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ASSESSMENT OF WATER INJECTION AS SEVERE ACCIDENT MANAGEMENT USING SAMPSON CODE

Masanori Naitoh *
Nuclear Power Engineering Corporation
Totanomon 4-chome MT Bldg, 6F
4-1-8, Toranomon, Minato-ku, Tokyo
105-0001, Japan
Phone: +81-3-4512-2551
Fax: +81-3-4512-2600
e-mail: ms-naito@nupec.or.jp

Seigo Hosoda
Nuclear Power Engineering Corporation
Totanomon 4-chome MT Bldg, 6F
4-1-8, Toranomon, Minato-ku, Tokyo
105-0001, Japan

C. M. Allison
Innovative Systems Software, LLC
Idaho Falls, Idaho, 83404

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ABSTRACT

Severe accident phenomena were analyzed with the SAMPSON code. The plant type calculated was a 3-loop steel-dry containment, 2440 MWt PWR. The accident scenario supposed was AE; 6-inch hot leg failure and failures of ECCS and containment spray. The power distribution at the end of cycle operation was supposed. Analyses without accident managements and in the case of water injection as the accident management were performed. The analysis results showed that the proposed water injection by restart of the RCP pump at the time when the core outlet temperature reaches 923 K is not effective to prevent core melt, because the time is after occurrence of core relocation and violent Zr-H_2O reaction occurs resulting in rapid increase of fuel temperature. Then other analyses were performed with a parameter of a fuel surface temperature. The latter analysis showed that earlier water injection before the time when the fuel surface temperature reaches 1,750 K is effective to prevent further core melt. Since fuel surface and fluid temperatures have spatial distribution and depend on a period of cycle operation, further analyses are required to determine the suitable location for temperature measurement which is an index for the pump restart.

1. INTRODUCTION

Severe accident analysis codes for light water nuclear power plants had been world-wide developed and used for understanding of accident phenomena and for evaluation of accident managements. Many of traditional codes apply simplified models and user tuning parameters. Overall trends under severe accident conditions can be obtained using such traditional codes. However, much detailed analysis must be required especially for assessment of accident managements, because multi-dimensional and complex phenomena must appear under severe accident conditions. And the traditional codes are considered not to be sufficient for quantitative assessment of accident managements.

Thus, the nuclear power engineering corporation had promoted the IMPACT project. IMPACT, an acronym for Integrated Modular Plant Analysis and Computing Technology, is the name of a software development project and of specific simulation software, which performs full-scope and detailed calculations of various phenomena in a nuclear power plant for a wide range of event scenarios (Naitoh, 1999).

One of IMPACT software system is the SAMPSON code for detailed analysis under severe accident conditions (Ujita, 1999a). Physical and chemical phenomena during fuel cladding damage, fuel melting, candling, crust formation, molten debris relocation and its cooling, re-solidification, fission products release and transport, debris-concrete interaction, steam explosion, hydrogen mixing, burning and detonation, etc. can be calculated in detail, and reactor vessel and containment structural integrities can be evaluated. Because it is difficult to clarify various phenomena in the full-range of an accident scenario by experiments that pinpoint the significant events and investigate the specific phenomena in detail, analysis must be relied upon for understanding physical and chemical processes in the entire scope of a severe accident. Therefore, the SAMPSON code is based upon fundamental physics principles and sophisticated modeling. SAMPSON's distinguishing features include interconnected hierarchical modules, theoretical-base equations and mechanistic models covering a wide spectrum of scenarios ranging from normal operation to severe accident events, and high speed simulation on parallel processing computers.

This paper describes analysis results of PWR plant without any accident managements using the SAMPSON code, followed by evaluation of water injection as an accident management.

2. OVERVIEW OF SAMPSON CODE

The SAMPSON has been developed to analyze integral plant behavior under severe accident conditions. The SAMPSON consists of eleven analysis modules to analyze specific phenomenon assigned and an analysis control module which manages the analysis modules according to the progression of the accident events as shown in Fig.1.

