THE 25 MW SUPER NEAR BOILING NUCLEAR REACTOR (SNB25) FOR SUPPLYING CO-GENERATION ENERGY TO AN ARCTIC CANADIAN FORCES BASE

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ABSTRACT

Nuclear energy represents a better alternative for the supply of heat and electricity to the Canadian Forces bases in the Arctic (CFS Alert and CFB Nanisivik). In this context, the Super Near-Boiling 25-MW_{th} reactor (SNB25) has been designed as a small unpressurized LWR that displays inherent safety and is intended to run in automatic mode.

The reactor employs TRISO fuel particles (20% enrichment) in zirconium-sheathed fuel rods, and is light water cooled and moderated with a normal output temperature is 95^{o}C at atmospheric pressure. Control is via 133 control rods and six adjustable radial reflector plates. The design work used the probabilistic simulation code MCNP 5 and the deterministic code WIMS-AECL Version 3.1, permitting a code-to-code comparison of the results. Inherent safety was confirmed and is mostly due to the large negative void reactivity coefficient of -5.17 mk per % void. A kinetic model that includes thermal-hydraulics calculations was developed to determine the reactor's behaviour in transient states, and the results further confirm the inherent safety. Large power excursions temperatures that could compromise structural integrity cannot be produced. If the coolant/moderator temperature exceeds the saturation temperature of 100^{o}C, the coolant begins to boil and the large negative void coefficient causes the reactor to become subcritical in 0.84 seconds.

The SNB25 reactor's core life exceeds 12 years between refuellings. A group of 4 SNB25 reactors meets both the heating and electricity requirements of a base like CFB Nanisivik via a hot water network and through an organic Rankine cycle conversion plant.

1. Introduction

The Canadian Forces are in the process of refurbishing the energy systems for their bases and stations. In addition, special attention is given to existing and projected bases in the Arctic (Alert and Nanisivik) in order to increase the Canadian presence in this remote part of this country and affirm the Canadian sovereignty in this rugged region. Because these military establishments are located too far from existing energy networks (electricity and natural gas), reliance on fossil fuels such as heating oil and diesel fuel for electricity generators must be minimized for costs and logistic reasons. In this context, nuclear energy provides an option that deserve consideration for the supply of reliable heating and electrical energy.

The objective of the present research is to design a small nuclear reactor able to provide 25 MW_{th} safely and reliably. The design is initiated on that of the NB (Near Boiling) 1 MWth nuclear reactor designed to provide “hotel power” on-board of Victoria-class submarines of the Canadian Navy [1]. The design of the SNB25 reactor is wanted such as to maintain inherent safety. The reactor is based on well known TRISO fuel particles [2] with a maximum 20% enrichment to respect the Non-Proliferation Treaty. The TRISO particle was developed in the early 1970s for High Temperature Cooled Reactors and Pebble-Bed reactors, and consists in a few mm diameter fuel kernel made of UO_2 or UCO surrounded by four layers: porous carbon buffer, inner Pyrolytic carbon, Silicon Carbide and outer Pyrolytic Carbon. In the SNB25 reactor, the TRISO particles are contained inside leak-tight Zircaloy sheathing with helium used as a filling gas.

2. Reactor Design and Simulation

The design of the SNB25 reactor was carried out using two well-proven computer codes: the probabilistic MCNP 5 simulation code and the deterministic WIMS-AECL Version 3.1 code. MCNP5 (Oak Ridge National Laboratory) [3] is a general-purpose 3-D coupled neutron/photon/electron transport code based on the Monte Carlo probabilistic method. WIMS-AECL 3.1 (Atomic Energy of Canada Ltd) [4] is a deterministic 2-D multi-group neutron transport code for multi-cell lattices with the possibility of performing fuel burnup calculations and neutron leakage corrections. Since there are no actual SBN25 reactors already built, validation of the results of either codes with experimental measurement is not presently possible, but verification of the results of one code against the other permits confidence in the accuracy of the simulations. Figures 1 and 2 and Tables 1 and 2 below present the main features of the SNB25 reactor with a comparison with the NB reactor.

