

Research Article

Analysis of Early Severe Accident Initiated by LBLOCA for Qinshan Phase II Nuclear Power Project

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Abstract: The purpose of this study is to simulate an early Severe Accident (SA) scenario more detail through transferring the thermal-hydraulic status of the plant predicted by RELAP5 computer code to SA Program (SAP). Based on the criterion of date extract time, the RELAP5 thermal-hydraulic calculation data is extracted to form a file for SAP input card at 1477K of cladding surface. Relying on the thermal-hydraulic boundary parameters calculated by RELAP5 code, analysis of early SA initiated by the Large Break Loss-of-Coolant Accident (LBLOCA) without mitigation measures for Qinshan Phase II Nuclear Power Plant (QSP-II) performed by SAP through finding the key events of accident sequence, estimating the amount of hydrogen generation and oxidation behavior of the cladding and evaluating the relocation order of the materials collapsed in the central region of the core. The results of this study are expected to improve the SA analysis methodology more detail through analyzing early SA scenario.

Keywords: Cladding oxidation, core degradation, effective stress, LBLOCA, RELAP5, severe accident

INTRODUCTION

Since the Three Mile Island unit-2 nuclear power plant accident in 1979 and Chernobyl Severe Accident (SA) in 1986, a great deal of research has been conducted to obtain an understanding of SA phenomena and to take measures for mitigating the SA consequence in nuclear power plants (US Nuclear Regulatory Commission, 1980, 1987). In 2011, Fukushima Daiichi Nuclear Power Plant accident led by gigantic tsunami has reminded again that the numerous uncertainties inherent in the SA phenomena of nuclear power plants (Hirose, 2012). As a result, the study on SA of nuclear power plant remains the most important in nuclear industry. In order to deepen the understanding of the SA, the codes such as RELAP5/SCADP, MELCOR, ASTEC and ICARE/CATHARE are used to simulate SA sequences and to study the physical phenomenon and chemical reactions in SAs of nuclear power plant.

RELAP5 has been considered to have sufficient accuracy in calculating the thermal-hydraulic behavior of a typical pressurized water reactor during a design basis accident. SCDAP can simulate SA phenomena, including cladding and fuel melting, relocation of core materials, lower head failure, corium-concrete interactions, etc. A deficiency in SCDAP is filling the complex input card, which need more relevant experience for user. Hence, Severe Accident Program

(SAP) to simulate SA has been developed with more flexibility. If the RELAP5 code transfers the thermal-hydraulic state parameters to the SAP as the initial boundary conditions for SA analysis, more realistic analysis can be performed for the whole transient.

In this study, based on the thermal-hydraulic state data calculated by RELAP5, SAP has been applied to simulate the SA initiated by Large Break Loss-of-Coolant Accident (LBLOCA) analysis for QSP-II. This study can be expected to make some contribution to improve the reliability of the SA research by combining with more reliable thermal-hydraulic initial conditions.

MODELS IN SAP

Oxidation models of cladding: In SAP, the simulation of cladding oxidation reaction is achieved through adopting classical oxidation correlations of Zircaloy cladding. According to the library (Schanz *et al.*, 2004), there are several classical parabolic correlations used to calculate the reaction rate in cladding oxidation at elevated temperature. Both RELAP5/SCDAP and MELCOR codes adopt the temperature transition of oxidation rate, the only difference between these two codes is that they take different correlations for ZrO₂ thickness and weight gain, due to Cathcart-Pawel correlations below 1853 K are adopted in RELAP5/SCDAP code because their expressions give the best fit to the pooled data and Urbanic-Heidrick

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correlations are taken in MELCOR code. Therefore, the Cathcart-Pawel correlations are adopted between 1000~1800 K and verified Volchek-Zvonarev “best-fitted” (Volchek *et al.*, 2004; Fichot *et al.*, 2004) correlations are taken above 1800 K in SAP.

Effective stress model of cladding: The gas release time of cladding has significant impact on the progression of core damage during a SA (Idaho National Engineering and Environmental Laboratory, 2003). The RELAP5/SCDAP code uses a mechanistic model called “the sausage deformation model” to calculate the elastic-plastic deformation that can occur in fuel rods during a SA. This sausage deformation model is based on a lot of assumptions (Idaho National Engineering and Environmental Laboratory, 2003), but cladding oxidation does affect the cladding mechanical properties to some extent by changing the external radius of cladding. In order to improve the gap conductivity and postpone the interaction between the fuel pellet and cladding, the gas helium is filled in the gap at the pressure about 2-3 Mpa. The cladding gas release may occur, once the effective stress is greater than the yielding strength at a certain temperature.

