Safety Evaluation of Topical Reports on SPACE Code, CAP Code, and SPACE-Based Safety Analysis Methodology

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1. Introduction

In August, September and December of 2013, five Topical Reports (TR) [1~5] were submitted by Korea Nuclear & Hydro Power Co.(KHNP) for a licensing approval from Nuclear Safety and Security Commission (NSSC) per Enforcement of Decree of the Nuclear Safety Act [6]. The proposed TRs consisted of two TRs for system thermal-hydraulic code (SPACE) and for containment analysis code (CAP). Three TRs were for a methodology on large break loss-of-coolant accident (LOCA) analysis, one on small break LOCA analysis, and one on Non-LOCA analysis, respectively. The purpose of those TRs was to secure an ownership of the key technology of safety analysis of nuclear power plants. Korea Institute of Nuclear Safety (KINS) has conducted the licensing review of those TRs since 2014 and issued four Safety Evaluation Reports at February of 2017 except the TR on large break LOCA methodology [7~10]. The present paper briefed the KINS regulatory position on those TRs. Regulatory requirements and technical standards applied to the review, the major issues and their resolutions, the limitations and conditions for use of those TRs and the perspectives were discussed.

2. Description of TR

Fig. 1 shows a conceptual diagram of five TRs applied. The SPACE code is used in all three accident analysis methodologies. The CAP code, in a coupled way with SPACE code, is used for LBLOCA methodology. Various features of SPACE model were selectively used in each methodology.

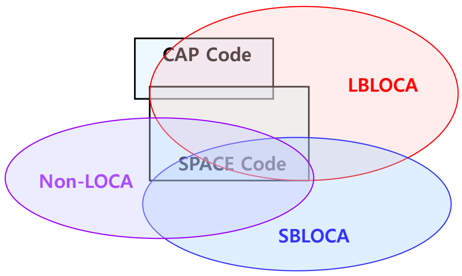

Fig. 1. Topical Reports based on SPACE code.

The SPACE code was described to have a similar capability to RELAP5 code [11]. One of the most outstanding features of SPACE code was 'Droplet field', which was considered with a separate field equation with specific models on droplet generation and dissipation. It was introduced to improve the known deficiency of the existing code especially for reflood phenomena. The CAP code was developed to have a similar capability with GOTHIC code [12] and intended to replace the existing CONTEMPT code [13]. The LBLOCA TR was intended to change the codes in KREM [14] with SPACE-CAP and also several improvements from the existing KREM. The SBLOCA TR was described to use SPACE code and to incorporate the conservative evaluation model features. The Non-LOCA TR was intended to replace the existing CESEC code [15].

3. Regulatory Requirements and Technical Standards

Currently available requirements in Nuclear Safety Act, Enforcement of Decree, Rule, Notice of NSSC relevant to the review of the proposed TRs were applied. As technical standards, Chapter 15 of Safety Review Guide (SRG) on Light Water Reactors [16], KINS Review Guide on Computer Codes and Methodologies of Accident Analysis [17], KINS Regulatory Guides of Evaluation Models of Emergency Core Cooling System Performance were applied as pertinent to each TR [18]. Especially various regulatory documents from USNRC including Information Notices on fuel thermal conductivity degradation (TCD) [19] were considered.

4. Review Metric

In August 2013, licensee submitted three TRs on analysis methodologies. From the docketing review, a condition was imposed to the licensee to separate the methodology TR with the code TR. Two separated TRs regarding the codes were re-applied in December 2013, the subsequent docketing review was conducted, and a main review has been conducted since January 2014. Extension of the review period was requested in second

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[1] Deog Yeon Oh, Seung-Hun Yoo, Joosuk Lee, Kap Kim, Hun Young Jeong, Won Jun Nah, Hye Dong Chung, Kyu Hyun Han, ChanYi Song, Juyeop Park, Kwan Young Kim, Jae Jun Lee, Chang Seon Jang, Junsoo Lee, Chang-Yong Jin, Dong Hyuk Yun, Il Seok Lee, Jeongyun Kim and Kwang Won Seul, Ae Ju Cheong, Kyung Won Lee, An Dong Shin

times due to change of the codes and revision of TRs. During the review, four times of official Requests Additional Information (RAI) were issued by KINS and responses on RAI were received. Table 1 shows a number of RAI related to TRs. And several communications with licensee via licensing meetings were done for facilitating the resolution of the issues. To support the KINS review, four subcontracting organizations, EN2T, KAIST, UNIST, and TUV Reinland have been participating by conducting an independent review and auditing calculations.

