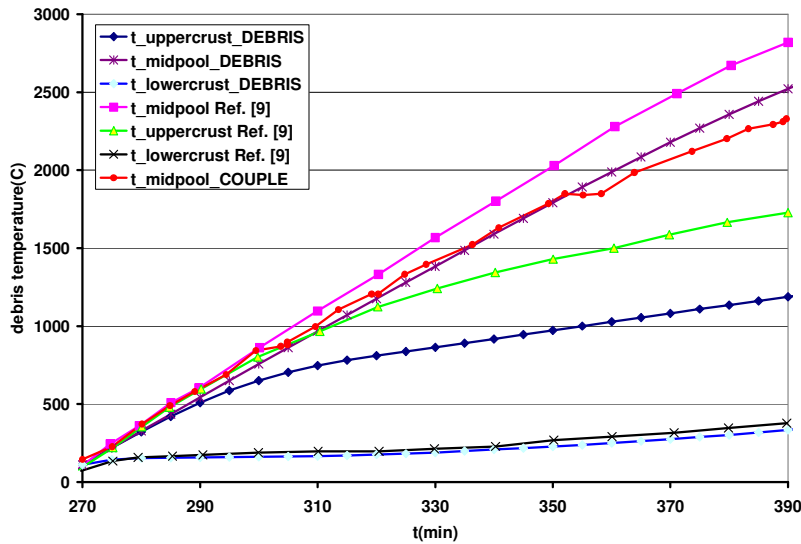

Fig. 3. Heat-up debris core temperatures in a CANDU severe accident.
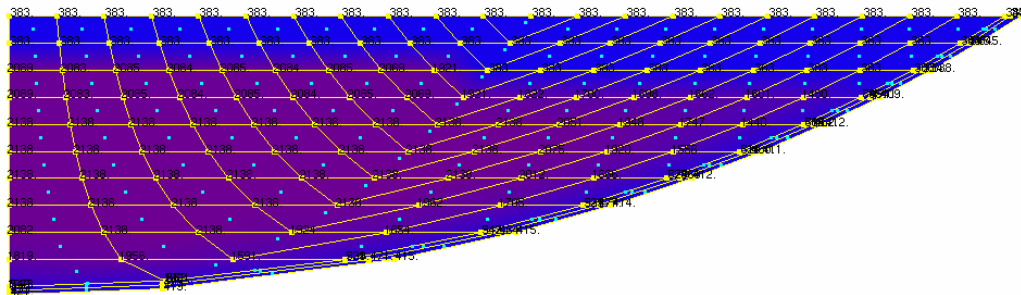

Fig. 4. RELAP5 SCDAP COUPLE debris temperature distribution
for a CANDU 600 severe accident.

4. Conclusions

Finally, we will summarise the important milestones of our CANDU6 severe accident evaluation. The pressure tubes reach 1000 C and contact the

calandria tubes. Therefore, a significant amount of decay heat is transferred to the calandria moderator. The initial heat transfer mode is sub-cooled boiling.

After 6 minutes the calandria tube and the pressure are in contacts and an important quantity of decay heat is transferred to the calandria moderator, the moderator starts sub-cooled boiling. The pressure inside the calandria increases and causes the rupture of pressure relief ducts disks break at 15 minutes.

After 24 minutes transition from sub-cooled boiling to full saturated boiling starts and significant quantities of calandria moderator is expelled out into the containment through the relief ducts.

Full saturated boiling in calandria moderator starts after 38 minutes. The calandria moderator boils off uncovering fuel cannels. At 43 minutes the first three rows of the pressure tubes is uncovered. The uncovered pressure tubes starts to heat up, starts pressure tubes sagging and eventually disintegrate and fall down onto calandria bottom after 53 minutes.

After 278 minutes all the remaining rows disintegrate and fall down on the calandria bottom. The calandria bottom as debris receiver and a retention volume for the fallen material can be regarded as a core catcher. Entire moderator is now expelled out into the containment.

At 278 minutes the debris begins to heat up. The middle of the molten pool reaches over 3300C and boils off. Only a part of the calandria wall melts, due to the cooling of the shield tank, and the molten debris pool remains confined inside the calandria vessel.

The proposed model of a CANDU severe accident seems to give satisfactory results, in comparison with AECL estimations. The data obtained during our evaluation is in good agreement with results from other severe accident assessments for the CANDU type reactors [8, 9].

The present CANDU severe accident model is still in development and we hope consider all the relevant severe accident issues associated with the fuel channels: sagging and disintegration mechanism, debris molten pool interaction with the basement concrete, hydrogen production and explosion, etc. Some of these issues are discussed in more recent papers dedicated to the problem [9].

These models presented are a contribution for CANDU severe accidents benchmark. CANDU severe accidents is still an issue to debate, given lack of experimental data on CANDU fuel channels behavior, their heat up and sagging during calandria moderator boil off and the calandria debris interaction. This analysis is a step to develop an alternate model to the MAAP4.

The model developed is planned to be integrated in the ASTEC code, potentially an EU standard code for severe accident analysis. The LWRs model is to be coupled with one PHWR model due to the fact the CANDU Cernavoda NPP is located now within the geographic border of the European Union. This kind of analysis is an important contribution to the European reactor safety.

Acknowledgements

R E F E R E N C E S

[1]. *P. Mani Mathew*, "Severe Accident Phenomena", in IAEA Meeting on Preparatory Review of Accident Management*,* Bucharest, Romania, 12-16 February 2007.

[2]. *J. T. Rogers*, "Thermal and hydraulic behavior of CANDU cores, under severe accident conditions"*,* in AECB, INFO-1036-3, June 1984.

[3]. *D. Dupleac,* "RELAP 5 CANDU Accident Analysis," in IAEA Meeting on Preparatory Review of Accident Management*,* Bucharest, Romania, 12-16 February 2007.

[4]. *J. T. Rogers,* "Heat and Mass Transfer in Severe Nuclear Reactors Accidents", Begell House, New York, 1995.

[5]. *D. A. Meneley, C Blahnik, J.T. Rogers, V. G. Snell and S Nijhawan*, "Coolability of severely degrade CANDU cores", in AECL-11110, January 1996.