The analysis control module manages multiple analysis modules while appearing to users to be a single code. In order to realize this, it calls and terminates analysis modules as appropriate with respect to time in the event and physical location, that is, it controls the parallel processing through allocation of modules to processor elements in a parallel computer. It also controls communication between modules and a time step. Thus, various analysis modules are executed in parallel with inter-module communication, exchanging boundary conditions with each other (called MPMD: Multiple-Program

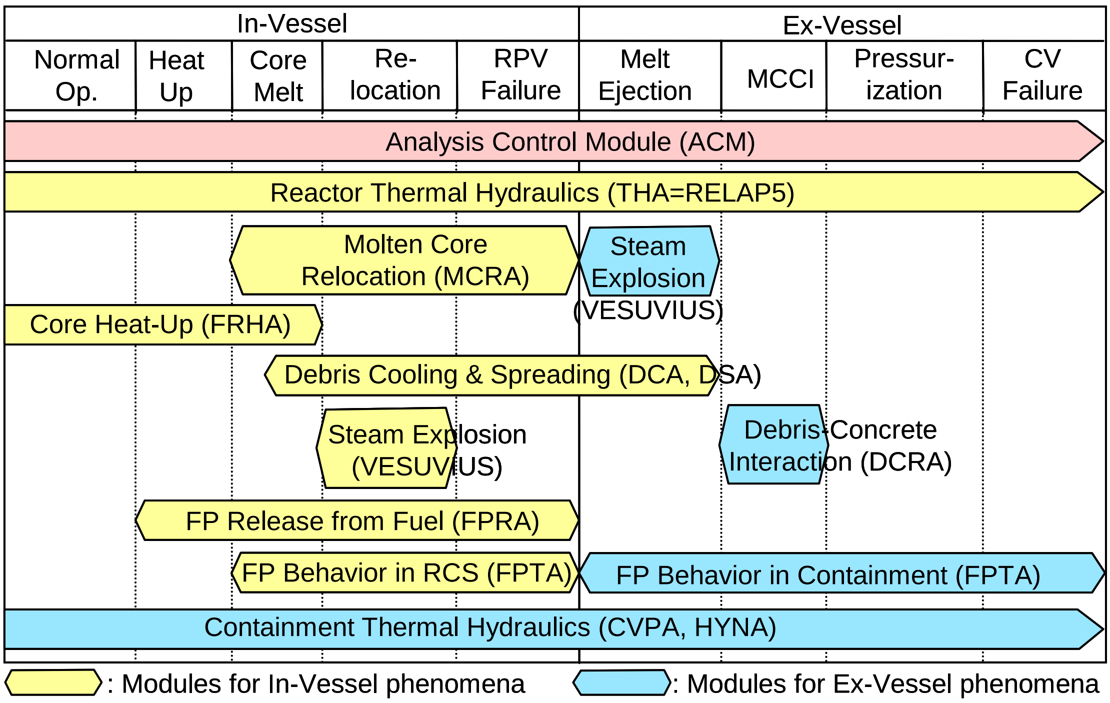

Fig. 1 Running Sequence of SAMPSON Modules

Multiple-Data stream), and independent analysis modules are also executed in parallel with communication between processors used for the single module (called SPMD: Single Program Multiple-Data stream).

Considering remarkable progress of computer hardware performance, as another version of the SAMPSON code, it was modified so as to run on a single processor. That is, each analysis module runs on a single processor and the SAMPSON code also runs on a single processor. Now, the SAMPSON and RELAP/SCDAPSIM are being merged complimentarily. The RELAP portion of RELAP/SCDAPSIM is introduced to THA, in-vessel thermal-hydraulic analysis module, and MATSIM portion is used in the SAMPSON modules for calculation of physical properties. Details of merger are described in the reference (Allison, 2005).

The eleven analysis modules in the SAMPSON code are as follows.

