DESIGN OF A GUARANTEED SHUTDOWN STATE USING SOLID RODS FOR THE ACR-1000 REACTOR

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Abstract

This paper presents the design of a rod-based system for long-term shutdown, known as the guaranteed shutdown state (GSS), of the ACR-1000**™ reactor. Previous CANDU®* designs rely on soluble neutron poisons to achieve long-term shutdown. However, due to the operational complexity of using soluble neutron poisons, an alternative shutdown method was desired. The GSS design presented here uses solid boron-carbide rods with a simplified drive system, to provide long-term shutdown. A design-target for subcriticality of -50 mk was chosen in accordance with the IAEA guidelines for long-term fuel storage. An additional –5 mk was added to the criteria to account for calculational uncertainties. To address the possibility of unavailable reactivity devices, the most valuable device was eliminated from the analysis. Also, the sub-criticality requirements assume that the core is cold and that the short-lived fission products have decayed, each of which contributes positive reactivity in the core. WIMS/RFSP/DRAGON [1,2,3] was used as a preliminary tool to determine the most valuable reactivity devices, and the limiting cases were subsequently simulated with the code MCNP5 [4], to determine if the design complied with the sub-critical criteria.

1. Introduction

The ACR-1000 is an evolutionary reactor that has been designed to meet both the needs of the customer and the requirements of the regulator. One common requirement for nuclear power reactors is that the reactor can transition from full power to a state of long-term shutdown. CANDU reactors currently invoke GSS conditions by injecting a soluble neutron poison such as Gadolinium, however issues such as removal time and pH control make liquid poison injection a less than optimal solution.

In order to establish a basis to design a solid GSS system, the current Canadian regulatory documents were examined. No specific acceptance criteria for GSS design was found, however, there are related documents pertaining to the shutdown system. CNSC regulatory document R-8, "Requirements for Shutdown Systems for CANDU nuclear power plants, Feb 21,1991 [5], states the following operating requirements for a shutdown state:

1. "Procedures for putting the reactor in a guaranteed shutdown state shall be prepared and shall require approval by the AECB prior to the issuance of an operating licence. Such procedures

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shall specify at least two independent means of ensuring that the reactor remains sub-critical" (Section 4.1.1).

2. "When the reactor is in an approved guarantied shutdown state, not less than one shutdown system shall be available when this is practicable" (Section 4.1.3). Therefore, SDS2 should be poised and available.

Another requirement relevant to the GSS is to ensure that the reactor is under the control of the reactor regulating system (RRS), in a GSS, or in an active transition between these two states. There is a period of risk during the transition state and this duration should be minimized. A few excerpts from "Operating Policies and Principles", RD-01364-L3, Rev. 12, Point Lepreau Generating Station, May 2006 [6] are listed below :

1. "The reactor shall be operated such that the Reactor Regulating System, acting alone, is capable of introducing sufficient negative reactivity to shut it down (Section 3.05 Reactivity Control)
2. "The reactor shall be either

a) under the active control of the Regulating System or
b) in a clearly poisoned out or Guaranteed Shutdown State or
c) it must be proceeding expeditiously between these two states."

As there are no formally identified GSS-specific regulatory requirements or acceptance criteria, the related requirements were considered in the development of what is considered to be appropriate and consistent with other requirements. The results of this assessment were:

1. As SDS1 will be positioned in-core as part of maintaining GSS, it cannot be credited as an available shutdown system during GSS.
2. As SDS2 will be required to be out of service for at least a significant portion of normal maintenance outages, it cannot be credited as an available shutdown system throughout GSS.

The possibility of maintaining partial availability of SDS2 during a maintenance outage was assessed and judged to be impractical. Also adding a third shutdown system to be made available during outages while SDS2 is not available was judged to be an unacceptable design change.

International requirements for the long-term storage of fuel require a sub-criticality of -50 mk. This requirement may be an overly stringent target, as GSS sub-criticality of international reactors indicates that the sub-criticality during long-term shutdown is generally between -10 mk and -30 mk. With this in mind, the ACR-1000 has been designed with the ability to achieve long-term shutdown using only solid rods, with the conservative -50 mk as the target. In addition to the 37 shut-off rods (SOR) present in an ACR there are 28 additional rods dedicated to the guaranteed shutdown state (GSS).

