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Severe accident analysis to verify the effectiveness of severe accident management guidelines for large pressurized heavy water reactor

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HIGHLIGHTS

- The progression of severe accident initiated from high pressure scenario of station black out has been analyzed using RELAP5/SCDAP.
- The effectiveness of SAMG actions prescribed has been established through analysis.
- The time margin available to invoke the SAMG action has been specified.

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ABSTRACT

The pressurized heavy water reactor (PHWR) contains both inherent and engineered safety features that help the reactor become resistant to severe accident and its consequences. However in case of a low frequency severe accident, despite the safety features, procedural action should be in place to mitigate the accident progression. Severe accident analysis of such low frequency event provides insight into the accident progression and basis to develop the severe accident management guidelines (SAMG). Since the order of uncertainty in the progression path of severe accident is very high, it is necessary to study the consequences of the SAMG actions prescribed. The paper discusses severe accident analysis for large PHWRs for multiple failure transients involving a high pressure scenario (initiation event like SBO with loss of emergency core cooling system and loss of moderator cooling). SAMG actions prescribed for such a scenario include water injection into steam generator, calandria vessel or calandria vault at different stages of accident. The effectiveness of SAMG actions prescribed has been investigated. It is found that there is sufficient time margin available to the operator to execute these SAMG actions and the progression of severe accident is arrested in all the three cases.

1. Introduction

The inherent design safety features and the engineered safety features used in the large PHWRs (PHWRs with two primary loop system) not only reduce the risk of occurrence of a severe accident arising from single failures but also help mitigate the consequences of such an accident by arresting its progress. However manual countermeasures are required to reduce the severe accident risks in case the inherent or design safety features fail to invoke necessary action either due to an inherent system failure or failure of multiple systems stemming from different initiating events occurring simultaneously. In such cases, the emergency operating procedures (EOPs) used to arrest the accident progress of design basis accidents may require additional information or modification due to failure or non availability of certain safety features. With a severe accident, severe accident management guidelines (SAMG) are used to control the accident progress. Typically for PHWRs loss of sub-cooling margin in inlet header combined with either drop in moderator level below top channel or high radiation level in containment is used as a criteria to switch from EOPs to SAMG. Detailed analysis of the accident situation along with assessment of availability of the various safety features constitutes the severe accident analysis, which provides necessary inputs to delineate the guidelines to arrest the severe accident progression. Since effectiveness of SAMG

Abbreviations: ASDV, atmospheric steam discharge valves; CT, calandria tube; CV, calandria vessel; ECCS, emergency core cooling system; EOP, emergency operating procedure; IH, inlet header; MSSV, main steam-line safety valve; OH, outlet header; OPRD, over pressure rupture disk; PCP, primary circulation pump; PHTS, primary heat transport system; PHWR, pressurized heavy water reactor; PT, pressure tube; RD, rupture disk; SAMG, severe accident management guidelines; SBO, station black out; SG, steam generator.

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actions depends on availability of certain safety features as well as the plant parameters at the time of execution of SAMG, thorough understanding of the accident evolution with analysis of the consequences of each possible management procedure is necessary to design and implement SAMG effectively and comprehensively.

This paper describes the accident evolution for a high pressure scenario arising due to station black out (SBO) along with loss of emergency core cooling system (ECCS) and moderator cooling for a large PHWR (a 540 MWe Indian PHWR has been considered as a case for analysis purpose). SAMG actions already developed and implemented for such a scenario include injection of water into steam generator (SG) secondary side post SG crash cooling (manual depressurization of SGs through manual operation of discharge valves), injection of water into calandria vessel post rupture of over pressure rupture disk (OPRD) and injection of water into calandria vault post rupture of vault rupture disk. As a part of regulatory exercise to ensure that the developed SAMG actions are able to arrest accident progression, the effectiveness of these SAMG actions in terms of the ability to arrest the accident progression and available time margin for operator actions have been investigated. The behavior of fuel temperature post SAMG action and time available for operator to execute SAMG action are the parameters used to assess effectiveness of SAMG action. SBO scenario has been chosen for the analysis since it follows a path in which all the three SAMG actions prescribed above are to be implemented one after other so that effectiveness of individual action can be demonstrated.