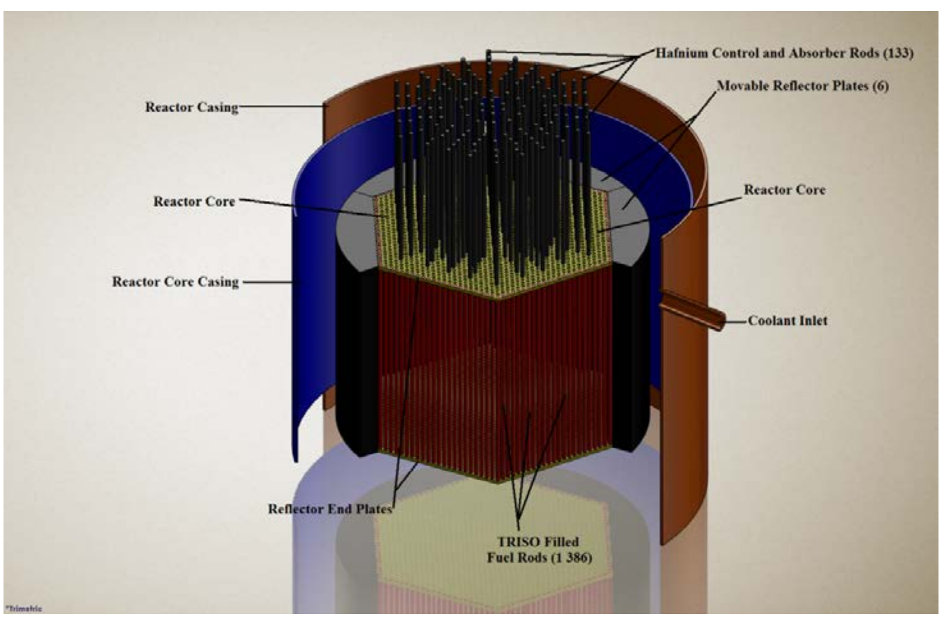

Figure 1: Configuration of the SNB25 nuclear reactor

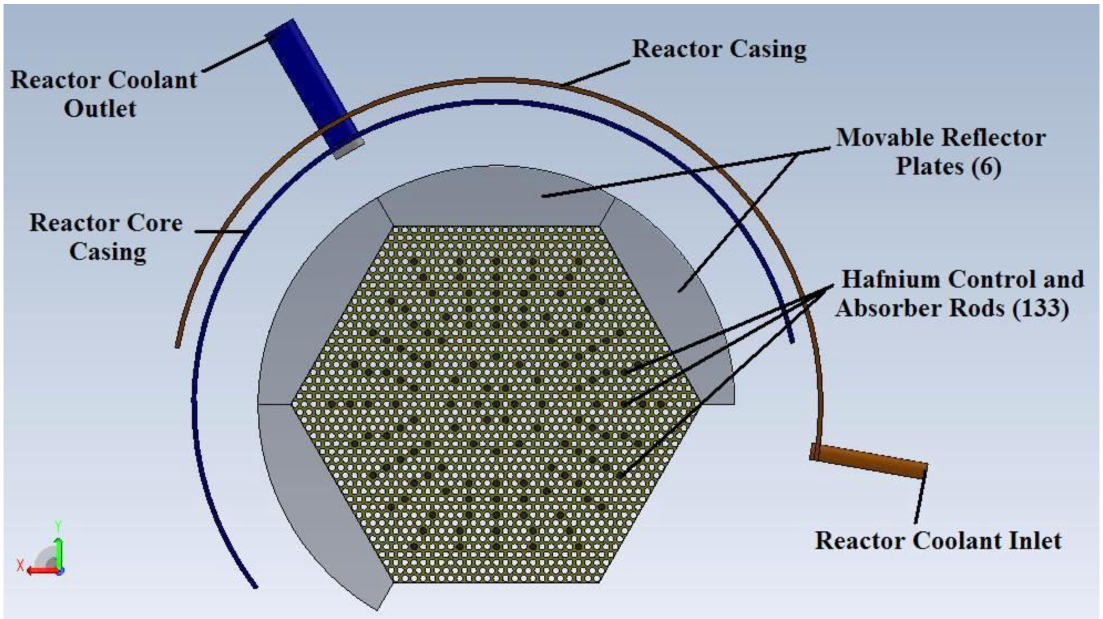

Figure 2: SNB25 Nuclear Reactor Top View

Table 1: SNB25 and NB Reactor Specifications

Physical Characteristics		
Description	**SNB25 Nuclear Reactor**	**NB Nuclear Reactor**
Core Arrangement	**Hexagonal**	
Core Outer Radius	**93.9 cm**	**39 cm**
Core (Fuel Rods) Height	**150 cm**	**80 cm**
Number of Fuel / Control Rods	**1,386 / 133**	**318 / 13**
Core Casing Material (Thickness)	**AISI Plain Carbon Steel (2 cm)**	
Coolant/Moderator	**Light Water**	
Fuel (Enrichment)	**Uranium Oxide TRISO Fuel Particles (20 weight%)**	
Fuel Mass ^{235}U	**300 kg**	**16.43 kg**
Fuel Rod Diameter (Pitch)	**3 cm (4.2 cm)**	**2.5 cm (4 cm)**
Control Rod Material	**Hafnium**	
Reflector (Thickness)	**Beryllium (15 cm)**	**Beryllium (20 cm)**

Table 2: SNB25 and NB Reactor Full Power Parameters

Operating Parameters		
Description	**SNB25 Nuclear Reactor**	**NB Nuclear Reactor**
Maximum Fuel Temperature	**120°C**	**102°C**
Reactor Inlet Coolant Temperature	**30°C**	**52°C**
Reactor Outlet Coolant Temperature	**95 °C**	
Thermal Power	**25.03 MW**	**1.1 MW**
Average Thermal Flux	**3.75×10^{12} n cm^{-2} s^{-1}**	**2×10^{12} n cm^{-2} s^{-1}**
Core Life	**4,270 Full Power Days**	**750 Full Power Days**
Moderator Temperature Coefficient	**-0.11 mk °C^{-1}**	**-0.19 mk °C^{-1}**
Void Fraction Coefficient	**-5.17 mk per % of void**	**-3.9 mk per % of void**
Fuel Temperature Coefficient	**-9×10^{-4} mk °C^{-1}**	**-7×10^{-3} mk °C^{-1}**
Regulatory and Shut Down Control	**Hafnium Control Rods**	
Burn-up Control	**Movable Reflector Plates**	

