Requirements Analysis and Research of Severe Accident Process Simulation Based on COS-SA Code and Emergency Decision Support

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ABSTRACT

According to the Fukushima accident inspiration, emergency decision support should enhance the ability of analyzing and predicting severe accident, and in order to meet the requirements of nuclear power technology self-reliance, using AP1000 plant as an example, the requirements of severe accident process simulation are analyzed from the respect of emergency decision support and the adoption of self-developed severe accident program. Furthermore, feasibility research of severe accident process simulation based on self-reliance severe accident code (later referred COS-SA) is carried out. The research shows that before COS-SA development completed, the requirements analysis is not only an essential prerequisite in the development of accident process simulation system, but also the basis and foundation of the development of COS-SA. In addition, the research shows that the developing COS-SA has already been provided with basic modules required for severe accident process simulation, and test results of the modules are reasonable and feasible. However, need to point out that, in order to practically be applied in severe accident process simulation, COS-SA integration research and test of all the modules are needed.

KEYWORDS
COS-SA, severe accident, emergency decision support, COSINE

1. Introduction

Experience worldwide dealing with the nuclear accident emergency shows that the correctness of the emergency response and decision-making is very important to reduce accident losses, and due to the Fukushima accident, new suggestions and requirements on nuclear emergency are raised [1][2]. Related experience on Fukushima accident and emergency decisions shows that: plant should have certain ability to simulate the severe accident. In addition to evaluate the core damage, it should also have the ability to evaluate the situation of the spent fuel damage. Therefore, the strength of the mitigation and emergency preparedness requires that a support system can simulate and predict accident process greatly. In addition, China is undergoing the self-reliance research on the large-scale advanced passive pressurized water reactor nuclear power technology, according to the revelation of the Fukushima accident, beside the in-depth study of the mechanism of severe accident, severe accident prevention and mitigation measures, and off-site emergency, technical research on in-site emergency decision support after nuclear power plant severe accident happened should actively be carried, which form a complete closed-loop nuclear safety research. Therefore, to adapt to the security and self-reliance requirements of the passive technology and meet the needs of the nuclear emergency under the new situation, using AP1000 plant as an example, requirements of severe accident process simulation will be analyzed from the respect of physical process, plant models and operating platform, and then study the feasibility of using self-reliance code COS-SA, while providing requirements and direction for future research and development.

2. Requirements Analysis of Severe Accident Process Simulation Used for Emergency Decision Support System

2.1. Emergency Decision Support System

Severe accident process simulation mainly refers to severe accident process simulating, forecasting, display and evaluation, such as the core melt, hydrogen generation, fission product release and so on, then guide the safety design of reactor and accident handling, and provide intervention objects and feedback for accident management and emergency decision support system. After the Fukushima accident, in-site emergency becomes more important in the whole emergency system, which requires that a new emergency decision support system can quickly simulate the accident process, forecast plant status and display the phenomenon, while using computerized severe accident management guidelines (later referred CSAMG) developed by using computerized procedures technology, appropriate mitigation measures are fast given, and then predict and analyze the effectiveness of the mitigation measures by super-real-time calculation of the accident, thus can provide some technical support for emergency decision makers.

Compared to the paper based SAMG, CSAMG could provide necessary information of plant status and equipment for user to determine the proper step and actions. Also the CSAMG could display the response of plant to help operator make the choice of next step. It could reduce both workload and errors. So, CSAMG application in the emergency decision support system is inseparable from predictive plant information and incident mitigation response provided by severe accident process simulation. Moreover, the emergency decision support system should also take advantage of the accident process simulation to predict the state of the plant, such as core damage state, containment state, the spent fuel pool state, auxiliary plants state and so on, and can provide users important phenomenon screens to quickly and intuitively understand accident situation so that the users can make rational decisions.

2.2. Requirements Analysis of Severe Accident Process Simulation

From the above analysis, severe accident process simulation is the core module of in-site emergency decision support system. To meet the requirements of the emergency decision support system, requirements analysis of severe accident process simulation from the following aspects should be carried out.

