Evaluation of Rod Ejection Accident for an Advanced Integral Reactor, SMART

Abdulrahman Khalid Alassaf [a*], Sung Won Lim [b], Kyoo Hwan Bae[b]
[a]*King Abdullah City for Atomic & Renewable Energy, P.O Box 2022, Riyadh 11451, Saudi Arabia*
[b]*Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Korea*
[*]*Corresponding author: a.assaf@energy.gov.sa*

1. Introduction

SMART (System-integrated Modular Advanced Reactor) is an advanced integral reactor that contains the major primary component within a RPV (Reactor Pressure Vessel) [1]. However, the CRDM (Control Rod Drive Mechanism) is installed above the reactor closure head and the CRA (Control Rod Assembly) is connected through a nozzle. Thus REA (Rod Ejection Accident) could be caused by a circumferential rupture of the CRDM housing or nozzle. The rupture initiates an instantaneous ejection of a CRA and causes a sudden power excursion due to a large amount of positive reactivity insertion. This paper describes the evaluation methodology and results of REA for SMART.

2. SMART Design Characteristics

SMART is an integral type PWR (Pressurized Water Reactor) with a rated thermal power of 365 MW. Unlike a conventional loop-type PWR, SMART contains the major primary components such as core, pressurizer, four RCPs (Reactor Coolant Pumps), and eight helically coiled once-through SGs (Steam Generators) an RPV.

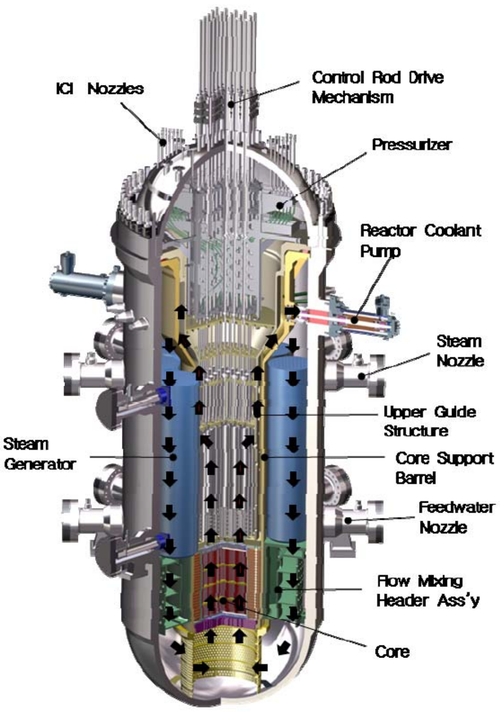

Fig. 1. SMART reactor vessel assembly and reactor coolant flow path

The reactor coolant flows upward through the core, upper plenum, and RCP region. And the reactor coolant flows downward through the shell side of SGs, FMHA (Flow Mixing Header Assembly), lower plenum, and into the core. The feedwater supplied to the SGs flows upward through the tube side with removing the RCS (Reactor Coolant System) heat. The reactor vessel assembly and reactor coolant flow path are depicted as Fig. 1 [1].

3. Evaluation of REA

3.1 General Phenomena

The REA is caused by an instantaneous ejection of a CRA. As the CRA is ejected, large amount of positive reactivity is instantaneously inserted and the core power is rapidly increased. When the core power reaches the high core power reactor trip setpoint, the reactor trip signal is generated. After the CRA fall into the core, the core power decreases. If the LOOP (Loss of Offsite Power) is assumed to occur simultaneously with the turbine trip, the power to the RCPs and the feedwater pumps are lost at the same time with turbine trip. After few seconds, the PRHRAS (Passive Residual Heat Removal Actuation Signal) is generated by the low feedwater flow rate or a high main steam line pressure, and the PRHRS (Passive Residual Heat Removal System) is actuated. With the PRHRS operation, the residual heat of the RCS is removed and the RCS pressure decreases.

3.2 General Regulatory Requirements and Acceptance Criteria

For REA, the regulatory body presents SRGs (Safety Review Guidelines) to prevent the failure of RCS pressure boundary, to maintain the coolable geometry of core and to keep the public safe from a postulated radioactive material release [2]. The specific guidelines are described as below.

1. Reactivity excursions will not result in a radial average fuel enthalpy greater than 230 cal/g at any axial location in any fuel rod.
2. Maximum reactor pressure during any portion of the assumed transient will be less than the value that will cause stresses to exceed the KEPIC/MN C class operating limit. To satisfy

these criteria, RCS pressure should be maintained below 110% of the design values.

3. The result of radioactivity consequence analysis must be within 25% of the value specified in the Notification No. 2014-10 of the Nuclear Safety and Security Commission. The specified values are 75 rem for the thyroid and 6 rem for the whole body doses.

3.3 Analysis Computer Program

The REA is analyzed with the TASS/SMR-S computer program which has been developed for the SMART [3]. The TASS/SMR-S computer program simulates thermal-hydraulic behaviors of system by using the conservation equations of liquid mass, mixture mass, non-condensable gas mass, mixture momentum, gas energy, and mixture energy. The TASS/SMR-S models an analyzed system using nodes and paths, and calculates the system parameters with numerical solution of the conservation equations and constitutive relations.

3.4 Evaluation Methodology

The evaluation is performed to evaluate whether or not to satisfy the acceptance criteria. Among these criteria, the REA is evaluated in viewpoint of radial average fuel enthalpy and fuel centerline temperature in this paper.

The evaluation is performed deterministically. The initial conditions are chosen to maximize the radial average fuel enthalpy based on LCO (Limiting Conditions of Operation). The initial conditions for the evaluation are tabulated as Table 1.