Absorber and regulatory control rods provide long term burn-up and reactivity control respectively. A total of 133 hafnium control rods provide enough negative reactivity to maintain the reactor subcritical in a "clean cold start scenario" with the reflector plates against the core. The control rods are divided into 5 distinctive banks, namely Control Rod A, B, C, D and E. A bank consists of a specific number of control rods connected to a common spider. As far as the operator and control system computer are concerned, the SNB25 reactor is fitted with only 5 control rods. The 1,386 fuel rods are cooled by light water entering the space between the reactor casing and the reactor core casing and flowing down to reach the bottom of the reactor core. The water would then flow upward and be heated by the fuel rods to exit the core at its top and flow out via the reactor coolant outlet.

3. Burnup Control

An overall control strategy, projected over the expected life of the SNB25 reactor core, is based on the six adjustable beryllium plates that serve as the radial reactor reflector. At first reactor start-up, the core is freshly fuelled and the reactor operates under full power conditions, and the reflector plates are 5 cm away from the core; control rods B, C, D and E are fully inserted and act as absorber rods. The reactor's available excess reactivity is then 6.25 mk (below prompt critical). A reactivity of 1 mk is equal to 0.001 dk/k = 100 pcm = 15.4 ¢ for a U-fueled reactor. Control rod A provides regulatory control and is inserted 22 % of its full length. The on-line reactivity is nil (k_{eff} is 1) and the SNB25 reactor outputs 25 MW_{th}. The gap between the reflector plate and the core, as well as the void created by the removal of control rod A, is filled with coolant (light water). As the fuel burns and fission products accumulate, the control system gradually removes control rod A from the reactor in order to maintain the system critical. Inserting control rod A by more than 22% would shut down the reactor at any time. The saturating fission products reaching steady state (saturation) in the fresh fuel cause a large drop of reactivity in the first few days of the reactor operation. After 18 hrs, the excess of reactivity is near 0. The reflector plates are then shifted inward by 2.25 cm (located at the 2.75 cm position) and the reactivity value increases to 5.85 mk. This excess of reactivity drops near the critical value 10 days later and the reflector plates must be moved to the 1.65 cm position to bring it back to 5.85 mk. After 82 days of operation, the excess reactivity approaches zero and is increased to 5.85 mk by moving the reflector to the 1.1 cm position. It will take another 149 days for the reactor to become near critical and once again, the reflector is moved to the 0.55 cm position. This process continues for the entire life of the reactor core. Prompt critical state will never be reached with this control strategy. Following the saturation of the fission products, the reactor can operate up to 7 months with the reflector plates in a specific position.

After a total of 680 full power days of operation, the reflector plates are against the core, and the excess of reactivity is near 0. At this point, control rod A will be fully withdrawn and will remain in this position for the remaining life of the reactor core. Fine reactivity control will be assumed by control rod B for the next 1,036 days, with control rods C, D and E fully inserted. Fully inserting control rod B can shut down the reactor under any circumstances. Control rod C will assume fine reactivity control from day 1,716 for 820 full power days. During this period, control rods A and B will be fully withdrawn and will remain in this position for the remaining reactor operating years. Control rods D and E are still fully inserted. Like control rods A and B, control rod C is capable to bring the SNB25 reactor to a sub-critical state at any time. This process continues for the entire life of the reactor. Therefore, control rod E will provide reactivity control from day 3,711 to day 4,283. During this operating period, all remaining control rods will be withdrawn and maintained in this position unless their full insertion is needed in an emergency shut-down of the reactor. The flexibility of the control system also allows for positive reactivity to be inputted if required. In the event that the SNB25 reactor needs to be restarted in the hours following a normal shut down, shifting the reflector plates inward and/or removing one or more control rods from the core can provide a “boost of reactivity” in order to overcome the saturating fission product poisoning effects. Figure 3 illustrates the variation of the reactor’s excess reactivity along this operating strategy.