2.2.1. Physical Process Simulation Requirements

As the core function of emergency decision support system, severe accident process simulation should be cleared that which physical processes need to be simulated. After preliminary analysis, including the flows:

1) Thermal-hydraulic response of reactor cooling system, reactor cavity, containment and the closed buildings;

2) Core nudity, fuel heating, cladding oxidation, fuel damage and core material melt;

3) Melt-concrete reaction, aerosol generation;

4) Hydrogen generation, migration and burning inside and outside the vessel;

5) The release, migration and deposition of fission products;

6) Radioactive aerosol behavior within the containment building, including pool washing, polymeric particles, gravity sedimentation;

7) The impact of engineered safety features on thermal hydraulics and radionuclide behavior, etc.

2.2.2. Plant Models Requirements

According to the physical process simulation requirements, plant models requirements analysis will be carried out as the flowing:

1) Plant model scope

Table 1 Plant Model Scope

No	Plant main models	Simulation degree
1	Primary system thermal-hydraulic model	Detail Simulation
2	Primary system heat-structure model	Detail Simulation
3	Core physical model	Simple Simulation
4	Core melt, relocate and debris bed model	Detail Simulation
5	Secondary loop model	Simple Simulation
6	Containment and auxiliary buildings thermal hydraulic and heat-structure model	Detail Simulation
7	Containment melt behavior model	Detail Simulation
8	Spent Fuel Pool model	Detail Simulation
9	Fission product release, transport and deposition model	Detail Simulation
10	Hydrogen combustion model	Simple Simulation
11	Security system model	Detail Simulation
12	Control Function Model	Functional Simulation

2) Model scheme, parameters requirement and screen design of critical phenomena

Model scheme not only determines the accuracy and speed of the accident simulation, but also is the foundation to meet parameters requirement and design phenomena screens. Because the plant models are complex, with the core melt, relocate, and debris bed model as an example, plant models requirements are analyzed as the flowing.

Figure 1 is a core node map, figure 2 is a design screen of core melt, and table 2 is a parameters requirement. Because there are too many output parameters of the model calculation, more important parameters need to be determined depending on the application. By analyzing these three Respects requirements, the scheme design, input and output, and the screen display of this model are basically defined, which provides basis for the subsequent development. Therefore, the requirements analysis for other models is also mainly from these three aspects, and it could be adjusted depending on the circumstances in the actual development.