1) THA: In-vessel thermal hydraulics analysis module. A solver part of this module is the same as one of the RELAP portion of RELAP/SCDAPSIM.
2) FRHA: Fuel rod heat-up analysis module (Morii, 1999). The sequence of fuel behaviors in severe accident events, such as fuel rod heat up, cladding oxidation, expansion, fuel failure by melting, embitterment, fracture mechanisms etc., are evaluated.
3) FPRA: Fission products (FP) release from fuel analysis module (Morii, 1999). FPRA evaluates fission product transport within the fuel pellet and release after fuel failure, release from crust, debris and the molten fuel pool, and calculates decay heat generation.
4) FPTA: FP transport analysis module. This module was made based on MACRES, which was developed by NUPEC and used to participate in the FALCON international standard problem exercise (Akagane, 1993).
5) MCRA: Molten core relocation analysis module (Satoh, 2000). MCRA calculates the relocation behavior of molten core and failed fuel, considering refreezing of molten material, re-melting, and interactions with structures and coolant. Under the concept of multi-phase, multi-component, and multi-velocity, the module considers momentum and energy transfers between coolant water, steam, non-condensable gases, intact fuel, molten fuel, debris crust and internal structures.
6) DCA: Debris coolability analysis module (Ujita, 1999b). Spreading and coolability of debris that has relocated to the pressure vessel lower plenum are evaluated by DCA. The module also includes a reactor vessel failure model with gap and crack cooling models.
7) DSA: Debris spreading analysis module. DSA analyses the debris spreading which has fallen to the containment vessel concrete base, following reactor pressure vessel failure. The model for debris spreading is the same as that in DCA.
8) DCRA: Debris concrete reaction analysis module. The module evaluates the longer-term core-concrete reactions, debris cooling by water injection to the containment vessel, erosion of concrete and production rates of combustible gases by chemical reactions.
9) CVPA: Containment vessel thermal hydraulics analysis module.
10) VESUVIUS: Steam explosion analysis module (Vierow, 1998). This module performs integral evaluations of steam explosion phenomena with mechanistic models when molten corium has been released to a coolant pool in a lower plenum of a reactor vessel and in a containment vessel.
11) HYNA: Hydrogen transfer analysis module. The function of this module is to analyze transfer behavior of hydrogen in an Ex-Vessel and to judge the existence of hydrogen combustion.

Each analysis module and the SAMPSON which integrates analysis modules were validated by several test analyses and by calculations of the OECD international standard problems (Ikeda, 2003a and b).

The single processor version of the SAMPSON was used for analysis described in the next section,, except the VESUVIUS module because the calculated fluid conditions did not reach the trigger conditions for steam explosion. And only CVPA was used for analysis of thermal hydraulics behavior in a containment vessel.

3. SEVERE ACCIDENT ANALYSIS

3.1 Accident Scenario and Analysis Conditions

(1) Plant Type: 3-loop Steel-Dry containment, 2,440 MWt PWR.
(2) Accident Scenario: AE (6-inch hot leg failure LOCA+ ECCS injection failure+ CV spray failure).

(3) Core Power Distribution: A typical power distribution at the end of cycle operation was applied.

(4) Fuel relocation conditions:
- The eutectic point of cladding with UO_2 is 2,473 K.
- Relocation of molten clad with dissolved UO_2 starts when the temperature of cladding reaches the eutectic point.
- Molten debris discharged from fuel rod is assumed to be spherical particles of 10 mm diameter.
- Discharged particles would scatter or fall down or coalesce in the case of liquid droplet according to the momentum analysis.
- Further, their accumulation on such as spacer regions was evaluated by a friction factor of flow.
- UO_2 itself melts at 3,113 K.
- When the solid UO2 becomes 50%, the solid UO_2 is discharged to a flow path.

(5) RV Failure Condition:
- When the reactor vessel inner wall temperature reaches the SUS melting point (1,700 K), the RV is supposed to fail.

