Transactions of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 29-30, 2008

CANDU Reactor Severe Accident Analysis for Accident Management

Young Choi*, D. H. Kim, J. H. Jin, J. H. Park
Korea Atomic Energy Research Institute
P.O.Box 105, Yusung, Daejon, Korea, 305-600
**Corresponding author: ychoi@kaeri.re.kr*

1. Introduction

As well known, the importance of the prevention and mitigating of severe accidents in nuclear power plants has increased since the TMI accident. Therefore, this analysis scope will serve to cover an overall appreciation of severe accident behavior, to understand the most likely severe accident sequences that could occur at CANDU plant, to identify any plant specific vulnerabilities to severe accidents, and to provide necessary information for the development of the containment improvement plan and accident management program that could help prevent or mitigate severe accidents comparing to typical PWR Plants.

2. Methods and Results

In this section some of the techniques used to model the CANDU plants are described. [1] Basically the same methodology used for PWRs is applied to CANDU plants. Core damage sequences delivered from the results of Level 1 PSA analyses are grouped into plant damage states (PDSs) to reduce the number of sequences for the back-end analyses. Containment failure mode and timing, and source term characteristics are considered in defining PDSs.

2.1 CADU Design Feature Model

One of the major credits of CANDU plants is a large inventory of moderator which surrounds the fuel channels. As the cooling capability of moderator in the calandria is larger than the decay heat generation rate, the fuel heatup process inside the fuel channel stops with the moderator cooling system available. If moderator cooling system fails, the moderator acts as heat sink and delays fuel melting progression for a while.

In addition, the shield cooling system that cools down the water both in the calandria vault and in the two end-shields could remove 7.3 MWth (about 0.35% of full power) during normal operation. It could slow down or even stop the debris melting process in the calandria. As the calandria itself is located submerged in the calandria vault, the similar effect of the exvessel cooling for PWRs is expected to occur for the debris collected on the bottom of the calandria. Existence of large water inventory in the calandria vault prevents or delays core-concrete interaction with calandria vault concrete and delays corium relocation into the basemat.

CANDU has a dousing spray system and local air cooler system as containment heat removal systems. The roles of spray system and the air cooler system are somewhat different from those of PWRs. For CANDU plants, the dousing spray works as a short-term heat sink without a recirculation mode and the local air coolers work as a long-term heat sink. Meanwhile, the PWR spray system has a recirculation mode and works as both short-term and long-term heat sinks. In addition, the containment fan coolers in PWRs cannot be credited during the severe accidents. CANDU plants also have hydrogen igniters like PWRs, which can control hydrogen concentration in the containment properly.

2.2 Containment Failure Model

Potential containment failure modes and mechanisms which are suggested in NUREG-1335[1] are considered in the development of containment event tree (CET) for severe accident analysis. [2] The progression of severe core damage in PWRs would be terminated by adding enough water to the core by the operation or restoration of ECCS before reactor vessel fails. Restoration of ECCS for a loss of offsite power case or availability of ECCS after the temperature-induced RCS failure during a high pressure sequence is also considered to mitigate the accident. Due to the characteristic of CANDU plants, core damage usually defined in PWRs can be categorized into limited core damage (LCD) and severe core damage (SCD). LCD separates the sequences which do not result in core disassembly or loss of geometry from all the core damage sequences, maintaining core integrity. An example of a sequence leading to the LCD state is a transient without secondary side heat sink but where the moderator cooling system and/or the emergency core cooling system is available. In this sequence, the core damage is limited to few channel ruptures, due to the effective removal of the decay heat and the stored heat using these systems. So severe core damage phenomena, such as a core disassembly or fuel melting within the calandria vessel, are avoided and a tiny fraction of the fission products is expected to be released.

