MODELLING OF LIQUID INJECTION SHUTDOWN SYSTEM (LISS) IN ACR-1000

M. Boubcher[1], A. Colton[1] and J.V. Donnelly[1]
[1]Atomic Energy of Canada Limited, Mississauga, Ontario, Canada

Abstract

Modelling of the Liquid Injection Shutdown System (LISS) in the ACR-1000®[1] reactor core must account for the major phenomena that occur following its activation, namely the moderator hydraulics and core neutronics. The former requires modelling of the poison volumes, their time of entry into the reactor, and their propagation into the moderator after emission from the nozzle. The latter requires the reactivity worth of varying volumes and geometries of poisoned moderator fluid in order to simulate the reactivity effect of the injected poison. The time-dependent poison map is generated from hydraulic calculations, and then the neutronics data for standard geometries and concentrations is constructed using DRAGON [1].

1. Introduction

During a postulated loss-of-coolant accident (LOCA), SDS-2 can rapidly shut down the reactor by injecting liquid poison at high pressure into the moderator through eight horizontal nozzles. The liquid poison, in the form of gadolinium nitrate dissolved in D_2O, is injected at high pressure into the moderator through holes in the nozzles, initially as jets, which rapidly merge into a curtain. LOCA analysis involving the dynamics of liquid-poison injection is complicated. The main challenge in its modelling is the representation of the propagation of the poison curtain in the moderator. The calculation of appropriate incremental cross sections to represent the poison involves intensive modelling and data manipulation.

2. Physics modelling

The physics modelling of SDS-2 accounts for the major phenomena that occur, by combining the effects of the moderator hydraulics and the neutronics. The moderator hydraulics provides modelling of the poison volumes and of the time of entry of the poison fluid into the reactor, as well as propagation of the poison into the moderator after emission from the nozzle. This data is generated by the moderator hydraulics code ALITRIG. This code produces an idealized representation of the moderator injection and dispersion. The neutronics provides an evaluation of the reactivity worth of varying volumes and geometries of poisoned moderator fluid for a range of poison concentrations, in order to simulate the reactivity effect of the injected poison. The neutronics data are generated for a number of standard geometries and concentrations using the supercell code DRAGON. The neutronics calculations simulate the variety of geometries that ensue from the poison injection, i.e., the poison inside the nozzle before emission, and poison jets exiting the pipe at two orientations: horizontally and at 60 degrees to the horizontal. In the model used here, the expanding evolution of the emitted jets is represented by parallelepipeds, like in the CANDU®[2] reactors.

---

[1]Advanced CANDU Reactor®, ACR® and ACR-1000® are registered trademarks of AECL.
[2]CANDU® is a registered trademark of AECL

The modelling of liquid poison injection requires five basic types of geometries:

1. Jets only, emitted horizontally (referred to as detached).
2. Jets only, emitted at 60 degrees to the horizontal (referred to as detached).
3. Horizontal jets, attached to nozzle.
4. 60-degree jets, attached to nozzle.
5. Poison in nozzle only

Geometries of the physical system such as pressure tube, calandria tube, which are circular-cylindrical, and the hexagonal-shaped tube (nozzle), are transformed to a three-dimensional rectangular (xyz) mesh. The 60-degree jets are modeled by a number of staggered blocks, (typically ten) as shown in Figure 1. This number (ten), is identical to the number of blocks used to model the 45-degree jets in CANDU.

The following rules are applied during the geometrical transformations for each of the five above models.

- Conserve the surface area of the fuel.
- Conserve the surface area of the poison jet.
- Conserve the surface area of the poison in the nozzle
- Conserve the moderator volume in the cell
- Conserve the number of poison molecule in the jet and nozzle
- Conserve the volume of the nozzle wall.
- The poison jet stops spreading if the jet hits the calandria wall

3. Code descriptions

The SDS-2 modelling for ACR-1000 involves several computer codes: WIMS-AECL [2], DRAGON, ALITRIG, and the following FORTRAN programs: ASSEM, INTERPL and DEVPPM. Figure 2 shows a schematic diagram of the codes and data flow used for SDS-2 simulation.