Other models: Other models such like core collapse models and core materials relocation models (Sandia National Laboratories, 2000) are adopted from MELCOR reference manual.

COMBINATION METHOD OF CODES

Procedure of appending the SAP: As a reliable code of analyzing the thermal-hydraulic behavior for LWRs, RELAP5 MOD3 has been originally designed to analyze complex thermal-hydraulic interactions that occur during either postulated large or small break loss-of-coolant accidents in Pressured Water Reactors (PWRs) (Idaho National Engineering Laboratory, 2001). However, as code improved gradually, it has been expanded to stimulate the transient scenarios that might occur in thermal-hydraulic systems, such as various transients in experimental and production reactors and reactor simulators. However, RELAP5 cannot simulate SA progression, including failure and melting of cladding, relocation of melts and various phenomena in the core central region. On the other hand, the SAP has been developed for stimulating the core behaviors, including cladding and debris behaviors during SAs in nuclear power plant. Relying on the thermal-hydraulic initial conditions generated by RELAP5, the SAP can be utilized for analyzing the following SAs scenario.

As shown in Fig. 1, the procedure of appending the SAP has been presented. The RELAP5 code version in this study is RELAP5/MOD3.2. At first, RELAP5 code has been run for the design basis accident scenario before which the time point for extracting the required data has been determined based on the proper criterion of the data extracting condition. The required thermal-

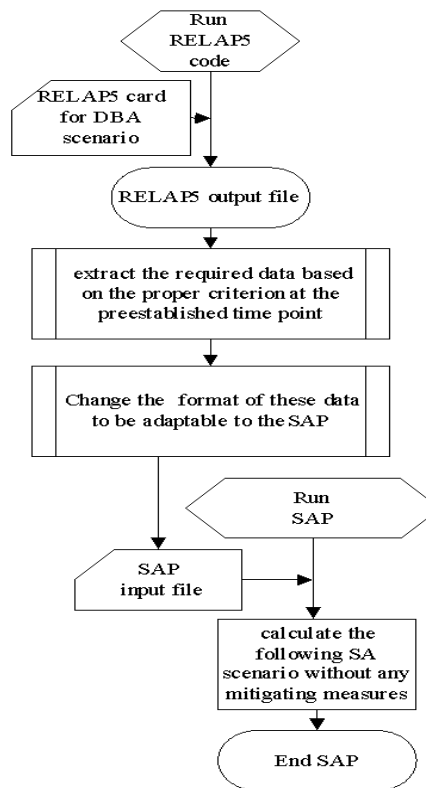


Fig. 1: Procedure of appending the SAP

hydraulic operating data has been extracted from the RELAP5 output file for the corresponding time point. The format of these data generated by RELAP5 is changed that is adaptable to the SAP. After this data transferring, the processed data has been transferred to the input file of the SAP. With the input file SAP can calculate the following SA scenario.

Data extraction and transfer: The detailed mechanistic models are employed in RELAP5/MOD3.2 code for single and two-phase flow. The one-dimensional, semi-implicit forms of the conservation equations for the two-fluid model are solved (Vierow *et al.*, 2004). Thus, several volumes and junctions can be connected as a one-dimensional composition through nodalizing the plant by user. The hydraulic channel and heat structure are separated in RELAP5 code, so the boundary interfaces of these two parts are defined for the calculation of the heat transfer. The lumped method has been applied for calculating the physical state of the core nodes in SAP likes MELCOR and MAAP4 codes. The core node of SAP code is composed of several ring-shaped sub-nodes, with fuel component, cladding component, control rod component, other structures component and thermal-hydraulic materials in it. The diagram is presented in Fig. 2 explains the corresponding correlation of heat structures between RELPA5 and SAP code.