2. Reactivity devices and layout of the ACR-1000 core

For rapid shutdown of the core, the ACR-1000 possesses 37 fast-acting shutdown rods. A shutoff unit (or control-absorber unit) is comprised of a shutoff rod, a vertical guide assembly, and a drive mechanism. The shutoff-rod design, shown in Figure 1, consists of a series of four rectangular stainless steel (304) tubes in commercially available sizes of 50 mm x 10 mm, welded at their narrow faces to form a four-compartment box structure 200 mm wide, 10 mm thick and 5.7 to 6.8 m long, depending on the location of the rod in the core. Each rectangular tube will contain a column of pressed and sintered boron carbide blocks 47.75 mm wide x 7.75 mm thick. The boron carbide in the 200 mm wide absorbers will have a linear density 1.473×10^{-3} m^3/m or 3.451 kg/m assuming 93 percent packing efficiency. The Zirconium guide (assumes Zircaloy-4) for the wider SOR absorber would have a linear volume of about 444.9×10^{-6} m^3/m and linear weight of ~2.92 kg/m.

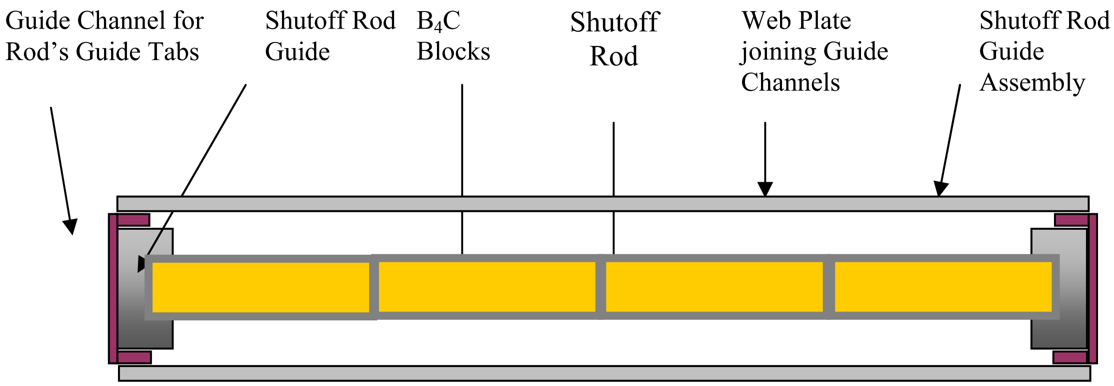

Figure 1: ACR-1000 Shutoff Rod (Drawing Not to Scale).

A guaranteed shutoff rod shown in Figure 2 is similar in design to a shutoff rod; with the in core difference being that the device contains two boron slabs instead of four. The guaranteed shutoff devices are significantly simplified outside of the core, relative to a SOR, as the GSR do not possess fast acting drive mechanisms which are cumbersome on the reactivity mechanism deck.

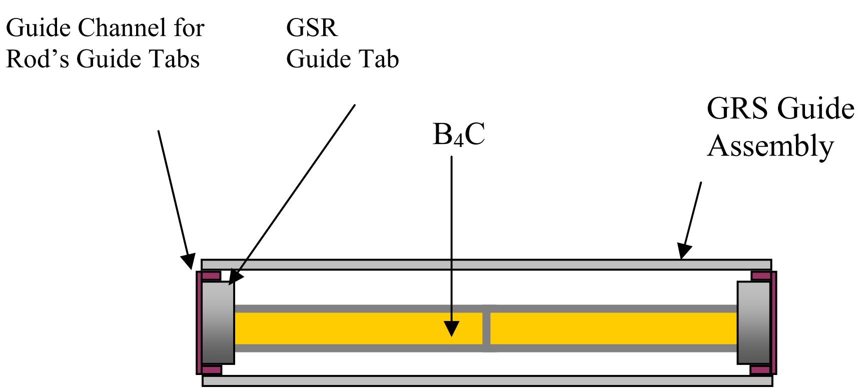

Figure 2: ACR-1000 Guaranteed Shutdown Rod (Drawing Not to Scale).

