Core Cooling Assessment of SMART against Severe Station Blackout Accident Scenarios

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I. Introduction

Recent Fukushima disaster was caused by a complete loss of electricity, that is, station blackout followed by unpredicted earthquake and consequent tsunami. This necessitated a re-examination of nuclear plant safety against station blackout accident scenarios. System-integrated Modular Advanced ReacTor (SMART) is an integrated pressurized water reactor developed by KAERI, whose standard design is under regulatory review by KINS. Intrinsic safety of the SMART is featured by; elimination of large pipe breaks, passive residual heat removal, large coolant inventory, low power density, high secondary design pressure and large containment, etc. Unlike Fukushima Mark-I design, SMART passive safety is insured by four-train passive residual heat removal system (PRHRS) that provides natural circulation cooling in the secondary sides of steam generators. In addition, two emergency diesel generators (DG) and an alternative diesel generator insure the AC power supply to active engineered safety features and twelve passive auto-catalytic recombiners in containment prevents potential hydrogen explosion. Thus, it is quite unlikely for SMART to experience Fukushima consequences. Nevertheless, it is worthwhile to assess SMART safety for severe station blackout scenarios in which multiple failures of DGs and PRHRSs are postulated. Thermal-hydraulic response of the SMART system is assessed using a best-estimate code, MARS3.1 in order to realistically estimate the time afforded for operator's mitigation actions.

II. Analytic Models and Methods

MARS3.1 code, a realistic thermal-hydraulic system analysis code developed by KAERI, is used to simulate beyond-design-basis transient responses of SMART. As shown in Fig. 1, SMART reactor coolant system (RCS) is modeled one-dimensionally and it consists of reactor pressure vessel (RPV) assembly, secondary steam system and passive residual heat removal system as designed. Reactor vessel assembly consists of average and hot core channels, upper plenum, internal pressurizer (PZR), annular gap between upper guide structure and core support barrel, four canned-motor pumps, four lumped channels for downcomer annulus, helical steam generator and flow mixing header assembly, and lower plenum. Secondary steam system is composed of four trains of lumped steam generator tubes, steam and feedwater lines. Four trains of passive residual system is modeled for pipings, compensation tank, condensation heat exchanger and emergency cooling tank (ECT). Safety features such as safety relief valves in PZR and PRHRS, and safety injection (SI) system are modeled as boundaries.

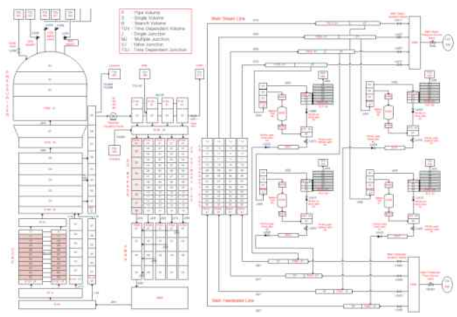

Fig. 1 SMART Reactor System Nodalization

Loss of offsite power (OP) is assumed an initiating event. Four station blackout scenarios are selected as given in Table 1. Case 1 represents a scenario where DGs and all the PRHRSs are available. Case 2 is a realistic station blackout scenario where all four passive PRHRSs are available. Case 3 represents a postulated station blackout scenario where two PRHRSs lost their function. Case 4 is a limiting scenario where all DGs and PRHRSs are unavailable after loss of offsite power. In all cases, operator's mitigation actions are not assumed.

Table 1 Case Scenario Identification

Case	OP	DG	PRHRS	Remarks
1	X	O	O	4 PRHRS
2	X	X	O	4 PRHRS
3	X	X	Δ	2 PRHRS
4	X	X	X	0 PRHRS

III. Analysis Results

It is inevitable that core and fuel eventually fails in the severe station blackout scenarios without any operator's mitigation actions. So, the focus of the analysis is how much time is allowed for operators to take proper actions to safely shutdown the reactor system before severe fuel damage. Severe core damage is assumed to occur when maximum cladding temperature is above 1250K considering operator's action time. Long-term system and core cooling responses of SMART system are evaluated and compared. In the following figures, legends of case studies are given as LOOP+SI for case 1,

TLOHS+4PRHRS for case 2, TLOHS+2PRHRS for case 3 and TLOHS+0PRHRS for case 4.
Fig. 2 and 3 show PZR pressures and RPV water levels repectively. PZR pressures decrease with reactor trip and PRHRS cooling in cases 1, 2 and 3. If DG is available as in case 1, continued SI increases PZR pressure up to SI shutoff head and RPV level is recovered. A safe shutdown condition of the system is, then, maintained. When, PRHRS loses its function by given scenario or by ECT dryout, RCS starts to reheat, which increases RPV water level and PZR pressure. When PZR pressure reaches PZR safety valve set pressure, PZR safety valves start to relieve RCS inventory. Prolonged loss of RCS inventory through the safety valves reduces RPV water level and leads to a core uncovery in the long run. Then, fuel starts to heat up when the core is uncovered at certain amount and, then, eventually reaches to a failure temperature as shown in Fig. 4.