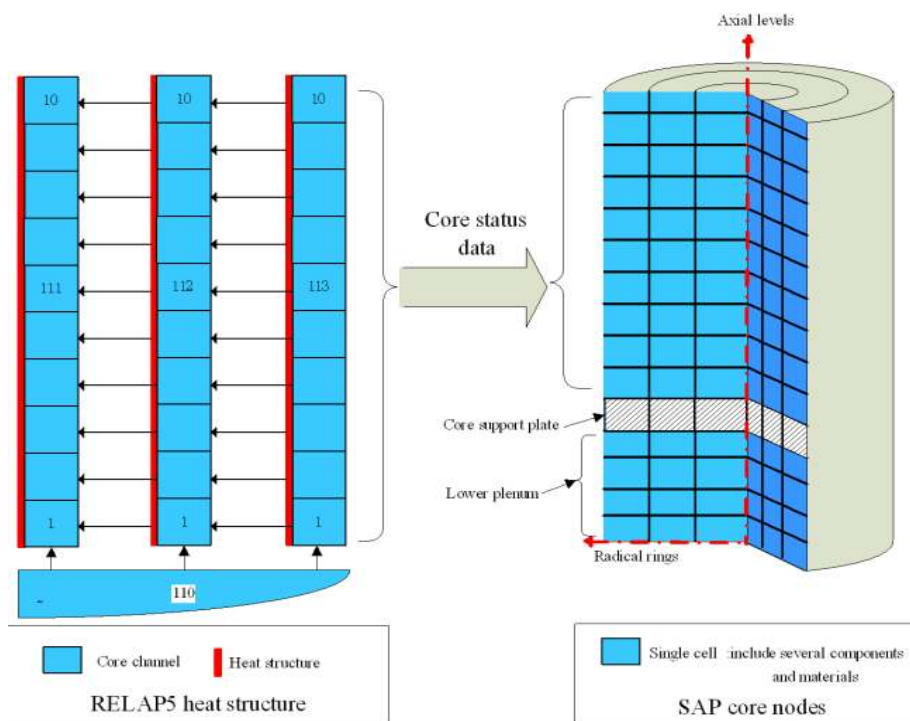


Fig. 2: Corresponding correlation between RELAP5 and SAP

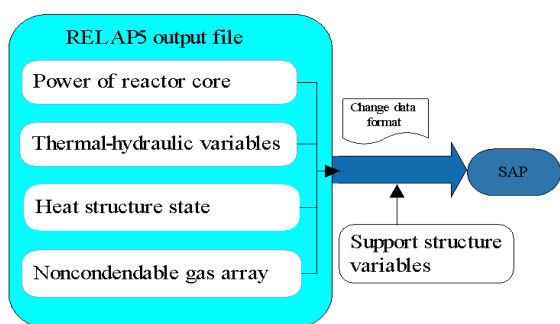


Fig. 3: Flow of the information from RELAP5 to SAP

Variables transferred from RELAP5 to SAP:

RELAP5 output variables have been transferred to SAP for simulating the behavior of the reactor core. These variables are composed of four parts, namely the reactor operation history, thermal-hydraulic variables, heat structure state and non-condensable gas array, as shown in Fig. 3. Besides the fuel rods and control rods, support structure is the most important component in the core region, so the variables of support structure are indispensable for the SAP input file.

Decision of the time point of data extraction: The LBLOCA in LWRs has highest risk among the design basis accidents with two acceptance criteria:

- The peak temperature of cladding is less than 1477 K.

- The maximum oxide scale thickness is less than 17% of initial cladding thickness.

According to “Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications” (ASME, 2002), published by ASME in 2002, the first two criteria of core damage in PWR has been mentioned:

- Collapsed liquid level below the top of active fuel for a prolonged period
- Code predicted core peak node temperature over 1477 K, using a code with detailed core modeling

Hence, taking into account the principles described above, the criterion of the data extract time can be set to the design basis accident peak cladding temperature, 1477 K, after liquid level below the top of active fuel. This criterion enables further application of the RELAP5 thermal-hydraulic calculation.

APPLICATION OF COMBINED CODES TO THE QSP-II DURING SA INITIATED BY LBLOCA

Description of LBLOCA for QSP-II: The base case LBLOCA sequence is assumed to occur with the break area of 0.3820 m² at 0.0 sec in a cold leg. The main input parameters are shown in Table 1. The several functional assumptions for LBLOCA scenario are:

Table 1: Main input parameters

System parameter	Nominal value
Core power, MW	1930
Primary loop pressure, MPa	15.5
Average temperature of coolant, K	583.15
Coolant loop flow, m ³ /h	46640
Active height, m	3.658
Number of assemblies	121
Total mass of zircalloy, kg	14027
Total mass of fuel, kg	63283