Additional reactivity devices in the core are the 24 Zone Controller Units (ZCU). A ZCU comprises two absorber elements, a vertical guide tube assembly and a drive mechanism. The absorber element of a ZCU is made up of a 304L stainless steel plate (18 Cr, 8 Ni or 18/8) 200 mm wide and 4.5 mm thick. The in-core portion of the zone control unit absorber guide assembly is fabricated from zirconium alloy to form a box-like section. The effective linear Zr density of the in-core portion of the guide is estimated to be 2.75 kg/m. There are three types of zone controllers, “white” controllers, which are designed to be nominally out of core, “grey” ZCU which are used to shape the power distribution, and “black” ZCUs that are nominally fully inserted in the core.

Eight Control Absorber Units (CAU) are also present. The in core configuration of these devices is identical to SORs.

3. **Analysis Codes**

Based on the functional and regulatory requirements for GSS in ACR-1000, the static reactivity of the core with GSS rods inserted will have to be at least -50 mk plus uncertainties below the normal operating pre-shutdown configuration. Based on previous assessment of ACR-1000 shutdown system performance, an uncertainty of 5 mk based on engineering judgment has been selected as an appropriate value to apply. ACR-specific validation of the calculation of the physical effects affecting the shutdown reactivity calculation is not yet available, and so this must be considered as a preliminary estimate.

Two independent analysis methods are used in these calculations:

1. WIMS/DRAGON/RFSP[1,2,3]: this suite of codes is the reference design toolset generally applied for most ACR-1000 design analyses. As these calculations are relatively quick, they have been applied for all of the survey calculations in this work, such as finding the most limiting rod.
2. MCNP.Full-core MCNP [4] models were applied for all of the final reactivity calculations in this work. The rigor of the theory and detailed ACR-1000 core representation in these analyses provides a great degree of confidence, in the calculation of the large perturbations involved in GSS.

For each candidate configuration, the shutdown capability was assessed. In this assessment, the calculations performed were:

1. Calculation of the reference hot normal operating eigenvalue for the nominal ACR-1000 core configuration (MCNP).
2. Calculation of the eigenvalue with the core cooled down to a uniform 27 °C (MCNP).
3. Calculation of the eigenvalue with the cold core with fuel decayed for about 100 days (MCNP).
4. Calculation of the maximum eigenvalue of the cold decayed core with a single shutoff rod or control absorber withdrawn and all of the other reactivity devices inserted fully into the core.
5. The missing rod search was carried out using RFSP, and the most limiting case was analyzed with MCNP.

4. Reactivity effects

The first unit of ACR-1000 includes an intermediate core in addition to the standard reference core.

Table 1 shows the nominal operating parameters of the reactor and the parameters during a guaranteed shutdown state. In terms of reactivity, the contributing factors are changes in temperature and density, which occur during shutdown.

Table 1:Approximate nominal and cold reactor conditions

State Parameter	**Nominal Conditions**	**Cold Conditions**
Thermal Power (MW)	3200	0
Coolant Density (g/cc)	0.71	1.0
Coolant Temperature (K)	573	300
Fuel Temperature (K)	960	300
Moderator Temperature (K)	346	300
Moderator Density (g/cc)	1.08	1.10
Purity (at.%)	99.76	99.76

In addition to the negative reactivity provided by the reactivity devices, there are two sources of primarily positive reactivity:

1. Positive reactivity induced by the cooling in the reactor core.
2. The decay of the short-lived fission products. Most notably the decay of ^{135}Xe to ^{135}I contributes a reactivity effect of the order of +25 mk.

There is some coupling between the two effects, as the decay products have a higher worth at lower temperatures. The isotope transformations that are taken into account, in the MCNP model during a long shutdown, are shown in Appendix A.

Table 2 shows the WIMS estimates of the reactivity changes due to temperature and isotope decay effects. The hot to cold reactivity is calculated by changing the parameters in table 1 from nominal conditions to cold conditions and the decay reactivity is calculated by running WIMS at zero power for ten days.

