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RELAP5 simulation of CANDU Station Blackout accidents with/without water make-up to the steam generators

Feng Zhou *, David R. Novog

Department of Engineering Physics, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L7, Canada

HIGHLIGHTS

- Benchmarking RELAP5 against Loss of Flow measurements from an operating 900 MW CANDU reactor.
- Prediction of Station Blackout response with and without operator action credits.
- Assessment of continuous and intermittent natural circulation heat sinks.
- Role of passive water supplies on event timing and emergency response times.

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ABSTRACT

In the event of a complete Station Blackout (SBO) of a CANDU reactor, the current safety practice is to initiate depressurization early in the transient once a lack of power has been declared. This requires operator actions to manually open the main steam safety valves (MSSVs) on the secondary side initiating a crash-cool procedure. The depressurization of the secondary side allows make-up water to be supplied to the steam generator (SG) secondary-side thereby extending natural-circulation driven heat removal from the fuel in the primary heat transport system. Once depressurized there are several additional water sources available to replenish the secondary-side inventory, and in the event that emergency power cannot be restored emergency mitigating equipment (EME) are available to provide alternative water make-up. The objective of this paper is to examine the processes and phenomena involved during and after crash-cooling and compare these results to cases where operator actions are not credited. Simulations are performed until such time as the secondary-side inventory is stabilized from alternative water sources or until it is depleted.

A detailed RELAP5 model of a 900 MW CANDU plant has been created including the primary heat transport system (PHTS), the feed and bleed system, the steam generator secondary side, the moderator system, and the shield water cooling system. The 480 fuel channels were grouped into 20 channels by elevation and channel power. The models were benchmarked against the 1993 loss-of-flow event at Darlington NGS and agreed with the station data within the reported measurement uncertainty. Then the models were used to simulate the Station Blackout accidents with loss of class IV, class III, and emergency power supplies. Five different scenarios with/without crash-cool and with different water make-up options are modeled and key sensitivities determined. The results show that the depressurization of the secondary side may create a situation where continuous natural circulation breaks down and intermittent buoyancy induced flows (IBIF) takes place. The RELAP5 predicted IBIF phenomena are discussed, as well as the limitations of the current RELAP5 code. The main focus of this paper is on the early stage of the accidents, i.e. when adequate steam generator secondary side inventory exists and where damage to the main heat transport system can be precluded. The results demonstrate that EME actions to maintain SG inventory are effective and ensure fuel and fuel channel integrity.

1. Introduction

The CANDU® reactor (CANada Deuterium Uranium) is a pressure-tube type reactor using natural uranium as fuel and separate coolant and moderator systems utilizing heavy water.

* Corresponding author.
E-mail address: zhouf5@mcmaster.ca (F. Zhou).

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Nomenclature

AECL	Atomic Energy of Canada Limited
ASDV	Atmospheric Steam Discharge Valve
BC	Bleed Condenser
CANDU	CANada Deuterium Uranium
CCFL	Counter Current Flow Limit
CNSC	Canadian Nuclear Safety Commission
CSDV	Condenser Steam Discharge Valve
CT	Calandria Tube
CWIT	Cold Water Injection Tests
DEA	Deaerator
ECCS	Emergency Core Cooling System
EME	Emergency Mitigating Equipment
EPS	Emergency Power Supply
ES	End Shield
ESV	Emergency Stop Valve
EWS	Emergency Water Supply
IBIF	Intermittent Buoyancy Induced Flow
IF	Inlet Feeder
LOF	Loss of Flow
LRV	Liquid Relief Valves
MCA	Mechanical Control Absorbers
MSSV	Main Steam Safety Valve
NGS	Nuclear Generating Station
OF	Outlet Feeder
PHTS	Heat Transport System
PT	Pressure Tube
RIH	Reactor Inlet Header
ROH	Reactor Outlet Header
SBO	Station Blackout
SDS	Shutdown System
SG	Steam Generator
SGECS	SG Emergency Cooling System