Table 2: Key events predicted during a LBLOCA sequence

Key events	Time/sec
Accident initiation	0.000
Reactor trip (manual)	0.000
Start of core uncover	0.001
Start of zircaloy cladding oxidation	1.275
Cladding failure of ring 1	2.211
Bottom level of core	4.127
Cladding failure of ring 2	5.507
Cladding failure of ring 3	37.246

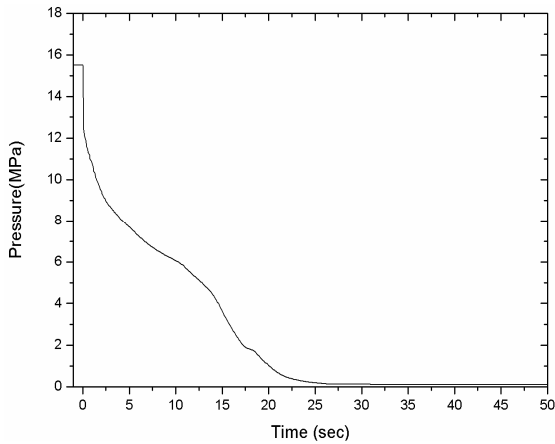


Fig. 4: Reactor coolant system pressure

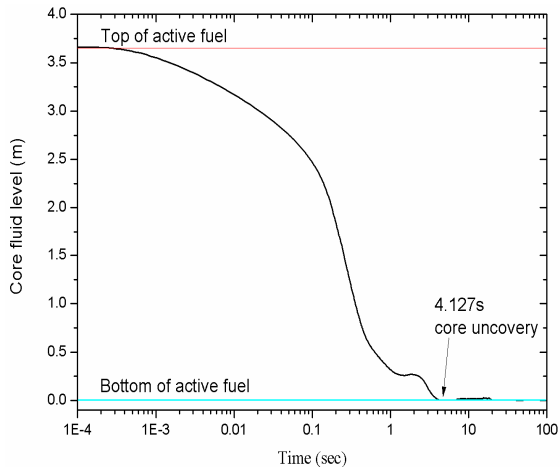


Fig. 5: Water level in the active fuel region

- The reactor trip occurs following the LBLOCA
- The Emergency Core Cooling System (ECCS) and safety injection pumps are unavailable
- The main pump runs down after the accident
- Gap release starts at 1173 K

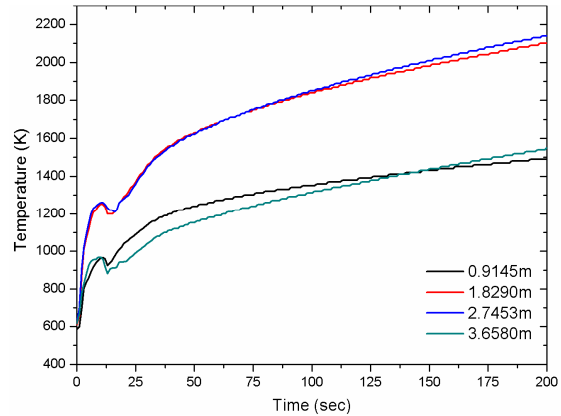


Fig. 6: Cladding surface temperature in core ring 1

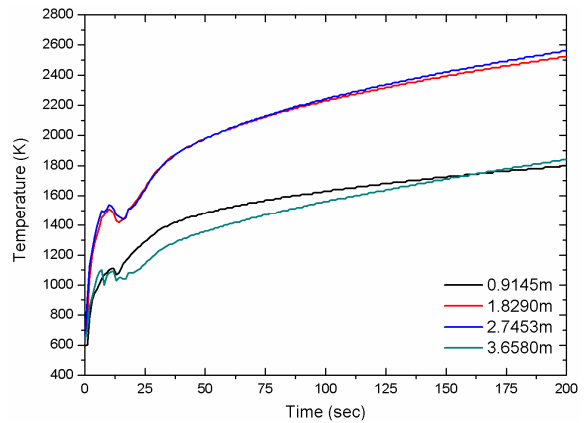


Fig. 7: Cladding surface temperature in core ring 2

Table 2 shows the key events predicted by RELAP5 code during LBLOCA for QSP-II. The reactor trip occurs immediately after the assumed double ended guillotine break starts in a cold leg. The initial phase of the sequence consists of a loss of coolant from the large break into the containment and a boil-off. The loss of the reactor coolant system inventory via the break is rapid, which leads to a rapid depressurization of the reactor coolant system. The top active fuel starts to be uncovered due to a substantial loss of the coolant at 0.001 sec. The cladding temperature increases rapidly as a result of the deterioration of cooling environment and a large amount of decay heat accumulated in the uncovered region of active fuel. Zircaloy oxidation reaction starts as the cladding temperature reached 1000 K at 1.275 sec. The cladding in core ring 1 begins to release Noble gases at 2.211 sec. When the active fuel region is uncovered completely, the deterioration of cooling environment continues until the middle ring and outer ring of core begin to fail.