3.1 WIMS-AECL

The lattice cell code WIMS-AECL is a two-dimensional multigroup neutron-transport code. Along with the 89-GROUP library, E65ACR [2], it can solve the physics problem for the CANDU cluster with single cell or multicell in two dimensions. The current standard version of WIMS-IST was used here only for 2-D-cell depletion calculations, to generate the reference fuel composition at the nominal mid-burnup, which will be used by DRAGON.

3.2 DRAGON

The DRAGON neutron-transport code was designed for general geometry and can analyse both CANDU clusters and PWR assemblies in two dimensions, with k-effective or critical buckling searches. The code can also carry out three-dimensional supercell transport calculations with the same group structure as the two-dimensional analysis to obtain few-group properties for supercells containing in-core reactivity devices. It has been selected as the standard three-dimensional supercell code for CANDU analysis based on the following considerations:

The DRAGON multigroup neutron-transport method is theoretically rigorous, relatively straightforward, and consistent with the WIMS-AECL lattice-cell calculations. It has either exact or nearly exact geometrical representation of the devices and the fuel channels. The results of the various benchmark comparisons are all within the acceptable ranges.

Two types of DRAGON calculations are performed; a reference cell with no reactivity device or poison, and a "device-inserted" cell. The reference cell and the "device-inserted" cell depend on the geometry used.

Case 1: for jets only, emitted horizontally or at 60 degrees to the horizontal (referred to as detached). The reference cell consists of a number of homogenized regions: the moderator region, the fuel bundle, and the surrounding annulus, which consists of the pressure tube, gas gap and calandria tube. In this case, the "device-inserted" cell also contains a poison jet.

Case 2: for horizontal and 60-degree jets (referred to as attached to a nozzle). The reference cell contains, in addition to the homogenized regions (described above), a nozzle with no poison inside. In this case, the "device-inserted" cell also contains a nozzle with poison inside and a poison jet.

Case 3: for a nozzle only. The reference cell is the same as in case 2. The "device-inserted" cell contains a poison-filled nozzle.

DRAGON is used to produce the incremental cross section in two energy groups for all jet-nozzle combinations with various poison concentrations. Figure 3 shows the poison concentrations considered in our calculations. The choice of concentrations used in the generation of incremental cross sections is arbitrary; however it is intended to provide a range of concentration values with which to interpolate, in order to find the cross section for jet geometries and concentrations that occur during the injection of poison.

Tracking was performed with the EXCELL module of DRAGON and the isotropic reflection option. The transport equation was solved in the same way as in the cell calculations, using the B_1 homogeneous leakage method. Homogenization and condensation were performed by weighting cross sections using the 89-group flux spectrum with an energy cut-off between the two groups at 0.625 eV.

3.3 ASSEM

Following the completion of all DRAGON calculations, the program ASSEM will be executed. This program, which was developed for this application, consists of a set of UNIX commands that assemble all the data files from DRAGON into a single file, which can then be accessed by INTERPL. This collated cross-section file for various jet and nozzle conditions is to be used as an input to INTERPL.

3.4 ALITRIG

ALITRIG is a moderator hydraulics code that is used to simulate injection into the reactor from the poison-filled tanks driven by high-pressure gas tanks. This code generates the jet length and injected poison volume at each time step.

3.5 INTERPL

The execution of INTERPL follows that of ASSEM. INTERPL reads the collated database of incremental cross sections produced by DRAGON and a data set from ALITRIG giving the jet height and injected poison volume at each node of each nozzle at a series of time steps. The cross sections for each (height, poison volume) data set are interpolated from the DRAGON cross-section database. The cross sections are tabulated as functions of jet length. Interpolation is performed using three-point Lagrange polynomials [3].

3.6 DEVPPM

DEVPPM reads the input data from INTERPL and then generates the poison concentration distribution in the core (poison map) at various time steps. The data output from DEVPPM can then be used in *CERBERUS, module of the diffusion code RFSP-IST [4].