2.3 Severe Accident Analysis

If the containment integrity is maintained during a severe accident, the radiological consequences will be negligible. If the containment function does fail, the timing of containment failure is very important. The longer the containment remains intact, relative to the time of core melting and fission product release from the reactor coolant system, the more time is available for the removal of radioactive material from the containment atmosphere by engineered safety features or natural deposition processes. Thus, in evaluating the performance of containment, it is appropriate to categorize the end points of CET based on the degrees of radiological severity into 1) no containment failure, 2) early containment failure, 3) late containment failure, 4) very late containment failure, 5) basemat melt-through, and 6) containment bypass.

According to the typical containment failure time in PWRs used here, early failure is defined as the containment failure at or just after reactor vessel fails, and late failure from two hours after the vessel failure to three days after accident initiation[3]. But in CANDU plants, the failure of the containment before calandria tank failure is defined as late containment failure using ISSAC[4]. Time span of "late" in this context is from about one day into the accident. Late containment failure can result from slow over-pressurization process due to water vaporization in the calandria vault, energetic late hydrogen combustion before calandria tank failure or in-calandria tank steam explosion (the alpha mode failure). Also very late containment failure, which is the second failure mode in the analysis, is defined as the failure of the containment at or after calandria tank failure in three-day mission time. The very late containment failure is CANDU-specific containment failure mode as mentioned in its definition. Its probability is very low compared to the late containment failure, because most of the slow pressurization sequences without engineered safety features contribute to the late failure mode. Also, the hydrogen igniters limit the pressure rise after the calandria tank failure for sequences which are supposed to cause the very late containment failure.

While the basemat melt-through in CANDU plants is excluded, it occurs in PWRs due to the relative faster accident progression than in CANDU. Between the two main contributors of interfacing system LOCA and SGTR for the containment bypass category, SGTRs are much dominant over interfacing system LOCA for PWRs, while SGTRs are the only cause in CANDU plants. Though the conditional probability of PWRs is two orders high than that of CANDU plants (0.144 compared to 0.0014), the absolute probability is about 7 times larger.

The conditional probability of containment failure given core damage for CANDU plants is lower than PWRs. One of the major reasons is the contribution of core damage sequences which do not cause fuel melting or channel disassembly. The availability of moderator cooling system and/or ECCS may mitigate the sequence into the limited core damage. Even for the severe core damage sequences, secondary heat removal function could save the intact loop during a LOCA sequence and maintain the containment integrity. These CANDU-specific features support a rather strong containment performance for the internal events. The conditional probabilities of no containment failure for CANDU plants and PWRs are 0.942 and 0.749, respectively.

As analysis results, CANDU plants respond to severe accident initiators uniquely, by using abundant water inventories in the various process systems and in the containment to limit the core damage. Even if fuel channels fail, the moderator cooling system and/or the ECCS can arrest the accident before a major release of fission products from the fuel can occur. The containment safeguard systems including the full-capacity air coolers, the end shield cooling system, and the reliable secondary heat removal systems keep the containment pressure below the failure threshold in most cases.

3. Conclusions

In order to identify the characteristics of CANDU plants, unique CANDU features are identified: a large water inventory of moderator and in the calandia vault, moderator and shield cooling capability, containment dousing system and local air coolers, and the relative lower containment failure pressure. Based on these features, CANDU has different CET headings from PWRs and the reason for their selection has been described with the PWR. Despite a low containment failure pressure compared to PWRs, the conditional containment failure probability is lower than that of PWRs. One of the main reasons is the contribution of limited core damage sequences not causing fuel melting or channel disassembly, thanks to the moderator cooling system and/or ECCS.

REFERENCES

[1].USNRC, "Individual Plant Examination: Submittal Guidance", NUREG-1335, August 1989

[2]. KAERI, "Development of Computer Code for Level 2 PSA of CANDU Plant", KAERI/RR-1573/95, 1995

[3]. KEPCO, “Ulchin Units 3&4 Final Probabilistic Safety Assessment Report”, Vol.5, November 1997.

[4]. KAERI, "Development of Computer Code for Level 2 PSA of CANDU Plant," KAERI/TR-1573/95, 1995.12