RESULTS

Analysis of results from RELAP5: After the break starts, the pressure and water level of the core are shown in Fig. 4 and 5, respectively. The active core

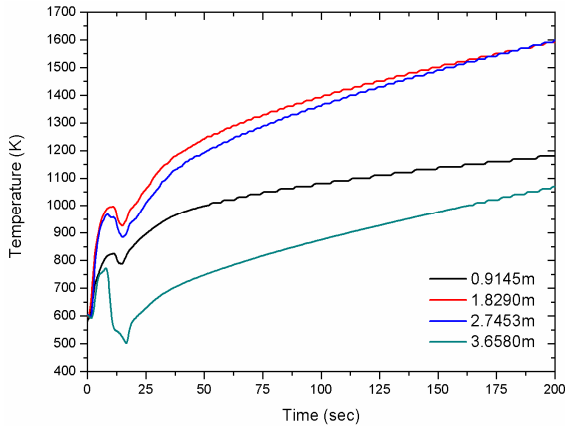


Fig. 8: Cladding surface temperature in core ring 3

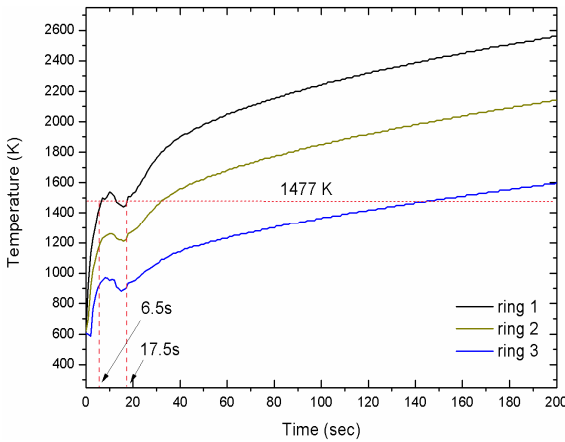


Fig. 9: Cladding maximum temperature in each ring

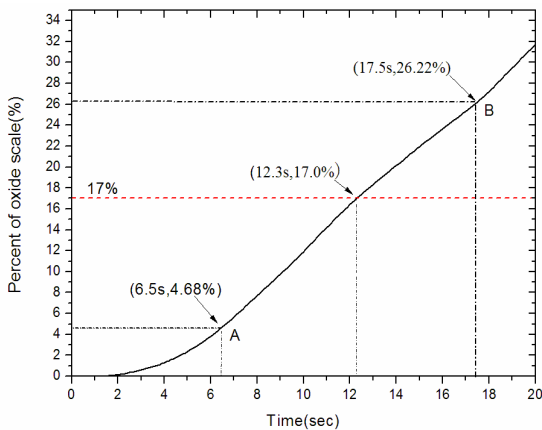


Fig. 10: Percent of oxide scale

region completely uncovers at 4.127 sec as shown in Fig. 5, due to the rapid drop of water in active core region. Hence, insufficient cooling of the fuel rod exacerbates the heat transfer from the core.

The axial cladding temperature of the 3 core rings is shown in Fig. 6 to 8. These three figures indicate the

temperatures at 1.8290 and 2.7453 m are higher than other two positions at the axial level, due to the temperature distribution in fuel rods seriously depends on the power distribution factors in the core active region. The comparison of the maximum cladding temperature of the three core rings is shown in Fig. 9, which points out that the maximum cladding temperature is at 1.8290 m in core ring 1. According to the LBLOCA acceptance criteria, two points have reached 1477 K at 6.5 and 17.5 sec, as shown in Fig. 10 respectively. The time point for extracting data has been chosen at 17.5 sec based on:

- The oxide thickness percent of the cladding have not reached the acceptance criteria at A point that means cannot utilize the RELAP5 thermal-hydraulic calculation to the maximum degree possible.
- The oxidation thickness percent is 26.22% at the B point, which over the acceptance criteria.