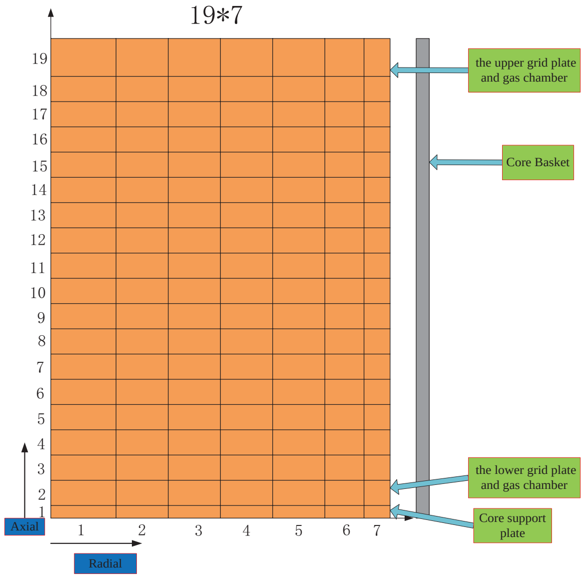


Figure 1 Core Node Map

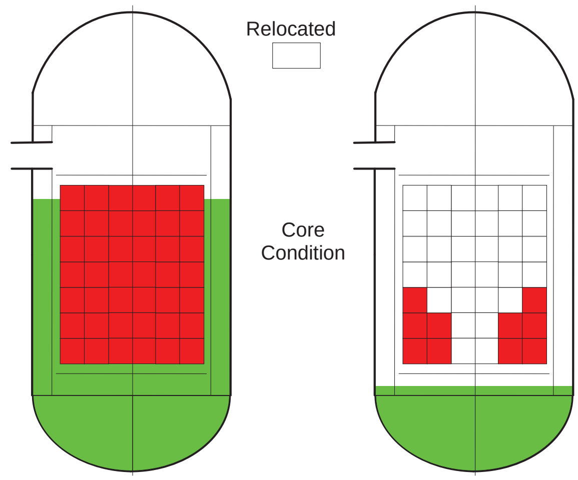


Figure 2 Screen of Core Relocated

Table 2 Output Parameters Requirement

Output Parameters	
Core Quality	Quality of hydrogen generated from core and the lower chamber
Water quality in core area	Heat transfer from the core to water
Core boiling and collapsed water level	Natural circulation flow between the core and the upper chamber
Melt quality in core area	The maximum temperature of the core
Core void fraction	Core decay power
Cladding and pellet temperature of each node	Gas temperature at core exit
Core exit total flow rate of hydrogen	Hydrogen flow rate of each channel
Melt jet flow	Steam flow caused by debris bed heating
Steam generation rate due to melt jet	The total decay power of debris bed in the lower chamber
Heat transfer between lower chamber melt and water	Mass of Hydrogen generated from pressure vessel internal structure
Total mass, temperature, melting temperature and total thickness of the lower chamber debris bed	Water quality and water temperature in the lower chamber
Total mass, temperature, melting temperature, thickness and diameter of the lower chamber particle bed	Mass, temperature, melting temperature and thickness of the lower chamber light metal layer

Mass, temperature, melting temperature and thickness of the lower chamber oxide layer	Mass, temperature, melting temperature and thickness of the lower chamber heavy metal layer
Mass, temperature, melting temperature and thickness of the lower chamber oxide crust	Quality, temperature, thickness of the lower chamber interior structure
Heat transfer between the layers of debris bed	Porosity of particulate debris bed

2.2.3. Running Platform Requirements

From the above, to achieve the data support and user intervention functions of severe accident process simulation, a favorable running support platform should be provided, which could make data exchange between severe accident process simulation and other functional modules of emergency decision support system. Therefore, running platform should have the following functions:

1) Real-time and super-real-time demands;

2) Teach-control functions: such as start, stop, freeze, thaw, snapshot, fault insertion, etc.

3) Real-time and historical database;

4) Efficient data communication functions;

5) Screen display, etc.

Severe accident process simulation should quickly adjust to the state that is prior to the accident, and then trigger the accident, which should make the accident from initial steady state smoothly transit to severe accident condition.

3. Feasibility Study on Severe Accident Process Simulation Based on COS-SA

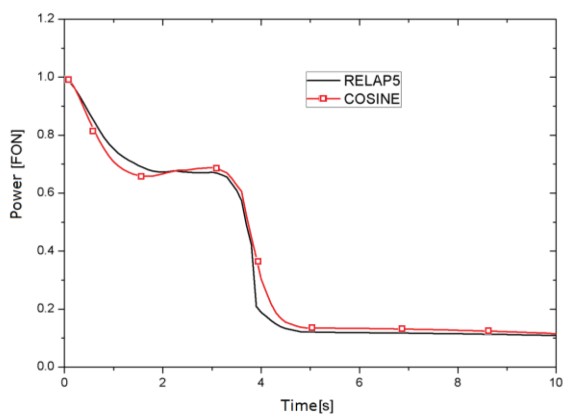
In order to support China's own nuclear power plant (NPP) software development, the Department of Energy of China has approved the NPP software research and design key project (i.e. COSINE) led by The State Nuclear Power Software Development Center (SNPSDC) in 2011. The objective of COSINE (COre and System INtegrated Engine for design and analysis) project is to develop a software platform which is used for nuclear power plant design and safety analysis. During the first phase of COSINE project, six pieces of code are being developed, including three of thermal hydraulics and three of physics. The three pieces of thermal code are sub channel, system analysis code, and containment code related [3][4].

In this paper, severe accident process simulation utilizes COS-SA code which is under self-developing to simulate. Since COS-SA development has not yet been completed, the feasibility study on severe accident process simulation based on COS-SA should be conducted according to the above requirements, which could provide reasonable request and basis for the subsequent development procedures. Because COS-SA is developed in the way of function module and with the integration of COSINE program, the integration of all modules has not been completed yet at present, and the function modules are too numerous, the feasibility analysis by taking part of the core function modules of COS-SA for example will be carried out in the flowing part of this paper.