The control rod configuration is safe, simple and provides an important amount of redundancy with little operator intervention required. With the exception of Control Rod A, all control rods first act as absorber rods and then, are used for fine reactivity control. Once a control rod has been used for fine reactivity control, it is completely removed from the reactor core and becomes in a stand-by mode. This control rod is not expected to be used again during normal reactor operation, but remains available as a reserve of negative reactivity. As an example, during the sixth year of operation, Control Rod C will be used for fine reactivity control. Control Rods A

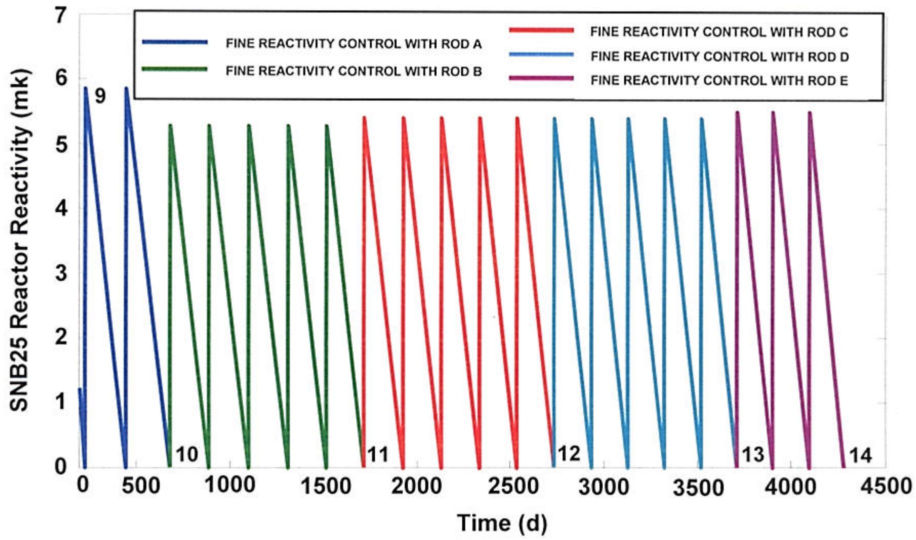

Figure 3: SNB25 Reactor Reactivity (From Day 200 to Day 4,283)

and B will be completely removed from the core, in a stand-by mode. Control Rod C is capable to shut down the reactor by itself, however, inserting Control Rods A and B with C would provide more negative reactivity, resulting in a quicker drop of the neutron flux in the case of an emergency shutdown (SCRAM). According to the Canadian Nuclear Safety Commission (CNSC) requirements for reactors licensing, the SNB25 reactor must be fitted with two independent, fast acting, safety shutdown systems. The SNB25 reactor is currently fitted with 133 hafnium shutdown rods capable of shutting the reactor down under any circumstances. A secondary independent shutdown system, involving the injection of a high pressure poison such as gadolinium nitrate into the low pressure moderator could easily be fitted (CANDU reactors are provided with such an emergency shutdown system that injects rapidly gadolinium nitrate into the D_2O moderator).

4. Toward Inherent Safety

Figure 4 below shows how the effective multiplication factor evolves as the reactor accumulates fluence from initial start-up. The burn-up evaluation at Figure 4 shows that there is ample excess reactivity for the SNB25 reactor system to remain critical for over 4,270 full power days. Calculations for the moderator temperature and void fraction coefficients are based on Figures 5 and 6. These curves are generated from reactivity calculations carried with both WIMS-AECL and MCNP5 codes for several moderator temperature and void fraction values. The reactivity coefficients are determined from the gradients of these curves. The moderator temperature reactivity coefficient is -1.1×10^{-4} K^{-1} (-0.11 mk K^{-1}) over a range of moderator temperature from 20 ^{o}C to 100 ^{o}C. As seen in Figure 5, this coefficient becomes more negative as the moderator temperature increases: a very desirable feature toward inherent safety. The void fraction coefficient (Figure 6), which represents the change in reactivity per increase in void

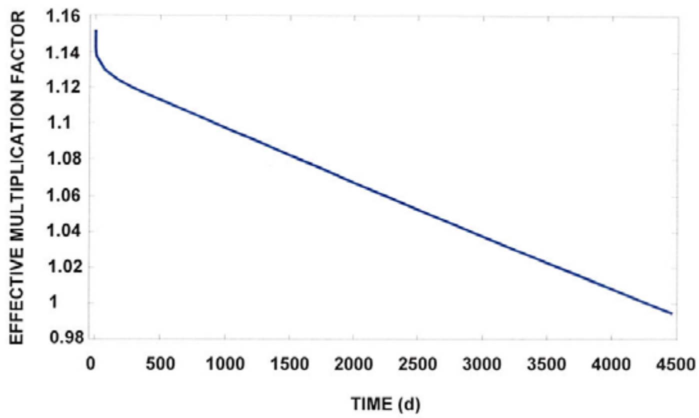

Figure 4: SNB25 Reactor Burn-up

fraction, is -5.17 x 10^{-3} per % of void (-5.17 mk per % of void) over a range of void fractions from 0% to 35%. These strong negative coefficient values are essential, but not sufficient, conditions for inherent safety.