2. Generic model for large pressurized heavy water reactors

A typical large pressurized heavy water reactor consists of fuel channels housed horizontally in calandria vessel. Each fuel channel consists of fuel bundle (containing 19 or 37 fuel pins) stacked one behind other. Shield plugs are used at both ends as a shield against radiation. Fuel bundles are enveloped in pressure tube (PT) which in turn is enveloped in calandria tube (CT). Heavy water used as coolant flows over the fuel pins through the pressure tube. The channels are connected on either ends to headers through feeder pipes. Heated coolant from the outlet header flows through U-tube steam generators (SG) and looses heat to the coolant on the secondary side of SG. It is then pumped back to channels via inlet header (IH) using primary circulation pumps (PCP) completing one of the two loops of the primary heat transport system (PHTS). The second PHTS loop is identical to the first and are connected to each other through pressurizer connected to the outlet headers (OH) of each loops. The channels are kept submerged under heavy water moderator contained in calandria vessel and maintained at 123 kPa(a) and 342 K. Over pressure rupture disks (OPRDs) are used to prevent pressurization of moderator. The calandria vessel is submerged in light water contained in calandria vault and is maintained at atmospheric pressure. Vault rupture disks are used to prevent pressurization of calandria vault. A generic model for the large pressurized heavy water reactors is developed with system code SCDAP/RELAP5 (Siefken et al., 1997). The model consists of 2 loop model of the primary heat transport (PHT) systems in a figure of eight (8) fashion with clubbed channel (more than one channel grouped into a single representative channel is referred to as clubbed channel) modeling of the reactor core, inlet and outlet headers, steam generators, primary circulation pumps, pressurizer, etc. The nodalization of one of the loops without connection to the pressurizer has been shown in Fig. 1. The core is divided into 8 zones for each loop depending upon the elevation of fuel channels. Each zone contains one clubbed channel representing the total number of channels in that zone. The convective heat transfer characteristic is conserved in the clubbed channel by providing equivalent fuel pins with internal heat generation, pressure tube (PT) and calandria tube (CT) with their corresponding surface areas. Equivalent flow rate has been provided in the clubbed channel to preserve heat transfer characteristics. The radiative heat transfer characteristics is conserved for a single channel and applied to all the clubbed channels.

SCDAP “fuel” and “shroud” components are used for fuel elements and PT–CT elements, respectively. Shield plugs at the end of each fuel channel are also modeled with “fuel” component in the SCDAP structure with zero power generation. Detailed model of the moderator in calandria vessel and vault water is also evolved to track the moderator level, vault water level and effect of moderator boil off on the channel temperatures. The heat transfer between the moderator and the calandria vessel and between the calandria vessel and vault water is modeled as convective heat transfer correlation based on the temperature of the calandria vessel and fluid conditions on either sides of the vessel. The nodalization of the moderator and vault modeling is shown in Fig. 2. Heat structures are used to represent the fuel, pressure tube, calandria tube, steam generator heat structures, etc. and substantial heat structures like the calandria vessel, tube sheets, channel end fittings, end shields, vault walls, etc. are also considered to account for losses through the system.

3. Severe accident scenario: station black out (SBO) with loss of ECCS

Multiple failure events can lead to transients involving higher pressure transients caused due to an initiating event of station black out. Evolution of an accident arising from SBO as initiating event has been discussed here. The analysis of station black out scenario for CANDU 6 reactors has been adopted (Maurya et al., 2008). The scenario assumes following postulated events:

- AC power and all emergency power (Class III – diesel driven AC generators and Class IV – AC grid power) are assumed unavailable.
- Reactor is shut down immediately after accident initiation.
- Primary circulation pumps trip and coast down.
- Moderator cooling and end shield cooling are unavailable.
- Shutdown cooling is unavailable.
- Emergency core cooling system (high, medium, low pressure) is unavailable.
- Main and auxiliary feed water pumps to steam generators are unavailable.
- Steam generator main steam safety valves (MSSVs) are available and they operate at the pressure set point.
- Turbine main stop valves close 20 s after the accident initiation.
- SG-auto crash cool down assumed unavailable.
- Air operated atmospheric steam discharge valves (ASDV) assumed fail closed.
- No operator intervention is credited.

The event sequence in the SBO scenarios is tabulated in Table 1. Station black out is declared with unavailability of Class III and Class IV power. The event is monitored with the help of steam generator pressure and level as well as reactor core pressure, fluid temperature and pressurizer level. Along with these measurements calandria level (moderator) and calandria vault water level are also measured. The initiating event of station black out (SBO) with failure of emergency core cooling system (ECCS) leads to reactor trip along with coast down of the primary circulation pumps. The auxiliary boiler feed water pumps are also assumed to be unavailable due to on site power failure. Due to continuous production of decay heat in the reactor core, the fuel temperature increases followed by increase in the pressure tube (PT) temperatures. Since the water available in the steam generators continues to evaporate through