(6) Core Noding : The core was divided into five radial rings and heated region was axially divided into 10 nodes, as shown in Fig. 2.

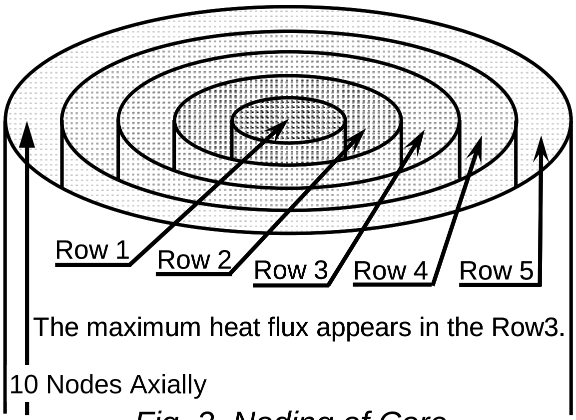

Fig. 2 Noding of Core

3.2 Analysis Results

Key event sequences by SAMPSON analysis are shown in Table 1.

Figure 3 shows peak fuel surface temperature transients. In Fig. 3, the peak fuel surface temperature represents the peak cladding temperature when the cladding temperatures are lower than the eutectic point and it represents the peak fuel pellet surface temperature after the melt of the cladding.

The cladding temperatures started to rise due to core uncovery at about 1,600 s. Molten debris started to fall down into a lower plenum at about 3,800 s. Then, steam was generated by heat transfer from high temperature molten debris to residual water in the lower plenum. The generated steam flowed up to the core. However the steam flow was intermittent, Zr-H_2O reaction was activated, resulting in rapid temperature rise. The fuel (UO_2) temperature reached melting point at about 4,400 s.

Table 1 Timing of key Events

Event	Time
Pipe rupture	0.0 s
SI signal	13.3 s
Accumulator	6.2 – 14.8 min
Core uncovery	26.3 min
Fuel cladding failure	40.3 min
Fuel falling starts	62.6 min
Lower plate failure	66 min
RV failure	85 min
CV failure	56 h

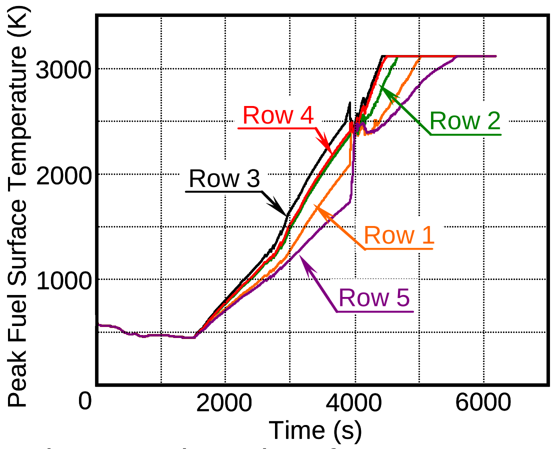

Fig. 3 Peak Fuel Surface Temperature

Figure 4 shows pressure transient in the reactor vessel. The rapid depressurization occurred initially until reactor water temperature reached saturation. Then, the depressurization was mitigated for a while due to accumulated water injection around 600 s. The temporal pressure increase at about 3,800 s was due to steam generation in the lower plenum by molten debris fall down as stated above.

Figure 5 shows peak temperature transient at an inner wall of the reactor vessel. The temperature rose to the melting point at about 5,100 s.