Analysis results from SAP: By calculation of the cladding effective stress, the value of effective stress increases gradually with the core depressurization and the continuous oxidation of cladding. As shown in Fig. 11, Point A indicates cladding effective stress is 9.95 MPa in core ring 1 at 17.5 sec and the gas release does not occur for the reason that is a great margin from 9.95 MPa to the danger area of yielding strength. Cladding gas release occurs in a very short time as a result of rapid increase of effective stress, due to oxidation corrosion on cladding wall.

The axial cladding temperature of the three core rings calculated by SAP is shown in Fig. 12 to 14 (regard the 17.5 sec in RELAP5 as the 0.0 sec in SAP). Those figures illustrate that the core heat-up rate is more rapid at the upper axial levels than the downer axial level when the core is uncovered completely. There are no any mitigation measures to take so that core damage occurs rapidly at the upper axial level in the core ring 2.

Core debris formation starts from the core ring 2 to the ring 1 and to ring 3, as shown in Fig. 15. The order of debris formation depends on the core power distribution at axial level and in the radial ring. Debris formation accumulation on the lower core support plant may lead the plant failure and debris formation degradation into lower plenum. The temperature of the lower core support plant increases rapidly each time when debris formation degrades into it, as shown in Fig. 16. Relocation order of the core materials accumulated in the lower core support plate is core ring 2 (97 sec), core ring 1 (137 sec) and core ring 3 (772 sec). The core materials of each ring relocate into the lower plenum in a short time.

