CANDU ORIGINS AND EVOLUTION – PART 5 OF 5

THE ORIGINS & EVOLUTION OF THE SECOND SHUTDOWN SYSTEM

by
G.L. Brooks[1] - 2001 February

Prepared as a contribution to a project sponsored by AECL, and carried out by the AECL Retirees Group, in the period of the 1990's. Published with permission of the authors.

Notes on injection experiments and later development added by D.A. Meneley[2].

[1] Former Chief Engineer, AECL
[2] Former Chief Engineer, AECL

Summary:

The historical origins of the second shutdown system, as applied to Bruce-A and all subsequent CANDU reactors, are discussed in two parts. The first deals with the evolution of licensing requirements for a second shutdown system and the second deals with the origins of the fast liquid poison injection system chosen for the second shutdown system.

Table of Contents

Historical Origins

The historical origins of the second shutdown system, as applied to Bruce-A and all subsequent CANDU reactors, are discussed in two parts. The first deals with the evolution of licensing requirements for a second shutdown system and the second deals with the origins of the fast liquid poison injection system chosen for the second shutdown system.

1. Evolution of Licensing Requirements

The original CANDU-type reactors, comprising NPD, Douglas Point, and Pickering-A, employed a single fast-acting safety shutdown system designed to provide the necessary negative reactivity depth and speed of insertion to satisfy all safety requirements for fast emergency reactor shutdown. In the cases of NPD and Douglas Point, a relatively simple moderator dump system proved adequate for this purpose. In the case of the Pickering-A reactors, the larger core size reduced the negative reactivity provided by moderator level reduction during the early stage of a dump, i.e. with a large core the moderator dump was inherently less effective in terms of achievable early negative reactivity rate. Following detailed studies, the Pickering designers concluded that, while a practical dump port configuration would result in negative reactivity rates adequate to cater to most potential accident situations, it would not be adequate for certain accidents such as large-break LOCA's. They, therefore, decided to add a number of gravity-drop mechanical shutoff rods to augment the moderator dump. A common electronic trip system actuated both the dump valves and the shutoff rods.

For the licensing of the Pickering-A reactors, the concept of single and dual failure accident analysis was introduced by the AECB as a requirement under the so-called "Siting Guide". As a consequence, each potential accident had to be analyzed assuming that the safety shutdown system was unavailable. The analysis therefore had to cover cases where there was an accidental insertion of positive reactivity terminated only by the physical disassembly of the reactor core resulting from the consequential reactor overpower transient. While the analysis, as carried out, indicated that this inherent shutdown mechanism would terminate the overpower transient without a serious threat to containment integrity, the analysis was somewhat speculative in nature because of a lack of fully relevant experimental information.

In the case of the Bruce-A reactors that followed Pickering-A, the changed containment concept resulted in the reactor's reactivity mechanism deck serving as a part of the containment boundary. As a result of this increased proximity between the reactor core and the containment boundary, the designers decided that the probability of an accidental physical disassembly of the reactor core resulting from an overpower transient should be greatly reduced. This led the designers to propose the introduction of a second, independent, and diverse safety shutdown system. In a presentation to the AECB's Reactor Safety Advisory Committee (RSAC), the designers proposed that the second shutdown system would be actuated only by neutronic signals since its intended purpose was limited to the prevention of reactor overpower transients, including localized overpower transients which might cause pressure tube failure. The RSAC did not accept this proposal to limit the trip parameters for the second system. Following the recommendation of the RSAC, the AECB issued a formal "Two Shutdown System Policy" statement which, in essence, stated that if the designers wished to incorporate a second shutdown system, it would have to cater to the full spectrum of accidents covered by the first shutdown system. If this were done, the Board would accept that at least one of the two shutdown systems could be credited for all accidents, the credited shutdown system being the one which was the least effective of the two for any specific accident scenario.