At each time step, the poison concentration distribution (in ppm) is generated and saved in a file to be used by the *CERBERUS module of the diffusion code RFSP-IST. Finding the incremental absorption cross section as a result of injection of a poison jet into the lattice cell allows the determination of the equivalent uniform poison concentration (in ppm) that results in the same incremental absorption cross section, see Figure 4. It is this poison concentration that is then recorded in the full core poison distribution map and is in turn used in *CERBERUS/RFSP calculations to determine the reactivity transient as a function of time.

4. Results

A coupled neutronics/thermahydraulics simulation of transients following a hypothetical large LOCA initiated from a nominal flux shape and terminated by SDS-2 action was carried out. In the LOCA analysis, one of the eight poison injection nozzles was assumed to be non-operational upon actuation of SDS-2.

All simulations were done in three spatial-time dimensions, with RFSP-IST coupled to the thermahydraulics code CATHENA. The two codes were coupled in the sense that neutronics and thermahydraulics equations were solved alternately for the sequence of time steps. At each step, the coolant density, coolant-temperature and fuel-temperature distributions calculated with CATHENA were input to the *CERBERUS module within RFSP-IST, along with poison incremental cross sections calculated separately, in order to calculate the three-dimensional flux and power distributions.

The SDS2 was performed with one of the 8 nozzles unavailable using the 1-D moderator hydraulics code ALITRIG. Results, which are presented in Figure 5 show that the case with nozzle number 7 inactive constitutes the worst case since the asymptotic reactivity is about –35 mk.

5. Summary

The liquid injection shutdown system was modelled by taking into account the moderator hydraulics and neutronics. Several codes were used to take the key input parameters (poison volume and propagation length given by ALITRIG, incremental absorption cross sections given by DRAGON) and convert them into a full core poison map in equivalent ppm to do full core calculations in RFSP-IST coupled with CATHENA and finally arrive at three dimensional flux and power distributions for each time increment. A computational fluid dynamics code (CFD) may be used in the future to model the propagation of poison into the moderator after actuation of the LISS. It has the potential to provide a poison distribution map as a direct output thereby foregoing any interpolation and approximation as required by ALITRIG. Note that the computational expense will be increased, as it will require creating and running one DRAGON input per lattice cell in the reactor.

6. Acknowledgements

The authors wish to thank the members of the ACR physics group for their co-operation, mainly, I. Martchouk and J. Hu. The authors wish also to thank the code developers in both the functional physics branch and Chalk River physics group, namely, P. Schwanke, T. Liang, W. Shen, D. Altiparmakov and D. Roubstov. A special thank to R. Noghrenkar and F. Song for providing thermohydraulic data.

7. References

[1] Shen W., “CANDU three-dimensional neutron transport calculations with DRAGON”, AECL, International Conference on the New Frontiers of Nuclear Technology – Reactor Physics, Safety and High-Performance Computing, Seoul, Korea, October 2002

[2] Irish J. D., Douglas S. R., “Validation of WIMS-IST”, 23rd Annual Conference of Canadian Nuclear Society, Toronto, Canada, 2002.

[3] Séroul, R. "Lagrange interpolation." *Programming for Mathematicians*. Berlin: Springer-Verlag, 2000, pp. 269-273.

[4] Rouben B., “RFSP-IST, the industry standard tool computer program for CANDU reactor core design and analysis”, 13th Pacific Basin Nuclear Conference, Shenzhen, China, 2002.