The reactor is divided into two identical primary heat transport loops each in a figure of eight arrangement with each loop having two alternating-direction core passes. The two loops are connected via small diameter piping to the pressurizer, and they can be isolated by closing the loop isolation valves. A 900 MW CANDU has a total of 480 horizontal fuel channels with 120 fuel channels per core pass. Each fuel channel consists of a Zr-2.5%-Nb pressure tube (PT) surrounded by annulus insulating gas and a Zr-2 calandria tube (CT). Coolant from each Class IV powered primary circulation pump is distributed to the channels via an inlet feeder and feeder pipes. Outlet feeders connect the channel outlets to the reactor outlet headers which are connected to the steam generators. Four large steam generators (one per core pass) transfer heat to the secondary side system. Power is normally supplied to key cooling systems through Class IV power (supplied by station or grid transformers) or Class III power (via Class IV or from standby generators). In addition the Emergency Power Supply (EPS), Emergency Water Supply (EWS) and Emergency Mitigating Equipment (EME) are available for implementing emergency measures.

The calandria tubes are contained in a large horizontal calandria vessel which is filled with heavy water acting as moderator. Under normal operating conditions about 5% of the fission power produced in the core is deposited into the moderator. The moderator cooling systems circulates the moderator to the main moderator heat exchangers where the heat is transferred to the recirculated cooling water system. The moderator system pressure is regulated via the cover-gas system and associated relief valves, and through rupture disks which prevent significant overpressure. The calandria vessel is contained within the shield tank in which a large volume of light water is used to provide biological shielding in the radial direction. Axial biological protection on both reactor faces is provided by the end shields which are filled with steel-balls and light water. The heat lost to the end shields as well as to shield tank is removed by a separate cooling circuit. Both the moderator cooling pumps and shield cooling pumps are powered by Class III power to ensure rapid restoration of circulation following a loss of Class IV power (Jiang, 2015).

The CANDU reactors have multiple heat sink provisions depending on the availability of systems, components and electrical power. In accidents where the PHTS remains intact but electrical systems are compromised, e.g. a SBO, continuous and/or intermittent natural circulation within the primary system allows heat from the relatively low elevation core components to circulate to the cooler steam generators providing an effective heat removal pathway provided that there is sufficient water in the steam generator shell side. The normal water inventory of the four steam generators in the 900 MW Darlington NGS is 340 Mg ± 10% which can provide 4–6 h of post-shutdown cooling (Blahnik and Luxat, 1993; Luxat, 2008). Several options for water make-up to the SGs are available including internal water sources such as the auxiliary feedwater pumps running under standby or emergency power supplies, stored inventory in the deaerator tank, or external water source makeup. The addition of water to the SGs can extend thermo-syphoning in the PHTS thus providing additional time for operators to take mitigating actions.

In a generic 900 MW CANDU the auxiliary feedwater pumps powered by Class III power can maintain SG inventory. The deaerator tank which has normal inventory of about 320 Mg may also provide makeup as it is one of the highest elevation vessels in a CANDU reactor system. If crash-cool of the steam generators occurs the associated depressurization of the secondary side will allow water in the deaerator tank to flow by gravity into the SGs (Harwood and Baschuk, 2015). Crash-cooling is an emergency procedure in CANDU to rapidly reduce the pressure of the SGs by the opening of main steam safety valves (MSSVs). The EWS powered by EPS may also provide inventory to the SGs after crash-cool. Depending on the specific CANDU design, emergency water may be supplied by gravity via the dousing tank and in others via pumping from the EWS. Furthermore, some stations, e.g. Darlington NGS, have a SG emergency cooling system (SGECS) consisting of two air accumulators pressurized by instrument air and two water tanks with each tank and an accumulator suppling two steam generators (Wu, 1993). Both the SGECS and the gravity-fed reserve water system are designed to provide interim water supply to the SGs following the steam line rupture and/or the loss of feedwater supply. After the Fukushima Daiichi accident additional provisions have been implemented in the Canadian NPPs including the EMEs such as portable pumps and power generators. With EMEs external make-up water can be supplied to the steam generators and/or to the calandria vessel.

In a SBO accident the loss of electrical power and service water will disable all active heat sinks including the feedwater system, the EWS system, the shutdown cooling system, the feed and bleed system, and the Emergency Core Cooling System (ECCS) (if pumps are used for the high-pressure injection). The moderator cooling and shield water cooling systems are also lost. However, the water