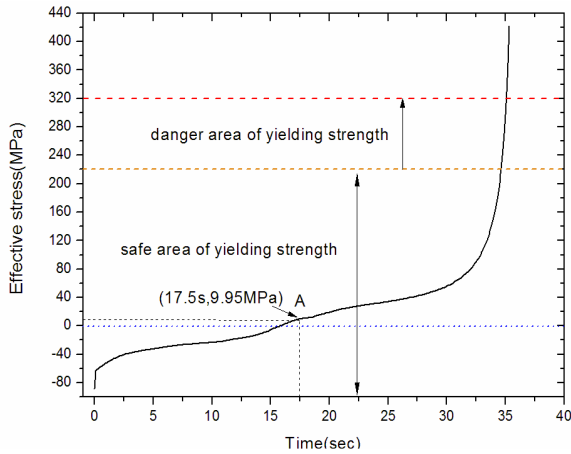


Fig. 11: Effective stress of cladding

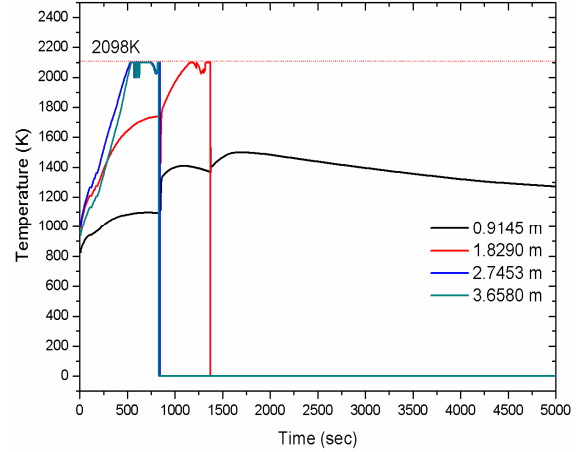


Fig. 14: Cladding temperature in core ring 3

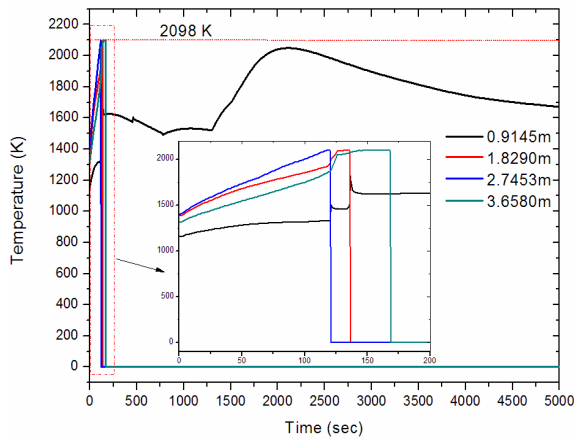


Fig. 12: Cladding temperature in core ring 1

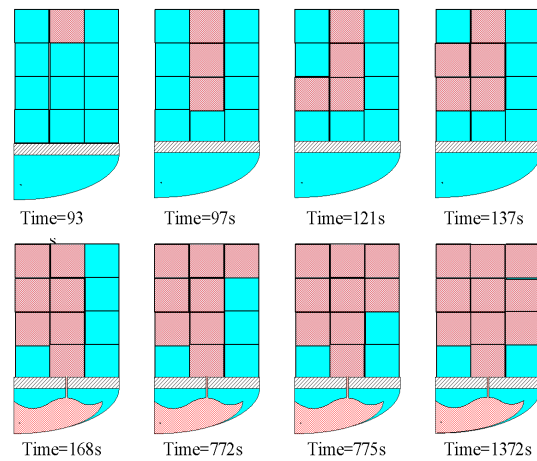


Fig. 15: Core materials relocation

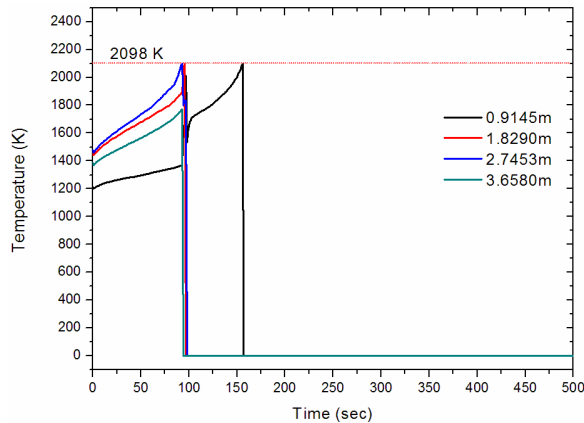


Fig. 13: Cladding temperature in core ring 2

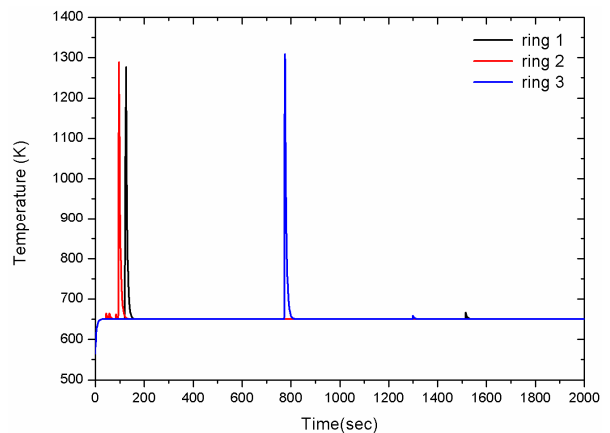


Fig. 16: Temperature of lower core support plate

The history of the accumulated hydrogen generated in the core from RELAP5 and SAP simulation is shown Fig. 17. A substantial oxidation of the Zircaloy cladding by steam occurs at 1.3 sec and about 46.1% (6472 kg) of the initial Zircaloy cladding (14027 kg) has been transformed to ZrO_2 before steam starvation.

The total hydrogen produced in the vessel is 283.8 kg. The oxidation rate of Zircaloy cladding seriously depends on the cladding surface temperature and the available steam mass. The raise of cladding

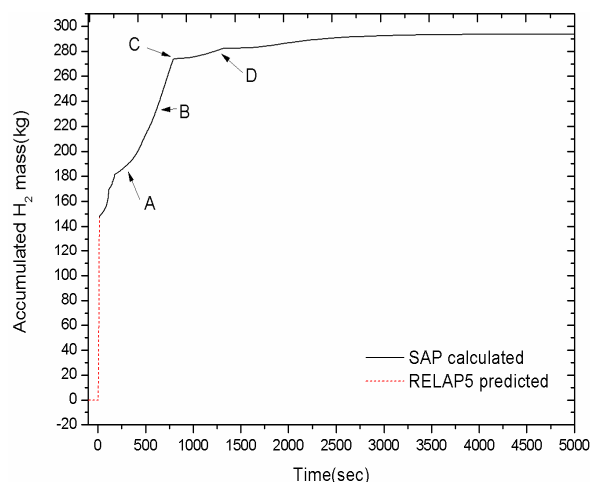


Fig. 17: Accumulated H₂ mass

temperature accelerates the oxidation procession on cladding surface and the energy generated from oxidation reaction accelerates the raise rate of cladding temperature, conversely. As shown in Fig. 17, oxidation rate of Zircaloy cladding is lower in region A due to the lower cladding temperature, but it increases quickly in region B with the cladding surface temperature raises rapidly, which plays a dominant role in this calculation. After 775 sec, namely C point, oxidation reaction hardly stops due to the steam starvation.