8. Figures

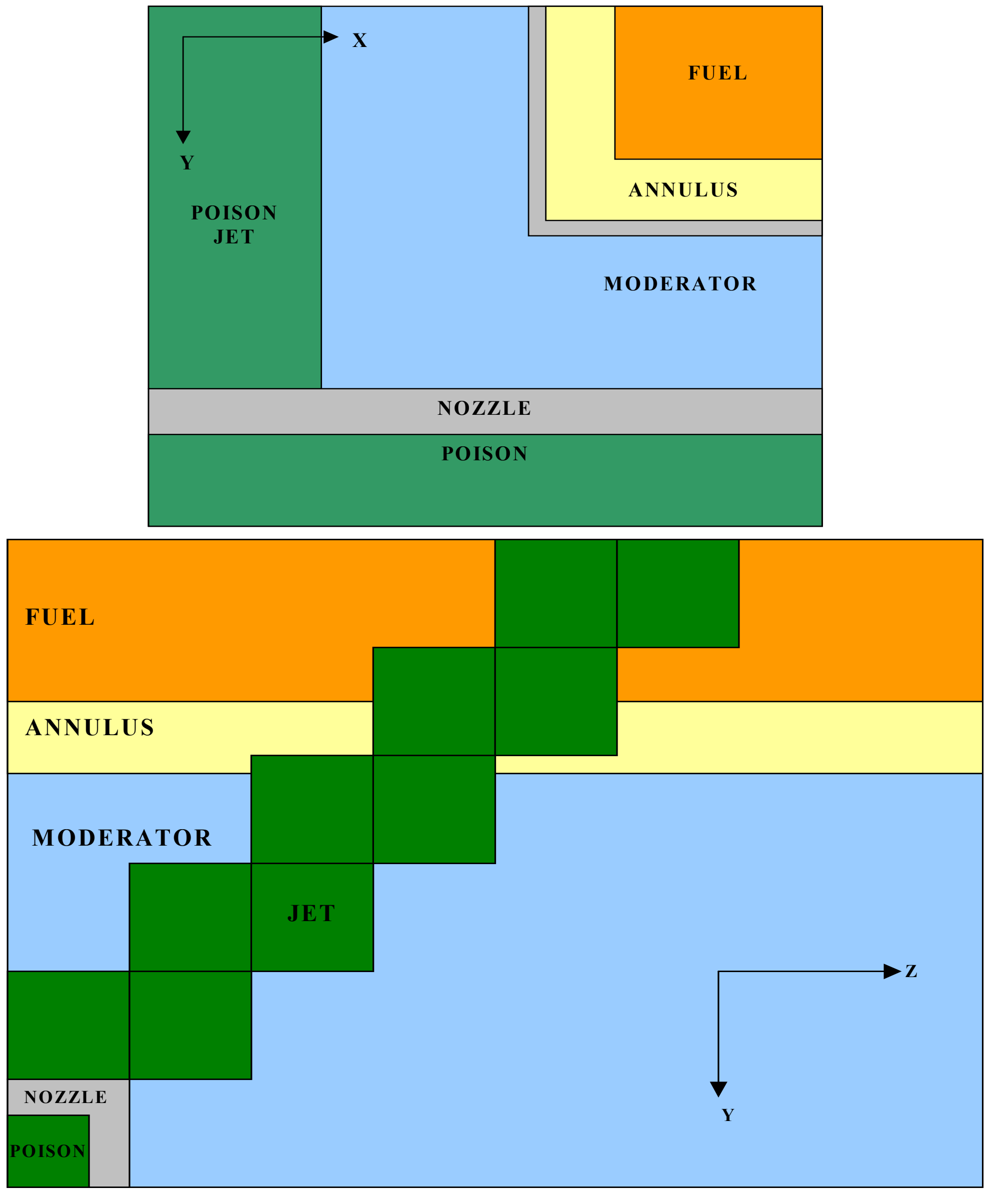

Figure 1: Model for Nozzle plus Jets, at 60 Degrees