Table 2:WIMS estimates of the reactivity changes from long-term shutdown

	WIMS	
Reactor Condition	**K-INF**	**Net Reactivity (mk)**
Hot	1.02795	
Hot →Decay	1.05444	**24.4**
Hot→Cold	1.05151	**21.7**
Cold→Decay	1.08114	**26.1**
Cold+Decay		**47.8**

Table 3 indicates that for a mid-burnup fuel bundle when the reactor transitions from a hot to cold state the reactivity induced is +21.7 mk. Subsequently when the fission products decay a 26.1 mk increase is seen in reactivity. If, however, the fission products decay under hot conditions the reactivity worth is less as the neutron distribution is centred about a higher energy, and will thus have a lower reaction rate when integrated over the primarily 1/v cross section.

Table 3: Parametric analysis of the thermal temperature feedback.

Condition	Reactivity change from hot to cold WIMS	Decay Reactivity after temperature perturbation WIMS
Cold Moderator	-0.1	24.6
Cold Fuel	10.5	24.4
Cold Coolant Temperature	12.8	25.9
Cold Coolant Density	-1.9	24.5
Sum Partial Effects	21.3	
Total Effect (Table 2)	21.7	

Employing a parametric test, it is seen that the fuel temperature and the coolant temperature are the largest contributors to the positive temperature feedback when transitioning from hot to cold conditions.

4.1 Accident Identification

To assess the licensability of the GSS design the reactor will be required to remain sub-critical under postulated accidents. A cursory discussion is presented below.

In current CANDUs, the limiting acceptance criteria for GSS design are to maintain the sub-criticality margin following an in-core break, as this is the accident with the greatest potential to reduce the effectiveness of the moderator poison used to maintain GSS. If the GSS was implemented in a CANDU similar to current designs, but with mechanical devices instead of moderator poisons, the acceptance criteria would have to be reassessed. In ACR, however, if light water coolant is added to poisoned heavy-water moderator, the reactivity effect is uniformly negative, and so would only result in improvement in the depth of GSS reactivity.

If the reactor is in GSS, it is shut down and depressurised, and, therefore, a loss of HTS flow is irrelevant. A large LOCA is not an issue and a single channel event is only an issue if it can damage any neighbouring rods, which is less likely if the system is depressurised, as the devices maintaining GSS will already be in their deployed positions in core and consequences of channel events will be minimized. And, if an in-core rupture were to occur, the light water injection into the moderator would only provide negative reactivity.

A loss of reactivity control is possible, but only by means other than rod movement if all rods are locked in. This would include moderator poison effects, but moderator poison is not being credited in rod-based GSS. Therefore, a LOR of any significance is unlikely.

Moderator failures, including loss of moderator cooling would not result in any reactivity increase, and are therefore non-issues.

If cooling is being provided by LTC, then LTC failures would necessitate heat removal by another means. However, such failures would not result in reductions in GSS effectiveness, as fuel plus coolant coefficients are negative.

Loss of heat sink (i.e. secondary side failures) will not result in a significant reactivity increase, so is not an issue for ACR.

Thus, there are no significant events that are likely to occur during GSS that would compromise static shutdown in ACR.

4. Results

The reactivity was calculated using two independent methodologies. The first was to simulate a long shutdown using RFSP the second was to simulate the shutdown with MCNP. The RFSP calculations were mainly used to select the locations of the rods, the reactivity insertion was calculated with MCNP.

The MCNP results for the sub-criticality of the guaranteed shutdown state at cold conditions are shown in Table 4.

Table 4: GSS Reactivity with RFSP and MCNP

Case	**MCNP (mk)**
Intermediate Core	-73
Reference Core	-77
Intermediate Core Without most effective SOR	-60
Reference Core Without most effective SOR	-62

To account for uncertainties in the parameters input to the code and the statistical uncertainty of the results, an additional –5 mk was added to the –50 mk design target, based on engineering judgment of the code uncertainty. Thus values lower than –55 mk are considered to meet design targets, while larger values do not. Both the intermediate and reference core meet the design criteria when all of the reactivity devices are inserted into the core.