CONCLUSION

In this study, the code which is combined by RELAP5 with SAP is developed and applied to analyze a SA caused by LBLOCA for QSP-II. The study mainly focuses on:

- Decision of the time point of data extraction from REALP5 operating file
- Calculation and analysis of cladding effective stress
- Core materials degradation
- Hydrogen production due to cladding oxidation

Major results and findings obtained from the analysis of SA initiated by LBLOCA are summarized as follows:

- For SA initiated by LBLOCA, three conditions ought to satisfy at the time point of data extracting from RELAP5:
 - Core uncover for a prolonged period,
 - Over 17% of the initial Zircaloy cladding has been oxidized
 - The cladding temperature has reached 1477 k Hence, using this criterion enables the utilization of RELAP5 thermal-hydraulic calculation to the

maximum degree possible and can also guarantee the accuracy of calculation of core behavior.

- The maximum cladding effective stress has a great margin from calculation value to the danger area of yielding strength at time point of data extraction. Gas release of cladding occurs in a short time as a result of rapid increase of effective stress, due to the oxidation corrosion of cladding.
- The oxidation rate of Zircaloy cladding seriously depends on the cladding temperature and the available steam mass. The raise of cladding temperature accelerates the oxidation procession on cladding surface and the energy generated from oxidation reaction accelerates the raise rate of cladding temperature, conversely.
- The relocation order of the core materials accumulated on the lower core support plate mainly depends on the core power distribution.

This study is a meaningful experience in combination of codes between the advanced thermal-hydraulic calculation code and SAP for SA analysis. Although technical deficiencies are still remained, this analysis method is considered meaningful to be applied in the SA research field. The present study will contribute to refine model of SA and to ensure the reliability of simulation results.

REFERENCES

ASME, 2002. Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications. American Society of Mechanical Engineers, New York, ASME Ra-S-2002.

Fichot, F., B. Adroguer, A. Volchek and Y. Zvonarev, 2004. Advanced treatment of zircaloy cladding high-temperature oxidation in severe accident code calculation: Part III. Varification against representative transient test. Nucl. Eng. Des., 232: 97-109.

Hirose, K., 2012. 2011 Fukushima Daiichi nuclear power plant accident: Summary of regional radioactive deposition monitoring results. J. Environ. Radioactiv., 111: 13-17.

Idaho National Engineering Laboratory, 2001. RELAP5 MOD3.3 Code Manuals, Volume V: User's Guidelines. NUREG/CR-5535, INEL-95/0174.

Idaho National Engineering and Environmental Laboratory, 2003. SCDAP/RELAP5-3D[®] code manual, volume 2: Modeling of reactor core and vessel behavior during SAs. INEEL/EXT-02-00589, Volume 2, Revision 2.2.

Sandia National Laboratories, 2000. MELCOR computer code manuals, Vol. 2: Reference manuals. NUREG/CR-6119, Vol. 2, Rev. 2.

- Schanz, G., B. Adroguer and A. Volchek, 2004. Advanced treatment of zircaloy cladding high-temperature oxidation in severe accident code calculations: Part I. Experimental database and basic modeling. *Nuclear Eng. Design*, 232: 75-84.
- US Nuclear Regulatory Commission, 1980. Analysis of three mile island-unit 2 accident. NSAC-80-1.
- US Nuclear Regulatory Commission, 1987. Report on the accident at the Chernobyl nuclear power station. US Government Printing Office, Washington, DC.
- Vierow, K., Y. Liao, J. Johnson, M. Kenton and R. Gauntt, 2004. Severe accident analysis of a PWR station blackout with the MELCOR, MAAP4 and SCDAP/RELAP5 codes. *Nuclear Eng. Design*, 234: 129-145.
- Volchek, A., Y. Zvonarev and G. Schanz, 2004. Advanced treatment of zircaloy cladding high-temperature oxidation in SA code calculations: Part II. Best-fitted parabolic correlations. *Nuclear Eng. Design*, 232: 85-96.