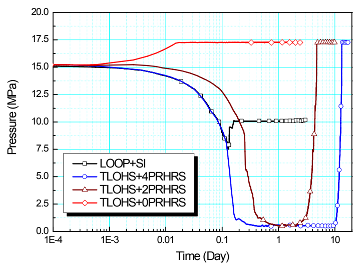

Fig. 2 Pressurizer Pressure

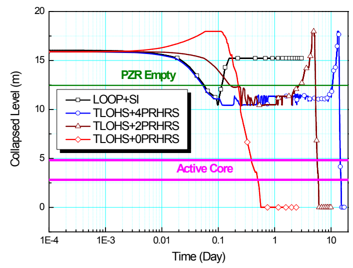

Fig. 3 RPV Water Level

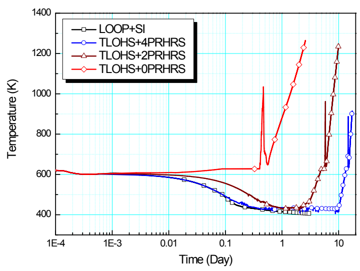

Fig. 4 Peak Cladding Temperature

Pressure trend of PRHRS follows that of RCS. When it reaches to PRHRS safety valve pressure, PRHRS valve starts to relieve PRHRS inventory. PRHRS inventory is completely lost at the end however, it should be noted that PRHRS inventory required for residual heat removal is maintained for a prolonged time by its high design pressure.
Adequate core cooling is insured by various cooling modes such as single-phase natural circulation, two-phase natural circulation and reflux condensation as far as PRHRS functions and proper amount of RCS inventory is maintained. On the other hand, relatively stable two-phase natural circulation cooling is maintained for residual heat removal until ECT is completely dried out.
Table 2 summarizes major sequence of events. From the results, it is found that a stable shutdown condition is insured by SI if DG is available (Case 1). In case 2, a realistic station blackout scenario, RCS and PRHRS repressurize to relieve their inventory in 13.2 and 13.5 days. Core is estimated completely uncovered in 14.4 days and severe fuel damage is estimated to occur in 18.9 days. In case 3, a conservative station blackout scenario with 2 PRHRS available, overall sequence is shortened due to degraded PRHRS performance, nevertheless, sufficient operator's action time of 10.0 days is allowed before severe core damage. Case 4, even though it is incredible for all four passive PRHRS to fail, still allows operator's action time of 2.6 days. Rate of RCS inventory loss and fuel heatup is a function of core decay heat. As given in the table, the rate slows down as relevant initiating time is deferred.

Table 2 Event Sequences

(unit: days)

Case	SI	ECT Dryout	PZR Relief	Steam Relief	Core Uncovery	Fuel Damage	Heatup Rate*
1	0.09	X	X	X	X	X	X
2	X	9.9	13.2	13.5	15.0	>20**	132.7
3	X	3	4.8	5.0	5.9	10.0	161.5
4	X	X	0.02	0.5	0.5	2.6	315.0

* Heatup Rate in K/day   ** Estimated Values

IV. Summary and Conclusions

Core cooling capability of the SMART reactor system has been assessed against severe station blackout scenarios. It is found that the core cooling is maintained quite long enough for operator's to take mitigation actions before severe core damage. This owes to intrinsic safety features of the SMART design. Large amount of RCS inventory and low power density retard time for RCS and fuel to heat up. And, large amount of ECT inventory and high design pressure of PRHRS maintain passive residual heat removal for a prolonged time. Since failure of all passive PRHRS is incredible, it should be noted that the core cooling and safety of the SMART system is insured as long as intact PRHRSs function is secured by replenishing inventory of intact ECTs.

REFERENCES

1) "Fukushima Incident Report", KAERI, 2011
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3) B.D. Chung, et al, "MARS Code Manual", KAERI/TR-2811/2004, 2009