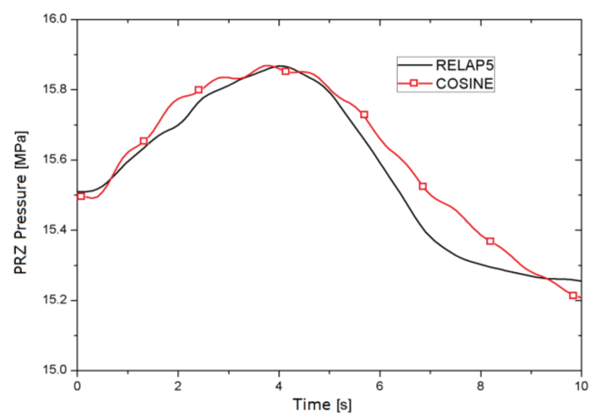
3.1. Thermal-hydraulic Calculation Module

The development and integration of COS-SA is based on COSINE program, especially the thermal-hydraulic solution module, which has a strong versatility with system analysis program, such as MELCOR and RELAP5. Therefore, COS-SA can integrate and use the thermal-hydraulic solution module of COSINE. Based on this, it can be improved and optimized according to severe accident solution characteristic, and which could save a lot of development time. Therefore, this paper can conduct a feasibility analysis of severe accident simulation according to the thermal hydraulic solution capability of COSINE system analysis program. Since the COS-SA has a high degree of integration with COSINE system analysis program, it can use system analysis program to simulate pre-accident steady state and design basis accident, which could realize a smooth transition from the initial steady state to the serious accidents.

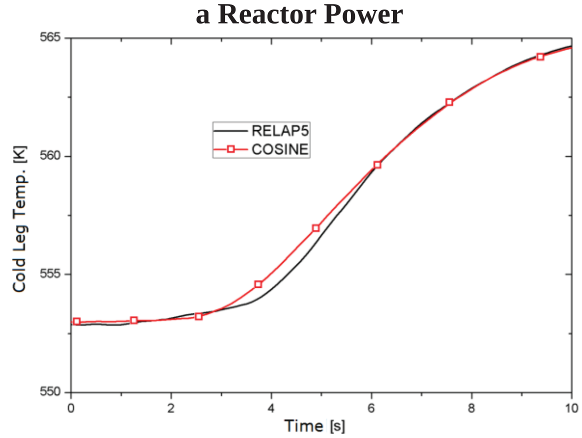
At present SNPSDC has released the engineering verification version of COSINE program, and made many engineering verifications of design basis accidents. As shown in Figure 3, figure 3 is the result of jamming of a reactor coolant pump(later referred RCP) shaft accident, and compared with RELAP5, both are consistent, which illustrates that COSINE system analysis program has ability to calculate and analyze the basic thermal-hydraulic transient, and according to the MAAP4 program, severe accident simulation node is relatively simple. And from figure 3f, the main system node simplified as the scheme in Figure 4, can be used for severe accident process simulation with COS-SA. In addition, the grid of COSINE system analysis program provides users free-division node method, which could facilitate users to a flexible modeling.