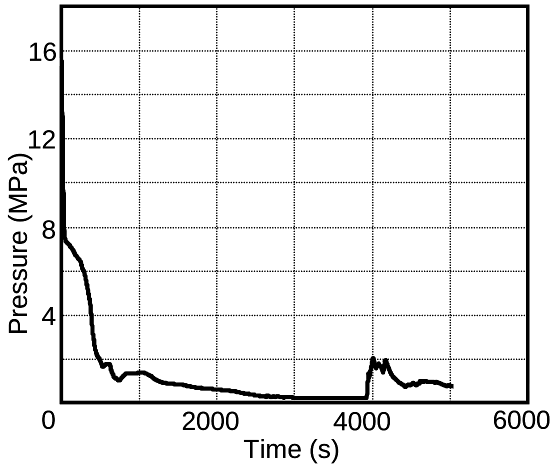

Fig. 4 Reactor Vessel Pressure

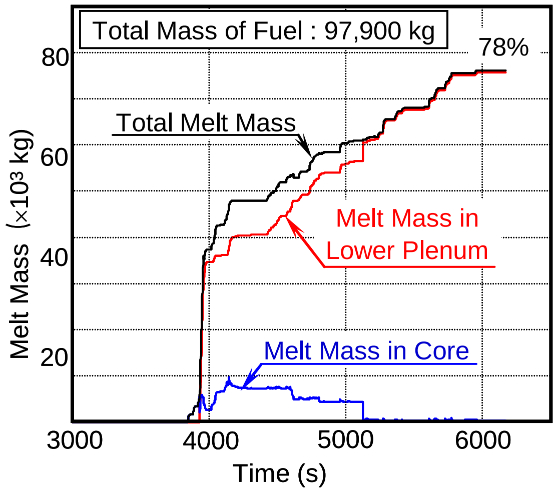

Fig. 6 Mass of Molten Debris

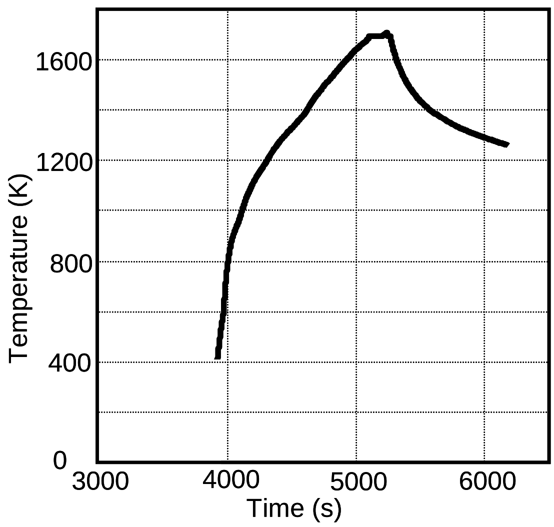

Fig. 5 RV Inner Wall Peak Temperature

Figure 6 shows mass of molten debris. However some molten debris temporarily stayed in the core, all molten debris finally fell down into the lower plenum. The final ration of molten debris to the initially loaded fuel mass including the cladding mass was 78 %.

3.3 Effect of Water Injection

Accident managements (AMs) were proposed to mitigate severe accidents. One of AMs is water injection into a core to cool down a damaged core, (or hopefully to cool down a core before the damage). As one of methods of water injection, the restart of a reactor coolant pump (RCP) was proposed. The proposal was that the RCP should be restarted when the core outlet fluid temperature reached 923 K, or 650 C (Allison, 2004).

First, the core outlet fluid temperature was analyzed using the SAMPSON to decide the time of water injection, or the time when the temperature reaches 923 K. Figure 7 shows the analysis result. In this analysis, any water injection as an AM did not supposed. The vertical axis of Fig. 7 shows the fluid temperature at the node just above the heated region of the Row 3 in which the fluid temperature showed maximum among the rows.

In Fig. 7, the fluid temperature exceeded 923 K temporally at the period between 2,000 s and 3,000 s. However, such temporal increase of temperature may not be captured by thermocouples due to their heat capacity. The fluid temperature in the upper plenum was much lower. Therefore, it is concluded that the time, when the core outlet temperature of 923 K is measured, is about 4000 s.