Table I: The Number of RAIs

TR	1st	2nd	3rd	4th	Total
SPACE	116	104	50	31	301
CAP	36	72	36	13	157
LBLOCA	45	36	33	23	137
SBLOCA	27	28	18	10	83
Non-LOCA	123	60	59	24	266
Total	347	300	196	101	944

5. Major Issues

Through the review, it was confirmed that the TRs on SPACE code, CAP code, SBLOCA methodology and Non-LOCA methodology were acceptable for the intended use. And it was found some of the issues related to LBLOCA TR should be resolved. Several issues raised were extensively discussed and closed through the response on the RAI and revision of TRs. The issues identified as outstandingly important and discussed for a long time are as follows:

(1) SPACE code TR
  a. Validity of Droplet Field Models
  b. Implementation of Specific Fuel Models
  c. Integrated Validation of Code Accuracy
(2) CAP code TR
  a. Scope of CAP Code Application
  b. Single/Multiple Compartment Modeling
(3) LBLOCA TR
  a. Application of Droplet Field Models
  b. Criteria of Data Covering Process
  c. Data Covering of ATLAS Calculation
  d. SIT/FD Modeling
  e. Determination of Limiting Break
  f. Effect of Droplet Field on Reflood
(4) SBLOCA TR
  a. Accuracy of Loop Seal Clearing Prediction
  b. Conservatism of Methodology
(5) Non-LOCA TR
  a. Conservatism of Steam Line Break (SLB) Methodology
  b. Validation of Code for Actual Plant Transients

The background, the TR contents, and its resolution for some selected issues are described as follows:

1a. Validity of Droplet Field Models

The droplet was addressed as a separated field from the continuous liquid field in SPACE code, thus constitutive models including interfacial drag and interfacial heat transfer were additionally incorporated. Especially, the models on droplet generation and dissipation can play an important role in the calculation. Although the models in SPACE code were based on the appropriate tests and theories, the validation should be justified. In addition to the existing experiments discussed in TR, licensee conducted two tests to measure the droplet behavior in a simple geometry and compared with the SPACE calculation, which showed some deviation from the test data. Although, the accuracy of the SPACE code in predicting the droplet behavior was not good enough for this small scale and simple experiments, the SPACE code predicted reasonably for the other experiments. KINS requested that the effect of accuracy of droplet on the accident progression should be considered in each methodology TR and the licensee responded the effect was addressed in a conservative manner at each accident analysis. Therefore, this issue was closed under the condition of improvement of accuracy based on specific tests for a long-term.

1b. Implementation of Specific Fuel Models

Effect of fuel burnup may impact on initial condition and progression of an accident. Thus, Information Notice 2009-23 was issued to evaluate the effect of thermal conductivity degradation with burnup on the accident progression. Originally, the models for fuel in SPACE code included gap conductance and fuel deformation model in a fixed burnup state. Through an extensive RAI to implement the fuel models considering the burnup, several models were newly incorporated or revised including. the pellet deformation model considering relocation, swelling and densification, cladding plastic deformation model as FRAP-T6 code, cladding rupture model, correction of cladding thermal conductivity for change of dimension by deformation, rod internal pressure model, a model for calculating the oxide layer thickness and Equivalent Cladding Reacted (ECR). Those models were validated with applicable tests and believed appropriate enough to evaluate the safety issues related to burnup.

1c. Integrated Validation of Code Accuracy

SPACE code has several hundreds of physical and mathematical models, however, it is difficult to conclude all the models were validated with an acceptable accuracy. The level of accuracy which a specific code has to have was frequently discussed in the several international research program. For an expression of code accuracy in terms of 'total sense,' the FFTBM (Fast Fourier Transform Based Method) has been proposed. Per the RAI on accuracy of SPACE code, the licensee proposed the accuracy evaluation using FFTBM for an integral effect test, each selected for LBLOCA, SBLOCA and Non-LOCA, respectively. This approach was acceptable for resolving the difficulty to evaluate the accuracy of model for which specific experiment was not available.

2a. Scope of CAP Code Application

As the scope of CAP code the licensee originally proposed the containment integrity analysis, a minimum pressure analysis for ECCS performance, an analysis to determine the envelope for environmental qualification, and hydrogen concentration analysis for design basis accident. Actually the CAP code was used only in LBLOCA analysis. From the review, it was found that the models and correlations in CAP code were available and the code validation was appropriate for the use of those analyses with some exceptional cases. However, the concrete information to constitute the methodology for each analysis proposed was not available in the TR. Thus it was concluded that the CAP code TR was acceptable within code itself and that the further use of CAP code to the proposed analyses needs the additional review subjected to the purpose.

2b. Single/Multiple Compartment Modeling

In the CAP code calculation, a difference in containment pressure response was found between the case using single compartment and the case using multiple one. Licensee responded the reason for the difference was non-uniform gas concentration over the cells and effect of localized heat sink. Also, it was describe the modeling approach can be adjusted in conservative way depending on the purpose of analysis. Actually, the difference was negligible for the typical analyses for minimum pressure and maximum pressure. Such a response was acceptable and it will be further discussed in the future methodology TR using CAP code.