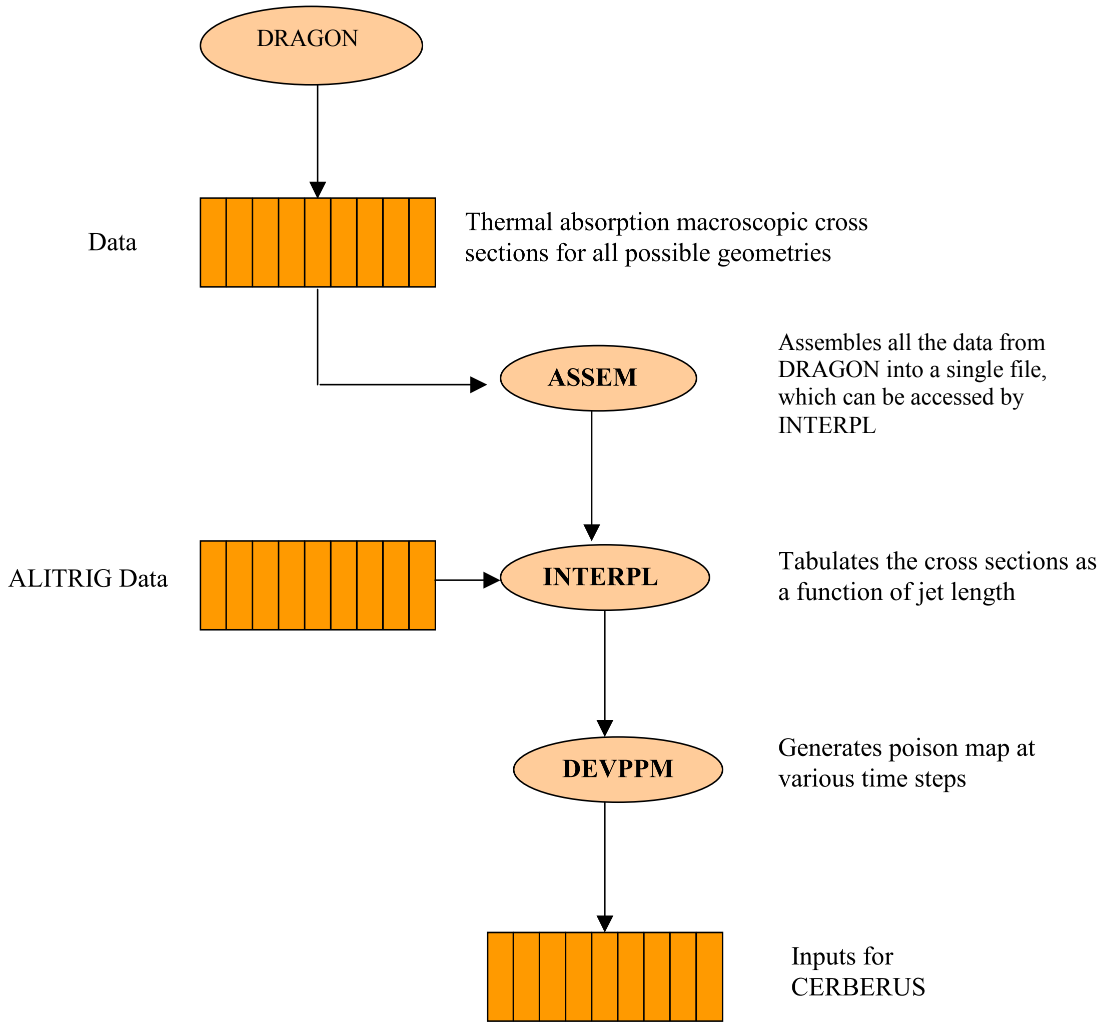

Figure 2: Schematic Diagram of the Codes and Data Flows Used for SDS-2 Simulation