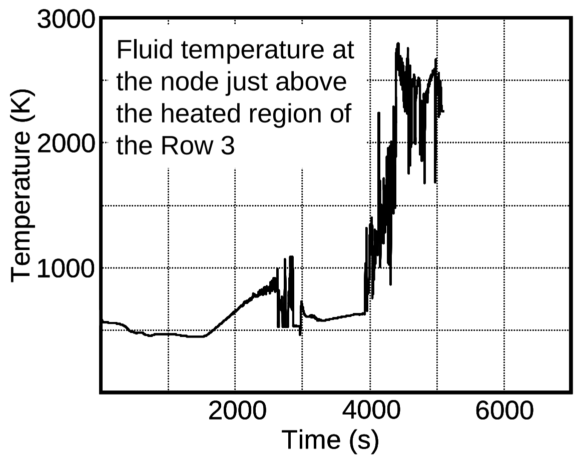

Fig. 7 Core Outlet Temperature

Now, from Fig. 3, the peak fuel surface temperature at the time of 4,000 s. is lower than the UO_2 itself melting point (3,113 K), but enough higher than the eutectic point of cladding with UO_2 (2,473 K). Therefore, the time of 4,000 s is after occurrence of relocation of molten clad with dissolved UO_2. And when water is injected into such high temperature core, violent Zr-H_2O reaction occurs resulting in much heat-up of the core, as stated later in this section.

Thus, it is concluded that the time for the water injection, when the maximum core outlet temperature reaches 923 K, is too late for the mitigation of the accident, because it is after the occurrence of relocation of the core and such water injection results in much heat-up of the core due to heat generation by Zr-H_2O reaction.

Next, the SAMPSON analyses were performed with a parameter of water injection time. In the SAMPSON analyses here, water injection by an ECC pump was supposed. Of course, the RCP restart might be possible. However, some other AM(s) should be applied before the restart in order to fill the pump and its adjacent piping with water to prevent its racing.

Figure 8 shows fuel surface temperatures at each radial row, when ECC water was injected at 3,522 s, which was the time when the peak fuel surface temperature reached 2000 K. The core outlet fluid temperature was about 600 K at this time. Due to water injection to the core, violent Zr-H_2O reaction occurred resulting in rapid temperature increase especially at rows 2, 3 and 4. The fuel surface temperature exceeded eutectic point resulting in core melt. This means that the time of ECC water injection was too late to prevent core melt.

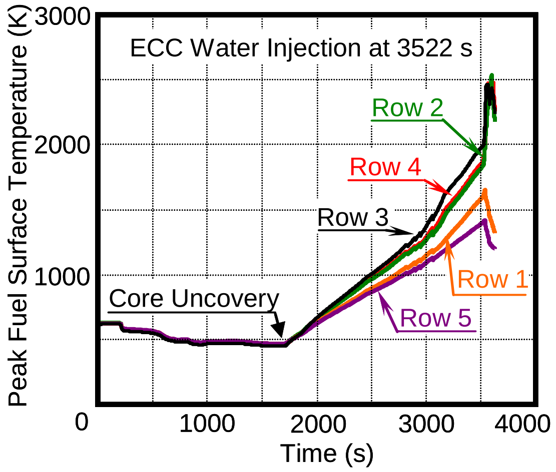

Fig. 8 Peak Fuel Surface Temperature under water injection at 3,522 s

Figure 9 shows fuel surface temperatures at each radial row, when ECC water was injected at 3349 s, which was the time when the peak fuel surface temperature reached 1,750 K. The core outlet fluid temperature was about 580 K at this time. This was the case in which the time of water injection was about 3 minutes earlier and the core outlet temperature was 20 K lower than ones in the case shown in Fig. 8. In this case, the Zr-H_2O reaction was not so violent because of lower fuel temperature. And therefore, temperature increase was about 250 K, lower than the eutectic point. Thus, in this case, ECC water injection was effective to prevent core melt.