Table 1: Initial Conditions for SMART

Parameter	Value
Core Power, %	103
Pressurizer Pressure, MPa	14.03
SG Inlet Coolant Temperature, ^{o}C	324.1
RCS flow rate, Design %	95.0
Main Steam Line Pressure, MPa	6.18
Pressurizer Level, %	55.0

Also, following assumptions are applied for the conservative evaluation.

1. The radial peaking factor is adjusted to achieve the LCO for linear heat rate.
2. The high core power trip setpoint is adjusted considering one ex-core detector failure as a single failure.
3. The minimum ejected time is used.
4. The maximum distortion factor with uncertainty is used to determine the post-ejected Fr.
5. The minimum net SCRAM worth is used.
6. LOOP is assumed simultaneously with reactor trip.
7. When the DNBR (Departure from Nucleate Boiling Ratio) is lower than safety criteria, the heat transfer from core to coolant is calculated with film boiling correlation.
8. The metal-water reaction is considered to increase heat generation at core.

3.5 Evaluation Results

With the CRA ejection, a large amount of positive reactivity is inserted into core and the core power is rapidly increased. When the core power reaches the high core power reactor trip setpoint, the reactor trip signal is generated. After the reactor trip, the core power decreases to the decay heat level. The normalized core power is represented as Fig. 2.

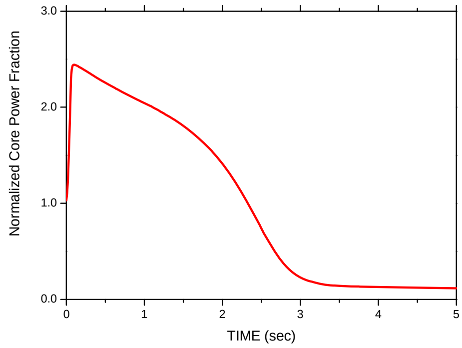

Fig. 2. Normalized Core Power vs. Time

The fuel temperature increases with the rise of core power. The SMART has negative fuel-temperature coefficient for reactivity feedback, thus negative reactivity is inserted by Doppler effect. Since the REA is a short transient, the RCS coolant temperature does not changed much. Therefore, the negative reactivity insertion from the moderator temperature coefficient is quite small. The SCRAM rod worth is about twenty times bigger than the ejected rod worth. So, the core power is decreased to the decay heat level after the reactor trip. The normalized reactivity is represented as Fig. 3.

The radial average fuel enthalpy is calculated from the amount of deposited energy in the core. Thus, the radial average fuel enthalpy increases with the rise of core power. With the same reason, it decreases after reactor trip. The normalized radial average fuel enthalpy is represented as Fig. 4. The result shows that the maximum radial average fuel enthalpy maintains well below the safety criteria during the transient.

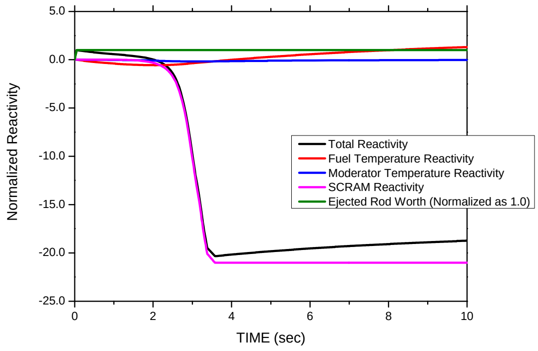

Fig. 3. Normalized Reactivity vs. Time

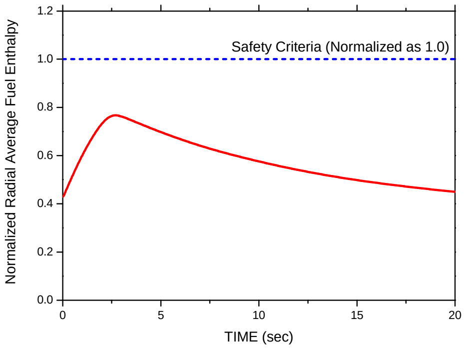

Fig. 4. Normalized Radial Average Fuel Enthalpy vs. Time

The fuel centerline temperature is changed as similar trend with radial average fuel enthalpy. The result shows that the maximum fuel centerline temperature maintains below the fuel melting temperature during the transient. Thus, no fuel is expected to melt.

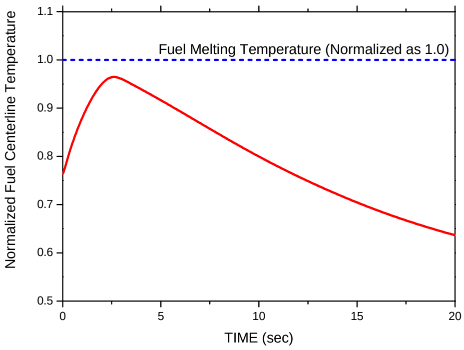

Fig. 5. Normalized Fuel Centerline Temperature vs. Time

4. Conclusions

The REA is evaluated in viewpoint of radial average fuel enthalpy and fuel centerline temperature using the TASS/SMR-S computer program. For the evaluation, most limiting initial conditions and conservative assumptions are used. During the transient, the radial average fuel enthalpy maintains below the safety criteria and no fuel is expected to melt.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT) (2016M2C6A1930041), in addition to funding from King Abdullah City for Atomic and Renewable Energy, Kingdom of Saudi Arabia, within the SMART PPE Project.

REFERENCES

[1] K. K. Kim, W. Lee, S. Choi, H. R. Kim, J. Ha. SMART: The First Licensed Advanced Integral Reactor, Journal of Energy and Power Engineering 8 (2014) 94-102, 2014.
[2] KINS, Safety Review Guidelines for Light Water Reactors, 15.4.8, Control Rod Ejection Accident, 2009.
[3] TASS/SMR-S Code Technical Report, KAERI, Daejeon, 2017.