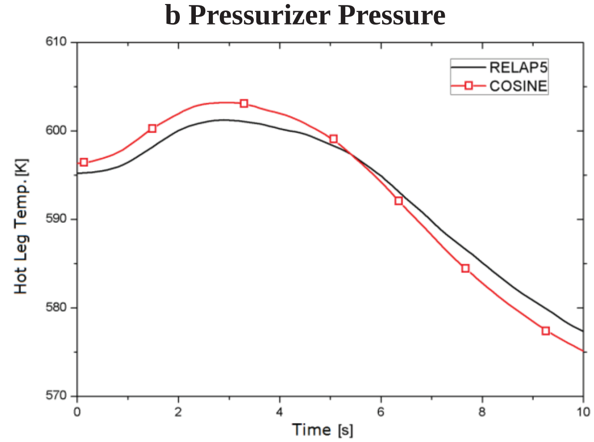
a Reactor Power



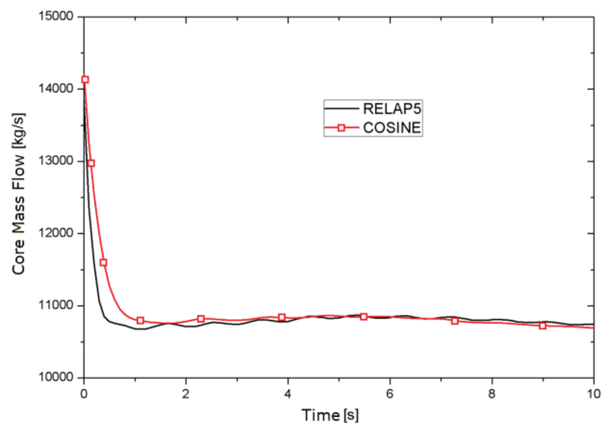
b Pressurizer Pressure



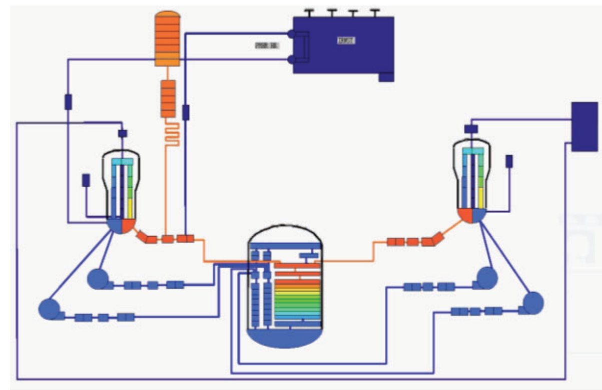
c Cold Loop Temperature



d Hot Loop Temperature



e Core Mass Flow



f RCS Node Map

Figure 3 Jamming of a RCP Shaft Accident Calculation

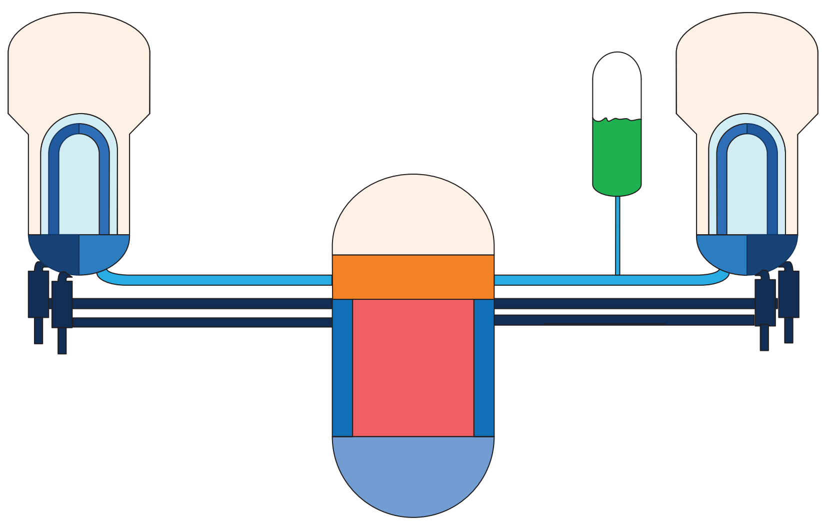
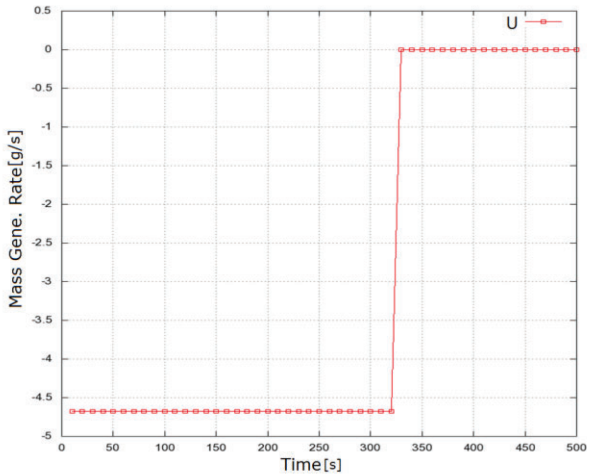