The Board's Policy statement did not explain the rationale for requiring the second shutdown system to be fully comprehensive, i.e. to have a full set of trip parameters. It is, however, the opinion of the author that the Board saw this as a reasonable "trade-off" for not requiring the designers to provide a "core dissassembly" analysis. Faced with this formal Board position, the designers felt they had little choice but to proceed on this basis. Subsequently, the CANDU-6 designers decided to follow the same route for sake of uniformity of approach even though the CANDU-6 design utilized a more traditional containment arrangement. It was also judged that avoidance of a "core disassembly" scenario for licensing purposes would improve marketability of the design in other countries. This was, indeed, a fortunate decision given the subsequent Chernobyl accident!

2. Origins of the Fast Liquid Poison Injection System

Turning now to the second part of this monograph which covers the design of the second shutdown system, the Bruce designers recognized that the design would have to be diverse from the design of the first shutdown system in order to preclude the possibility of common-mode failures which could disable both systems. Such diversity would need to extend to all elements of the system including choice of specific instruments and hardware and should employ a fundamentally different mode of operation and, to the extent practical, be located in different parts of the reactor core, the latter being necessarily common to both shutdown systems. These considerations led to a decision that the in-core elements of the second system should be arranged horizontally since the first system had these elements arranged vertically. Horizontal mechanical shutoff rods were a possible choice - such rods were employed in the Hanford N reactor. This choice was not pursued because it was recognized that such rods could suffer disabling damage from core disruptive accidents in the same way as could the vertical shutoff rods. Liquid horizontal shutoff rods were another possibility but a relatively large number would have been required to achieve the necessary reactivity depth. The in-core tubing of such rods, even if fabricated from Zircaloy, would have presented a significant reactivity load during normal operation.

The alternative finally chosen was an adaptation of a design originally developed for the Gentilly-1 CANDU-BLW reactor. This was a fast-acting liquid poison injection system comprising a number of small tanks containing gadolinium nitrate solution which were connected to perforated Zircaloy in-core injection tubes. The top of each poison tank was connected to high pressure helium storage tanks via an array of valves which were opened on a trip signal, thereby pressurizing the poison solution and causing it to flow rapidly into the perforated in-core tubes and, hence, into the bulk moderator. Rapid dispersion of the poison solution within the moderator resulting from the jets of poison solution emanating from the perforations provided a very high degree of negative reactivity with only a small number of tubes being necessary. In the case of Gentilly-1, the fast-acting poison injection system was added late in the design as a means of providing additional negative reactivity rate to augment that provided by the moderator dump system. It was actuated by the same electronic trip system as actuated the moderator dump and therefore performed a similar function to that provided by the shutoff rods in the Pickering-A reactors. In the case of Gentilly-1, the in-core poison injection tubes were vertically oriented whereas for the reasons discussed earlier, in the Bruce-A reactors, the tubes were oriented horizontally.

During the development of the fast-acting liquid poison injection system, a number of interesting problems arose which will now be discussed. The first problem involved "water hammer". As originally conceived, the piping downstream of the poison tanks was to be gas-filled (helium) while the system was in a normal poised state. This gas space in the piping was intended to ensure that poison solution did not diffuse into the in-core injection tubes and the bulk moderator during normal operation. Moderator heavy water was, however, unavoidably present in the injection tubes and for some distance back into the piping connecting the tubes to the poison tanks. As a result, when the system was "fired" by the rapid helium pressurization of the poison tanks, the poison solution flowing out of the tanks rapidly achieved a very high velocity. This flow of poison solution progressively pressurized the helium gas in the interspace leading to the in-core injection tubes. While this pressurization would start to push the previously static moderator water out of the injection tubes and adjacent piping, a significant time delay was inherently involved because of the inertia of this water and the initial relatively show buildup of pressure in the helium gas (a very non-linear spring, in effect). The non-linearity of this "spring" resulted in a severe "water hammer" type pressure transient in the pipework as confirmed by tests carried out in a mock-up in the Sheridan Park Engineering Laboratory (SPEL). This gave rise to concerns regarding potential high stress, low cycle fatigue failures in the pipework.