3d. SIT/FD Modeling

Currently, the review of the LBLOCA methodology TR was not completed, but the issue regarding the modeling of Safety Injection Tanks (SIT) with Fluidic Device (FD) was resolved by some RAI and their responses. In the original TR, a modeling scheme using ‘accum’ component and two switching-over valves was used. It was found that such a modeling may lead to an inaccurate prediction at the validation of the SIT blowdown tests of SKN Unit 3. Also, potential of the nitrogen intrusion from the SIT to the reactor vessel may not be considered. Licensee revised the modeling scheme using general ‘pipe’ component and modeled the standpipe, tank portion outside the standpipe, and FD in detail with appropriate K-factors. The result from the revised modeling was good agreement with the test data. Thus, such a modeling scheme was concluded to be acceptable.

4a. Accuracy of Loop Seal Clearing Prediction

Thermal-hydraulic phenomena of Loop Seal Formation and Clearing (LSC) is one of the most important one for Peak Cladding Temperature (PCT) during SBLOCA. In original TR on SBLOCA, five conservative evaluation model (EM) features were introduced: decay heat model based on 1.2 times of ANS-73 model, critical flow by Henry-Fauske model for single phase and of Moody model for two-phase, Baker-Just model for metal-water reaction, critical heat flux (CHF) model using B&W, Barnett and Modified Barnett with addition of uncertainty, post-CHF heat transfer model by Groeneveld 5.7 film boiling correlation. Regarding the IET validation, however, LSC phenomena were not accurately and conservatively predicted due to several reasons including water inventory distribution. Thus, several RAI requested the improvement of the accuracy of LSC prediction. This issue was resolved by addition of conservative modeling of Counter Current Flow Limitation (CCFL) as discussed at the next section.

4b. Conservatism of SBLOCA Methodology

In the course of review, it was found that the conservative post-CHF model was not actually activated for a certain range of break size because of the predicted inventory distribution induced by LSC. Per the RAI of this issue, the licensee proposed an addition of conservatism by delaying the time of LSC by imposing a conservative treatment of CCFL at the steam generator. The licensee showed such an approach led to a conservative prediction of LSC and cladding thermal response both in the associated IET calculation and the plant calculation. Such an approach was acceptable, although the specific requirement on LSC was not specified in the technical standards.

5a. Conservatism of SLB Methodology

In the original Non-LOCA TR, a methodology to calculate the SLB was not conservative in several uncertain models including upper head region. In the revision of the TR, the method of SLB using CESEC was adopted to have conservatism which was requested by the RAI, thus, it was acceptable.

5b. Validation of Code for Actual Plant Transients

In the course of review of Non-LOCA TR, a RAI to request the validation of SPACE code and modeling capability using an actual SKN Unit 3 startup test. The response was significantly delayed due to several reasons. At end of 2016, the licensee responded with the results of validation using two startup tests (Turbine trip and natural circulation test and Loss of two main feedwater pump test at 80% power). The SPACE calculation result was in good agreement with the plant test data. Thus, it was found that the SPACE code and modeling capability is acceptable for the plant transient and this issue was closed.

6. Limitations and Conditions

From the review result, the following limitations and conditions were imposed for the further use of the proposed TR.

1) Use of cladding deformation model and cladding rupture model in SPACE code is limited to Zircaloy-4 cladding and non-rupture case. For the different cladding, further justification of the current model is needed.
2) Use of CAP code is limited to the large dry containment. The containment having boiling phenomena and significant film on the wall during transient is not covered by the current CAP code. Prediction of hydrogen concentration in multi-dimensional flow and stratified condition is not covered by the current CAP code. And the specific methodologies should be reviewed for the use of the CAP code for an analysis of containment integrity, an analysis of the minimum pressure for ECCS performance, an analysis to determine the envelope for environmental qualification, and an analysis of hydrogen concentration.
3) Use of the SBLOCA TR is limited to the analysis for ECCS performance for APR1400.
4) Use of Non-LOCA TR is limited to the scope described in chapter 1 of the TR.

7. Perspectives

The TRs on the SPACE code, CAP code, Non-LOCA methodology and SBLOCA methodology can be used for their intended purposes within the limitations described above. It is expected that those TRs will be subsequently applied to change of operating license, change of construction permit, and reload design of APR1400 plants including SKN unit 3.

It is also expected the SPACE code and SPACE based methodologies will contribute to the clear evaluation of the safety margin for the important safety issue when compared to the case using the previous codes and methodologies. Especially, several specific fuel models incorporated into SPACE code can contribute to address the safety issues related to fuel burnup, which is believed to be extinguished features from the other system thermal-hydraulic codes including RELAP5 and TRACE. For this direction, the improvement of accuracy of droplet field models and extension of the fuel model to the different cladding are needed.

For the technical aspect, the review of those TRs was significantly supported by the technology and experiences developed through the nuclear safety R&D program sponsored by NSSC. Thus, the continuous sponsorship to such a nuclear safety R&D program is needed and should be organized in more specific ways and areas.

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