Figure 4 Severe Accident Core Node Map

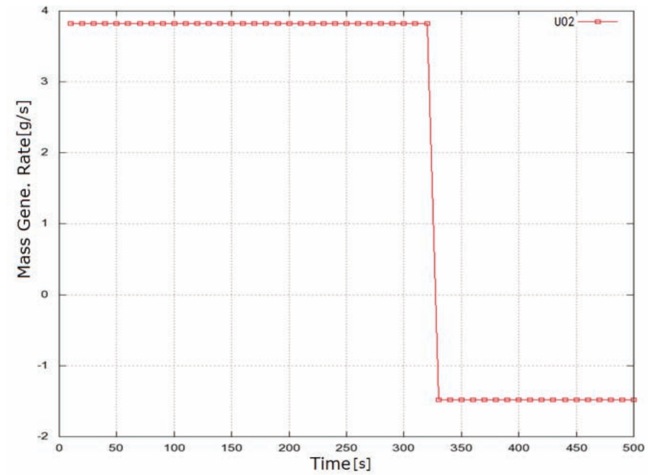
3.2. Severe Accident Source Term Analysis Module

The tests of the major accident modules in COS-SA have been currently completed, including the interaction between the melt and the concrete module, fission product release and migration module, core debris pool module, the material oxidation module, material creep rupture module and so on. Such as the following two examples:

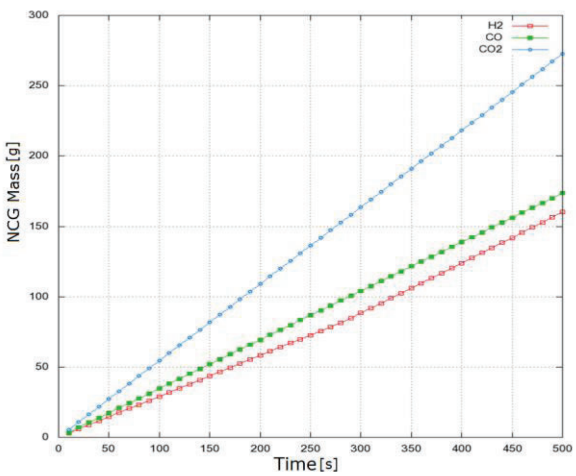
1) As shown in the figure 5 is test results of chemical reaction between melt and concrete, which tests the various chemical reactions in the melt and the concrete, the produce ratios of main component in the mixture are presented.(Fe, SiO_2, CaO, Al_2O_3, U, FeO, non-condensable gases (NCG), and other inert gases).