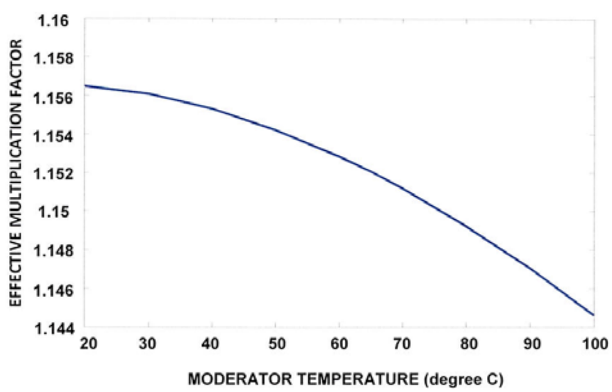

Figure 5: Variation of the Effective Multiplication Factor with Moderator Temperature

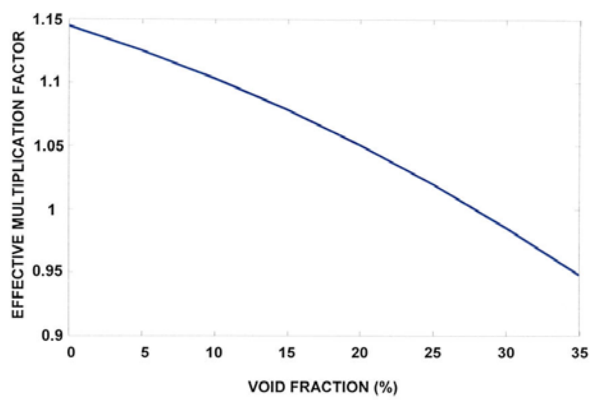

Figure 6: Variation of the Effective Multiplication Factor with Void Fraction

5. SNB25 Simulation in transient states

In order to determine whether the SNB25 is inherently safe, a point kinetic model has been developed to predict the time behavior of the reactor in transient states. A 6-delayed neutron group kinetic model was used, resulting in a set of 7 differential equations solved by MATLAB [5]. Step positive reactivity insertions from +1 mk to +6.25 mk were simulated. Thermalhydraulics equations as described in Glasstone & Sesonske, Chapter 6 [6], were used to determine the temperatures of the reactor components and the reactor power as time progresses following the step reactivity insertion using a quasi-static approach. The full power operating conditions for the SNB25 is a 25 MW_{th} thermal power output with the coolant outlet temperature at 95 ^{o}C (368.15 K), the Zircaloy sheath temperature at 95.5 ^{o}C (368.65 K) and the average fuel temperature at 120 ^{o}C (393.15 K), all these temperatures well below the point where any structural damage can occur. Of course, the k_{eff} is equal to 1. Figures 7 to 10 show how several

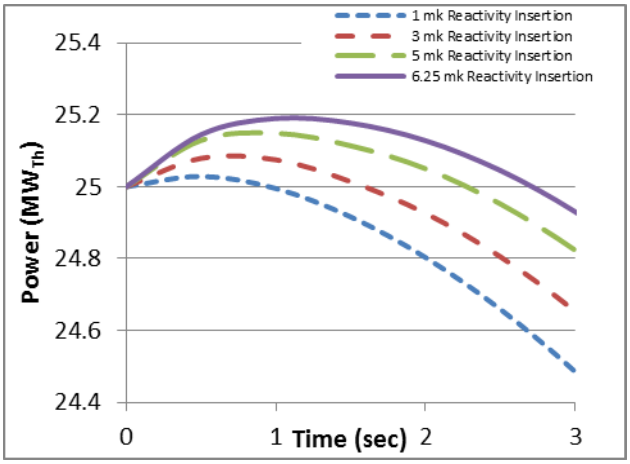

Figure 7: Variation of Reactor Power with Time for Positive Step Reactivity Insertions

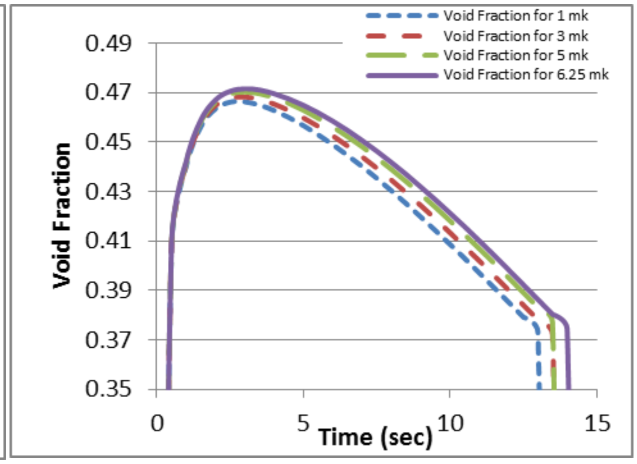

Figure 8: Variation of the Void Fraction with Time for Positive Step Reactivity Insertions

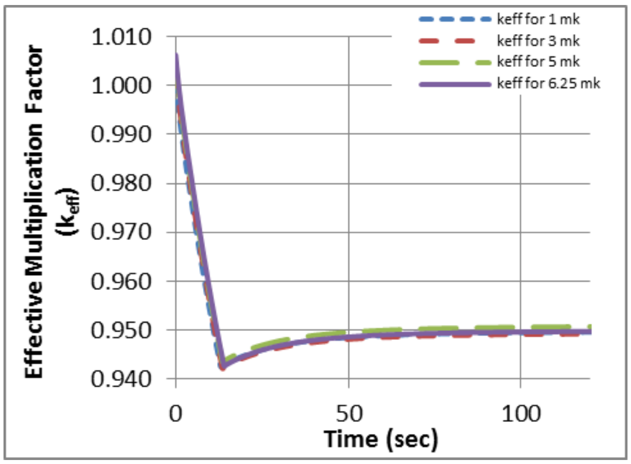

Figure 9: Variation of the Effective Multiplication Factor with Time for Positive Step Reactivity Insertions