Concentration (ppm)
0.00
320
960
1280
1600
1920
2560
3840
5760
8000

Figure 3: Poison concentration for the jets emitted at 0 and 60 degrees

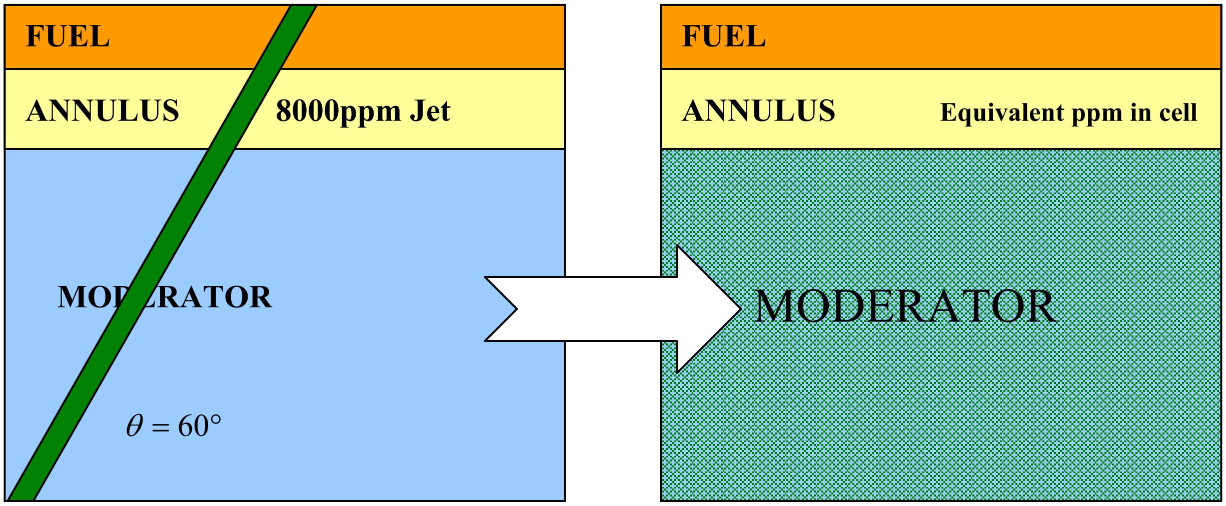

Figure 4: Generation of Equivalent PPM

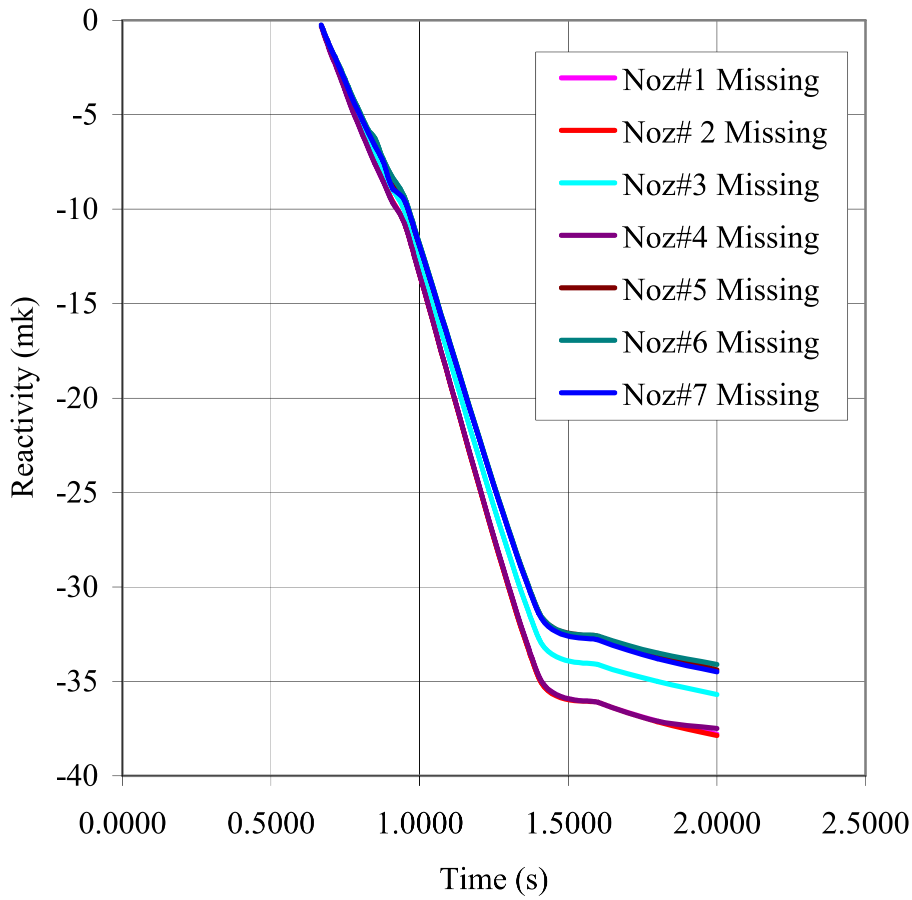

Figure 5: Reactivity Transient vs. Time*

*Note that in this figure, the poison jets are modelled as frozen after 1.4 seconds. While in reality, the jets would continue to propagate and mix within the moderator reaching a reactivity depth of at least -150 mk.