3. Problems and Solutions

The designers therefore concluded that the gas interspace between the poison tanks and the in-core injection tubes would have to be eliminated. As a result, the designers had to reconsider the problem of avoiding possible diffusion of poison into the moderator during normal reactor operation. One possible solution would have been to introduce valves in the connecting piping. However, to permit the on-line periodic testing of such valves - essential to meet safety system reliability requirements since the valves would have to open on a trip signal, a multiple series/parallel valve array would have been needed in each line, adding cost and presenting maintenance problems. The designers therefore investigated a possible "valveless" arrangement. With this arrangement, the poison tanks would be located at an elevation such that the free surface of poison solution in the tanks would be the same as the free surface elevation of the moderator in the reactor assembly. A helium gas connection would be provided between the reactor cover gas system and the top of each poison tank such that cover gas pressure transients would not induce significant flow in the liquid-filled pipework which was, in effect, a part of a large U-tube, formed by the calandria, the pipework, and the poison tanks. Diffusion calculations indicated that the movement of the gadolinium nitrate poison along the pipework would be very slow. Hence, it was concluded that the design approach was practical provided poison solution was periodically drained from the poison tanks thereby moving the interface between the poison solution and unpoisoned moderator back towards the poison tanks. This required the periodic replenishment of the poison solution in the poison tanks but this was judged to be acceptable from an operations standpoint. This overall design approach was therefore accepted and implemented.

A second "interesting" problem involved the question of how to handle the high-pressure helium remaining in the system once the liquid poison had been injected into the bulk moderator. If no special design provisions were made, the high-pressure helium would simply follow the poison solution into the moderator resulting in a large "belch". The designers concluded that this would be undesirable from several standpoints. Firstly, it would pressurize the moderator cover gas system and while the calandria overpressure protection rupture discs might not fail, they would be subjected to a sharp transient load which could shorten their fatigue life. Secondly, the sudden injection of gas bubbles into the moderator would give rise to severe reactivity "noise", upsetting neutronic measurements. Thirdly, the helium cover gas pressure would have to be returned to normal subsequently, by removing the excess helium, giving rise to a potential problem in handling helium contaminated with heavy water vapour with a high tritium content. The designers therefore concluded that the high-pressure helium should be isolated from the system downstream of the poison tanks once the tanks emptied. The use of conventional fast-acting valves in the pipework leaving the poison tanks was considered but discarded based on judgments of complexity and reliability.

A relatively simple solution was suggested. This involved the use of a buoyant ball in each tank which would follow the poison outflow and subsequently seat at the bottom of the tank, thereby isolating the high-pressure helium. Obviously, such a ball would be subjected to high shock loading as it seated and must, therefore, be highly rugged. Furthermore, there must be "absolute" certainty that the ball would remain buoyant since, if it lost its buoyancy, it would effectively disable subsequent poison injection. The designers therefore chose balls made from solid polyethylene which is inherently buoyant and a very "tough" material. To prove this "toughness", an experiment was carried out in SPEL which consisted of dropping a prototype ball from the top of the tower onto the concrete floor. The ball survived unscathed!

A third "interesting" problem was the determination of the optimum array and sizing of the nozzle holes in the injection tubes in order to maximize achievable negative reactivity rate. This problem was solved experimentally by a calandria mockup in SPEL in which colored water was injected into pure water. High-speed photography showed the pattern and rate of insertion of these colored jets as they emerged into the "moderator" water. These patterns then were input directly to physics codes to determine the effectiveness of the injection.

Conclusion

It was found that very fast and effective reactor shutdown could be achieved by this design, even with relatively few injection nozzles. Operating experience at Bruce A and elsewhere quickly eliminated residual problems. This design of shutdown system 2 then was incorporated into all designs following Bruce A.