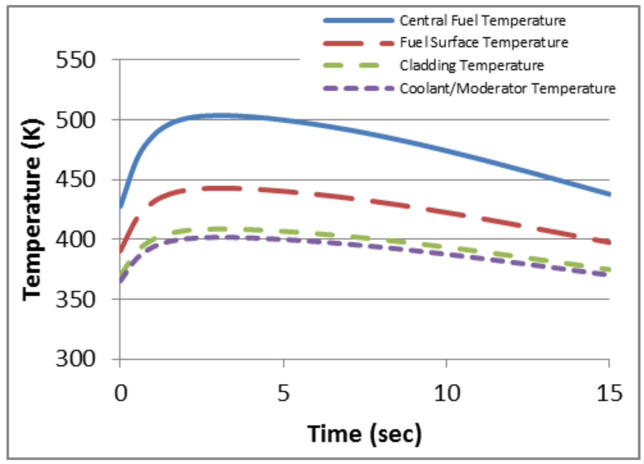

Figure 10: Variation of the Average Reactor Component Temperature with Time for a +6.25mk Step Positive Reactivity Insertions

of the key parameters of the reactor evolve with time following a step insertion of reactivity when the reactor was in operation at full power and steady state before the perturbation. One may see in Figure 7 that the reactor power reaches higher values for larger values of the step reactivity insertion, and also the maximum power is reached later after the insertion. Past the maximum power, there is a steady decrease because of the void that is created when the coolant starts to boil, caused by the large negative reactivity coefficient due to the void fraction. Figure 8 shows how the void fraction evolves during the transients. In the case of the +6.25 mk insertion, the void reaches 47.25%, nearly half the coolant volume. However, this does not last long as the void fraction rapidly drops, permitting liquid water to cool the fuel rods more efficiently. The sudden drop between 13 and 15 s indicates that the temperature of the coolant is back to values below 100 ^{o}C. In Figure 9, the effective multiplication factor decreases rapidly within 14 seconds of the perturbation from values as high as 1.00625 to about 0.943, then increases slightly to 0.950 because the void fraction becomes zero and the reactor temperature decreases slightly. The reactor then remains subcritical. Figure 10 shows the evolution of the average reactor temperature for the maximum step positive reactivity insertion investigated (+6.25 mk). The curves present the values for the central fuel, the fuel surface, the cladding and the coolant/moderator temperatures. At a maximum value of 504 K, the central fuel temperature never reaches the value of 1,600 ^{o}C (1873 K) at which the TRISO fuel particles have been tested and proven to be able to withstand without damage. Similarly, the fuel surface and the sheath maximum temperatures (443 K and 409 K, respectively) are way below the 2,140 K melting point of the Zircaloy 4 sheathing material. As for the moderator/coolant, the maximum temperature reached was 402 K, well below temperatures for which metal-water chemical reactions would produce hydrogen in significant amounts.

More abnormal conditions were investigated and consisted in inserting large positive step reactivity increases at the same time the reactor incurred a loss or coolant (LOCA) event or a loss of coolant flow (LOCF) event. Since the heat produced by the fuel cannot be removed in the case of the LOCA or only partially removed for the LOCF, the potential exists for the temperatures of the fuel and sheath to reach values for which damage may occur. The SNB25 was designed such that in the event of a LOCF, the reactor core would remain flooded since the supply and discharge lines are located above the top of the core. The LOCF is simulated using the kinetic model with the mass flow rate of the coolant reduced from the 63.45 kg s^{-1} to a near-zero value, chosen as 0.05 kg s^{-1}. The simulation included a quick rise of the coolant inlet temperature from 35 ^{o}C to 95 ^{o}C, and also included the +6.25 mk reactivity step increase. To simulate the LOCA, the void fraction was set at 100% and the mass flow rate again reduced to 0.05 kg s^{-1}in the model. The scenario of assigning suddenly a 100% void fraction represents an extreme case far worse than in reality where the only very improbably way the coolant could be rapidly lost is via a large perforation near the bottom of the reactor vessel. Figures 11 to 14 present the results of these abnormal condition transients.