Additionally, to account for mechanical failure of a device during GSS, the GSS sub-criticality was analyzed when the rod of highest worth is unavailable. In the intermediate core the most valuable rod, as found by RFSP was SOR 16. When SOR 16 is unavailable the GSS –55 mk criteria is met with a 5 mk margin. In the reference core without the most valuable rod, SOR 2, the criteria is met with a 7 mk margin.

7. Conclusion

A solid rod guaranteed shutdown state is part of the ACR-1000 design. Full core MCNP analysis has shown that the design meets the –50 mk target.

8. References

[1] G. Jonkmans, “WIMS-AECL Version 3.1 User’s Manual”, ISTP-05-5115, Aug 01,2006.

[2] P. Schwanke, “RFSP-IST Version REL_3-04: Users’ Manual”, SQAD-06-5054, Dec 01, 2006.

[3] G.Marleau, “A User Guide for DRAGON: Version DRAGON_000331, Release 3.04”, IGE-174 Rev 5.

[4] “MCNP – A General Monte Carlo N-Particle Transport Code, Version 5”, X-5 Monte Carlo Team, 2003 April 24, Los Alamos National Laboratory

[5] R-8, “Requirements for Shutdown Systems for CANDU nuclear power plants, Feb 21,1991

[6] "Operating Policies and Principles", RD-01364-L3, Rev. 12, Point Lepreau Generating Station, May 2006

Appendix A: Table of decay reactions taken into account in MCNP that contribute to the decay reactivity in long-term shutdown.

ZAID	Isotope	Half-Life	Decay Reaction
Decay Chain #1			
53135	**^{135}I**	**6.57 h**	**β^- to ^{135}Xe**
54135	**^{135}Xe**	**9.10 h**	**β^- to ^{135}Cs**
55135	^{135}Cs	2.3 x 10^6 y	β^- to ^{135}Ba
Decay Chain #2			
93239	**^{239}Np**	**2.355 d**	**β^- to ^{239}Pu**
94239	^{239}Pu	24110 y	α to ^{235}U
Decay Chain #3			
93238	**^{238}Np**	**2.117 d**	**β^- to ^{238}Pu**
94238	**^{238}Pu**	**87.74 y**	**α to ^{234}U;**
Decay Chain #4			
63156	**^{156}Eu**	**15.2 d**	**β^- to ^{156}Gd**
64156	^{156}Gd		
Decay Chain #5			
61149	**^{149}Pm**	**2.212 d**	**β^- to ^{149}Sm**
62149	^{149}Sm		
Decay Chain #6			
61151	**^{151}Pm**	**1.183 d**	**β^- to ^{151}Sm**
62151	^{151}Sm	90 y	β^- to ^{151}Eu
Decay Chain #7			
61148	**^{148}Pm, ^{148m}Pm**	**5.37 d**	**β^- to ^{148}Sm**
62148	^{148}Sm		
Decay Chain #8			
60147	**^{147}Nd**	**10.98 d**	**β^- to ^{147}Pm**
61147	**^{147}Pm**	**2.6234 y**	**β^- to ^{147}Sm**
Decay Chain #9			
59143	**^{143}Pr**	**13.57 d**	**β^- to ^{143}Nd**
60143	^{143}Nd		
Decay Chain #10			
54143	**^{133}Xe**	**5.243 d**	**β^- to ^{133}Cs**
55133	^{133}Cs		
Decay Chain #11			
45105	**^{105}Rh**	**35.4 h**	**β^- to ^{105}Pd**
46105	^{105}Pd		

Where a bold **isotope** indicates that the isotope has decayed to a negligible concentration.

Assumptions:

$^{135}Cs = {}^{135}Cs + {}^{135}Xe + {}^{135}I$

$^{239}Pu = {}^{239}Pu + {}^{239}Np$

$^{238}Pu = {}^{238}Pu + {}^{238}Np$

$^{149}Sm = {}^{149}Sm + {}^{149}Pm$

$^{151}Sm = {}^{151}Sm + {}^{151}Pm$

$^{147}Pm = {}^{147}Pm + {}^{147}Nd$

$^{143}Nd = {}^{143}Nd + {}^{143}Pr$

$^{133}Cs = {}^{133}Cs + {}^{133}Xe$

$^{105}Pd = {}^{105}Pd + {}^{105}Rh$