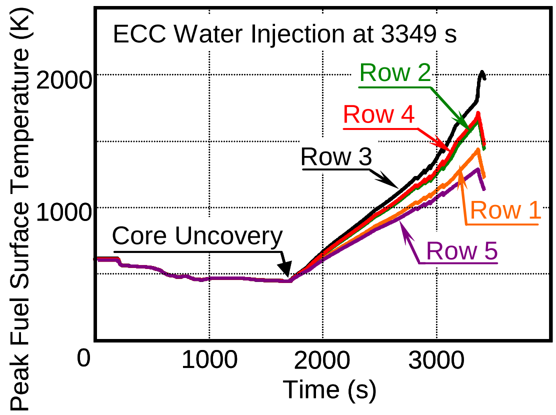

Fig. 9 Peak Fuel Surface Temperature under water injection at 3,349 s

From SAMPSON analyses as shown in Figs. 8 and 9, it is concluded that water injection as an AM is effective to mitigate accident progression when water is injected before the peak fuel surface temperature reaches about 1,750 K.

Assessment of water injection as an AM.

From analyses and discussion stated above, the following conclusions can be derived.

(1) Water injection at the time when the maximum core outlet temperature reaches 923 K, or 650 C is not effective to mitigate accident progression, because it is the time after occurrence of core relocation and fuel temperature increases rapidly due to violent Zr-H_2O reaction by water injection.

(2) Earlier water injection, for example at the time when the peak fuel surface temperature reaches about 1,750 K, is effective for accident mitigation. This is the time when the maximum core outlet fluid temperature reaches about 580 K.

Problems to be solved in future.

The problem is how to decide the time for water injection as the AM. As stated above, the peak fuel surface temperature is a good index for the restart of the pump. And another index is the core outlet temperature. However, the location, where these temperatures show the maximum in the core, changes depending on a period of its cycle operation. The SAMPSON analyses showed radial distributions of peak fuel surface temperatures depending mainly on power distribution. At the end of cycle operation, the power in the row 3 becomes the maximum, resulting in the maximum peak fuel surface temperature as shown in Fig. 3. And naturally, the core outlet temperature becomes maximum. However, at the beginning of the cycle operation, the power in the row 1 is the maximum. Thus, the location, where the peak fuel surface temperature and the peak core outlet temperature appear, changes with the cycle operation. it is not realistic to measure temperatures of all of the fuels in the core.

The realistic method to decide the time to restart the pump for water injection is considered to measure a temperature at a location where it does not depend on a period of the cycle operation and shows spatially the maximum value. A possible location may exist in the upper plenum. In order to decide such location in the upper plenum, a wide variety of analyses is required. The analyses should be multi-dimensional and in detail, because a spatial distribution should be quantified.

During an accident progression, water in a pump and its adjacent piping must boiled away due to depressurization. Therefore, some other AM(s) should be applied before the restart of the pump in order to fill it with water to prevent its racing. Thus, some time delay to complete such other AM(s) must be considered to decide the time for water injection.

4. CONCLUSIONS

(1) SAMPSON calculation showed that water injection as the AM at the time when the maximum core outlet temperature reaches 923 K, or 650 C is not effective to mitigate accident progression, because the time is too late and after occurrence of core relocation, and the fuel temperature increases rapidly due to violent Zr-H_2O reaction by water injection.

(2) Earlier water injection, for example at the time when the peak fuel surface temperature reaches about 1,750 K, is very effective for further core melt. This is the time when the maximum core outlet fluid temperature reaches about 580 K.

(3) The problem is how to define the maximum temperature in the core to decide the time for water injection as the AM, because temperatures have spatial distributions and dependency on cycle operation time. The realistic method to decide the time to restart the pump for water injection is considered to measure a temperature at a location where it does not depend on a period of the cycle operation and shows spatially the maximum value. A possible location may exist in the upper plenum.

(4) In order to decide such location in the upper plenum, further analyses are required. The analyses should be multi-dimensional and in detail, because a spatial distribution should be quantified.

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