Because of the large negative reactivity coefficient due to the void fraction, both instances of LOCA and LOCF immediately result in a sudden drop of the k_{eff}, effectively shutting down the reactor. This is obvious in Figure 13 and Figure 11 shows that the reactor power drops immediately. The thermal-hydraulics parameters behave differently as a result of their “inertia”. In the case of the LOCA, this situation is represented by a 100% void fraction, hence the horizontal dashed green line in Figure 12. As for the LOCF, the sudden lack of cooling efficiency represented by the red dotted line indicates that the liquid water present soon flashes to steam and remains as such until the temperatures decrease enough to enable condensation and eventual return to liquid form after some 20 seconds. Figure 14 is representative of the temperature variations in the reactor components, and similar graphs are obtained for the sheath and the coolant (in the case of the LOCF). For all these graphs, the maximum occurs at about 3 s after the initiation of the transient. The maximum fuel temperature is 942 K, the sheath temperature reaches a maximum value of 856 K and the steam has a maximum temperature of 849 K in the case of the LOCF. It is also worthy of noticing that the curves overlap for both the LOCA and the LOCF transients, indicating the very poor efficiency of steam as a coolant when compared with liquid water. Again, these maximum temperatures remain well below values for which damages would occur, and it can be concluded that the integrity of the SNB25 is not compromised.

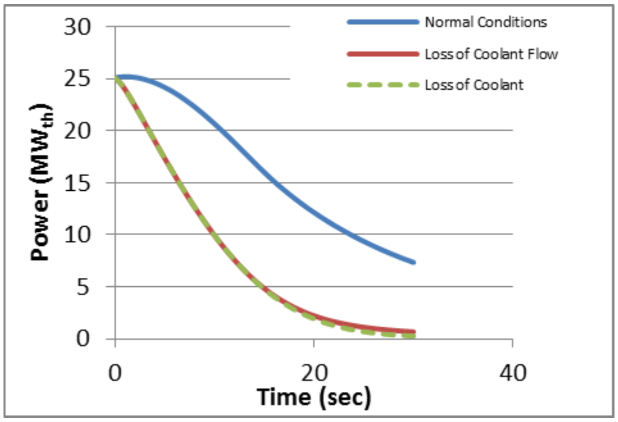

Figure 11: Variation of Power with Time during Abnormal Conditions

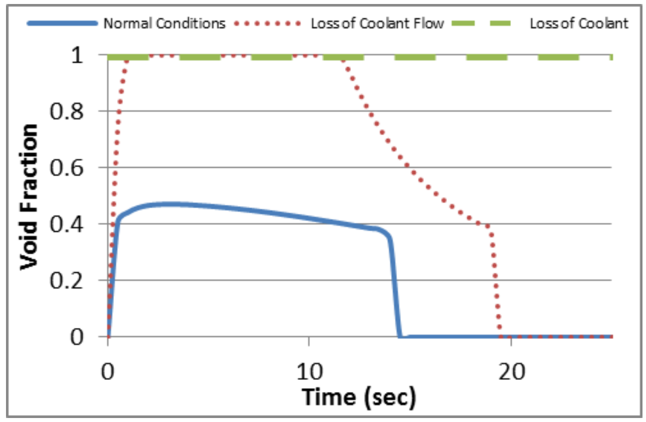

Figure 12: Variation of Void Fraction with Time during Abnormal Conditions

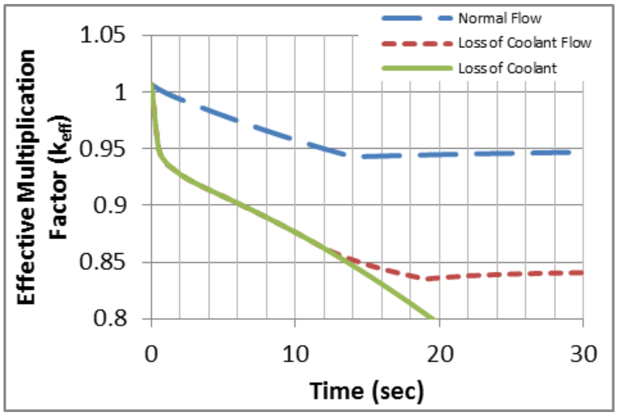

Figure 13: Variation of the Effective Multiplication Factor with Time during Abnormal Conditions

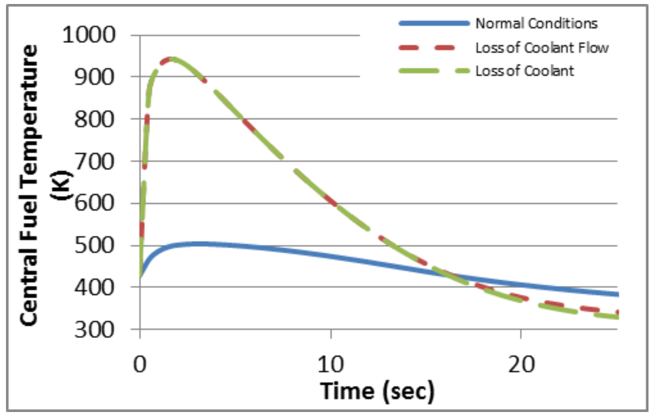

Figure 14: Variation of the Central Fuel Temperature with Time during Abnormal Conditions

6. Reactor Shut-down

The kinetic model can also simulate the reactor shut-down. It is a requirement of inherent safety that the reactor be provided with a reliable shut-down system that not only can bring the reactor to a shut-down status, but also maintain this status. In the case of the SNB25, the control rods system has been designed such that any one of the five banks can bring the reactor to a shut-down condition. In addition, chemical shims or poison may be injected in the moderator at all times. Except for the early part of the life of the reactor, the beryllium reflector plates can be moved away from the reactor core, thus providing yet additional negative reactivity. This part of the present study focusses on using the control rods to insert negative reactivity. Using the kinetic model, the scenario chosen here is with the reactor operating at steady state and critical at the time of the negative step reactivity insertion, when all the beryllium radial reflector are against the core (close to end-of-core life). The central control rod is then able to provide a -5.25 mk reactivity insertion, and the simulations covered other values of reactivity up to -5.25 mk.