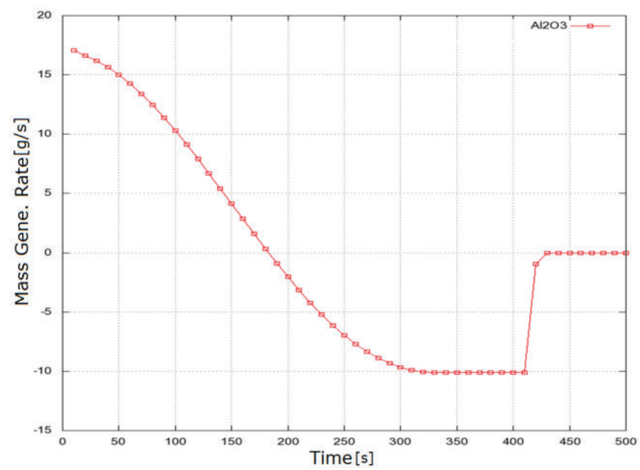
a Mass Generate Rate of U



b Mass Generate Rate of UO_2



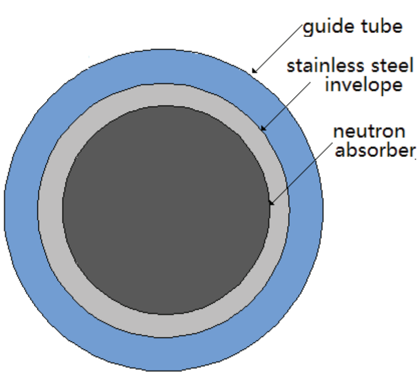
c Mass Generate Rate of NCG



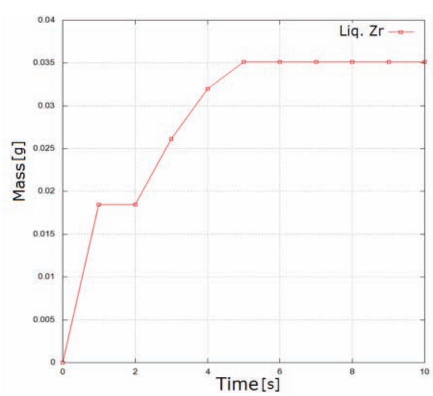
d Mass Generate Rate of Al_2O_3

Figure 5 Test Results of Chemical Reaction between Melt and Concrete

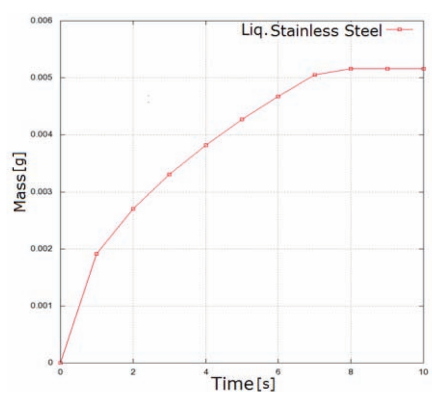
2) As shown in the figure 6 are the control rod melting and relocating function tests, the result shows that: because the eutectic reaction of zirconium and stainless steel, both will melt before they lower to their melting temperature, which should be explained that the melting rate of zirconium alloys is faster than the stainless steel.



a Control Rod Structure



b Liquid Quality of Zr



c Liquid Quality of Stainless steel

Figure 6 Function Tests of Control Rod Melting and Relocating

The above analysis and examples show that the accident modules of COS-SA can be used for severe accident process simulation.

3.3. Other Modules Explanation and Requirements

The above briefly analyzes the feasibility of thermal-hydraulic calculation modules and severe accident source term analysis modules of COS-SA code, but containment calculation is also essential for severe accident code. Containment code is integrated in COSINE package too, and the corresponding development and testing are also carried out, due to limited space of this paper, here no longer illustrate. In addition, according to the revelation of Fukushima, the spent fuel pool also should be concerned, but development of this module in COS-SA has not been carried out so far, which should be added in the subsequent work.

It should be noted that, due to the COS-SA has not conduct the integration and test of the modules, the above are just the independent phenomenon calculation and analysis for each module, but in the actual process there is a strong correlation between the various phenomena, such as the role of humidity on eliminate aerosols, so whether the integration between the modules is reasonable is also crucial to severe accident process simulation.

In addition, real-time intervention and calculation result display are demanded in severe accident process simulation used for emergency decision support, so it is required that COS-SA should be integrated into the simulation platform, and simulation functions which should be added in COS-SA on the basis of platform interface include:

1) Simulation command response (start, stop, freeze, thaw, snapshots, etc);

2) Real-time data communication and interaction;

3) Equipment model real-time response for user intervention actions;

4) Operational control: synchronous and asynchronous, real-time and super real time.

4. Conclusion

According to the Fukushima accident inspiration, this paper analyzed the requirements of severe accident process simulation used for emergency decision support, which from the respect of strengthening the in-site emergency decision support research. Furthermore, feasibility research of severe accident process simulation based on COS-SA is carried out. The research shows that before COS-SA development completed, the requirements analysis is not only an essential prerequisite in the development of accident process simulation system, but also the basis and foundation of the development of COS-SA. In addition, the research shows that the developing COS-SA has already been provided with basic modules required for severe accident process simulation, and test results of the modules are reasonable and feasible. However, we have to point out that, in order to practically be applied in severe accident process simulation, COS-SA integration research and test of all the modules are needed.

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REFERENCES

1. Yao Ren-Tai. Review and Progresses in Studies of Nuclear Accident Consequence Assessment. Radiation Protection Bulletin, 29(2), pp.1-10,2009.
2. Qu Jing-Yuan, Cao Jian-Zhu, Liu Lei, Xue Da-Zhi, Xi Shu-Ren. Status and Perspective on the Research and Development of the Chinese Decision Support System for Nuclear Emergency Management. Atomic Energy Science and Technology, 35(3), pp.283-288,2001.
3. Y. H. Yang, Y. X. Chen, et al. Requirement Analysis and Primary Design of COSINE Code, ANS Annual meeting , Chicago, IL. Hyatt Regency Chicago, No. 5805, June, 2012.
4. Y. H. Yang, Y. X. Chen, et al. Core and System Analysis Integrated Code Platform Developed in China, ANS Annual meeting, Hollywood, FL, The Westin Diplomat Resort and Spa , No.4195, June, 2011.