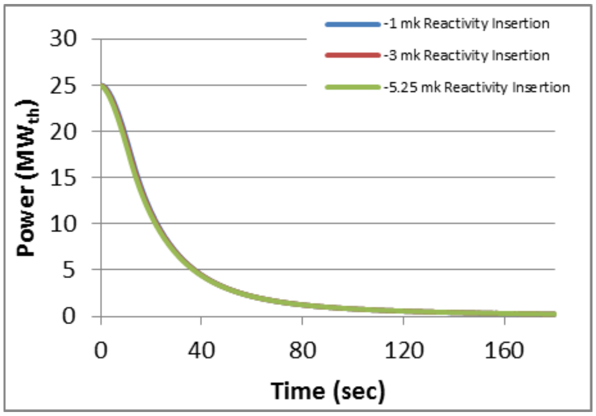

Figure 15: Variation of Reactor Power with Time during Shutdown

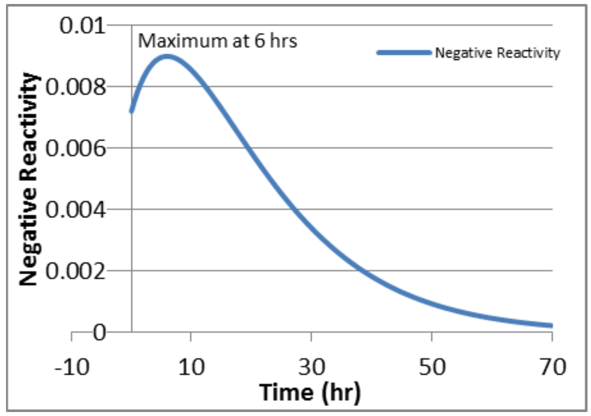

Figure 16: Variation of Negative Reactivity with Time due to Xenon Buildup

Figure 15 is representative of the results obtained with the reactor power from 25 MW to a few MW within a minute. When the reactor is shut down, the accumulated ^{135}I at the time of the reactor shut-down decays into ^{135}Xe and the total cumulative ^{135}Xe concentration in the reactor then increases to a maximum some 6 hours following the shut-down. The ^{135}Xe concentration then decreases as this radioisotope undergoes radioactive decay. With a thermal neutron absorption cross section of 2.6 million barns [7], ^{135}Xe has a large negative reactivity associated with its concentration as shown in Figure 16 above. Due to the relatively small thermal neutron flux in the SNB25 reactor, the -9 mk reactivity at the xenon peak can be overcome by the +153 mk excess reactivity of the reactor, with concern about re-starting the reactor occurring only close to the very end of the core life.

7. Discussion and conclusions

The many simulations carried out in this work indicate that the SNB25 reactor has the characteristics of inherent safety. Inherent safety of a reactor is defined by the International Atomic Energy Agency (IAEA) as: *"Inherent Safety refers to the achievement of safety through the elimination or exclusion of inherent hazards through the fundamental conceptual design choices made for the nuclear plant. Potential inherent hazards in a nuclear power plant include radioactive fission products and their associated decay heat, excess reactivity and its associated potential for power excursions, and energy releases due to high temperatures, high pressures and energetic chemical reactions. Elimination of all these hazards is required to make a nuclear power plant inherently safe. For practical power reactor sizes this appears to be impossible. Therefore the unqualified use of "inherently safe" should be avoided for an entire nuclear power plant or its reactor"* [8]. The transient simulations have shown that temperatures for which the reactor integrity would be compromised are never approached. Both MCNP 5 and WIMS-AECL are widely used for the design of several types of nuclear reactors and about 6% uncertainty is given to both codes by the authors in a conservative fashion. As for the point kinetics and the thermalhydraulics models, well proven equations have been used here and a 15% uncertainty is given conservatively for this part of the work. Comparisons of the results produced by MCNP 5 and WIMS-AECL yielded very good agreement resulting in high confidence in the validity of the results of this work. Of course, it is only when a prototype SNB25 reactor is actually built and operated that experimental data will be available for a thorough validation of these simulations. Work on the design of the reactor is continuing and focusing on the energy delivery systems to an Arctic base of the Canadian Forces. The district heating component is designed with a 4% loss target for the heat exchangers and warm water conduit system, and the electricity generating system is based on a Rankine cycle with a turbine and generator propelled by n-pentane fluid with an expected 16.5% efficiency. Details of this research are presented at this conference in a companion paper [9].

8. References

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