SEALER: A very small lead cooled fast reactor for commercial energy production in off-grid communities.

J. Wallenius
LeadCold Reactors, Dalgatan 3C, Märsta, Sweden
janne@leadcold.com,

S. Bortot
Paul Scherrer Institut, Villigen, Switzerland
sara.bortot@psi.ch

Abstract

SEALER (Swedish Advanced Lead Reactor) is a small lead cooled fast reactor operating on 20% enriched UO_2 fuel. It is designed for commercial production of electricity and heat in the Canadian arctic. In this paper, we present an updated set of reactivity coefficients for the SEALER core, used in simulations of un-protected transients such as control-rod withdrawal, and loss of flow. The analysis is carried out using the SAS4A/SASSYS-1 (SAS) system code developed by ANL [1] and the BELLA multi-point dynamics code developed by KTH and PSI [2].

1. Introduction

SEALER is a very small lead cooled fast reactor, designed to produce commercial power for off-grid applications, such as arctic communities, mining industry and shipping industry [3]. It's design power is 3 MWe (8 MWth), and it is intended to function as a nuclear battery, meaning that no fuel reload will take place during the life of the reactor. Corrosion protection of structural materials is achieved by formation of thin (100 nm) alumina scales, using surface alloyed austenitic steels for fuel cladding tubes, and bulk FeCrAl-RE steels for heat exchanger tubes [4]. The reactor is designed to retain large margins to failure of fuel and cladding during design basis and design extension accidents. Should a fuel cladding failure occur, volatile fission products form compounds with the lead coolant having very low vapour pressure. The resulting source term and radiological dose is very low. Hence, the reactor is suitable for power production in locations where evacuation is not an option.

In this contribution, we present an updated set of safety parameters for the SEALER core, together with dynamic simulations of a set of un-protected transients.

2. Safety parameters

The geometry of the SEALER core is illustrated in Figure 1. Some of the more relevant design characteristics are listed in Table 1. Following corrections in the density of fuel and cladding at operating temperature, we have carried out a new set of Monte-Carlo simulations of the system using the SERPENT code [5]. The corresponding kinetic parameters and reactivity coefficients at Beginning of Life (BOL) are displayed in Table 2.

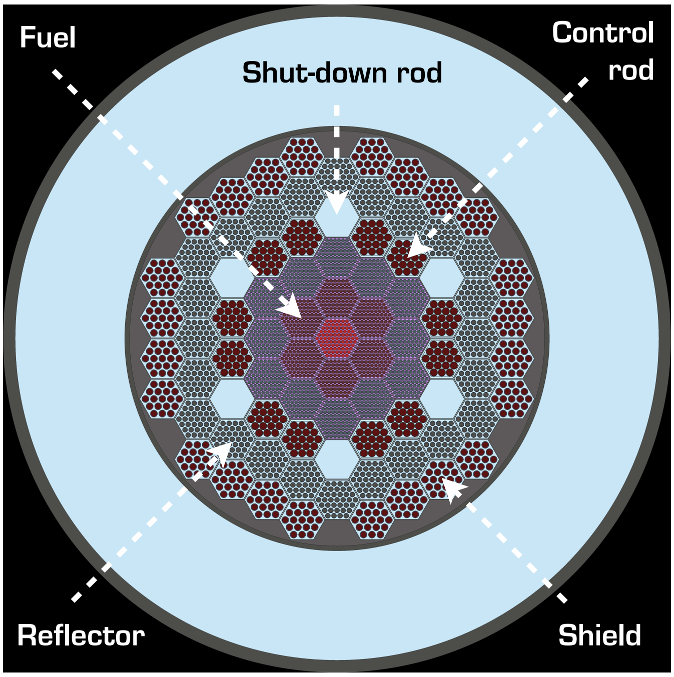

Figure 1: Core map for SEALER

Item	Value
Core power	8 MW
Primary lead coolant mass flow	1310 kg/s
Fuel rods per assembly	91
Number of fuel assemblies	19
Fuel column height	1100 m
Linear power density	4 kW/m
Average coolant velocity	1.1 m/s
Peak coolant velocity	1.6 m/s
Fuel assembly pressure drop	108 kPa
Primary system pressure drop	130 kPa
Coolant temperature at core inlet	390°C
Coolant temperature at core outlet	432°C
Number of pumps	8
Number of steam generators	8
Secondary water coolant pressure	130 bar

Table 1: Design characteristics of SEALER

Item	Notation	Value
Effective delayed neutron fraction	β	717 ± 1 pcm
Effective neutron generation time	Λ	212 ± 1 ns
Doppler constant	K	– 265 ± 5 pcm
Coolant temperature coefficient (core)	α	– 0.35 ± 0.01 pcm/K
Coolant temperature coefficient (global)	α	– 0.88 ± 0.01 pcm/K
Fuel axial expansion coefficient	α	– 0.38 ± 0.01 pcm/K
Grid radial expansion coefficient (T91)	α_{radial}	– 0.40 ± 0.01 pcm/K
Grid radial expansion coefficient (SS316)	α_{radial}	– 0.54 ± 0.01 pcm/K
Coolant void worth (core)	W	– 3 060 ± 5 pcm
Coolant void worth (global)	W	–7 570 ± 5 pcm

Table 2: Safety parameters of SEALER @ BOL

The axial distribution of the coolant temperature void worth is shown in Figure 2. It is interesting to note that the void worth is more negative in the centre of the core, than in the periphery. This phenomenon is due to a reduction in the spectrum averaged fission cross section of U-235 upon voiding. This reduction is of larger magnitude in the centre.

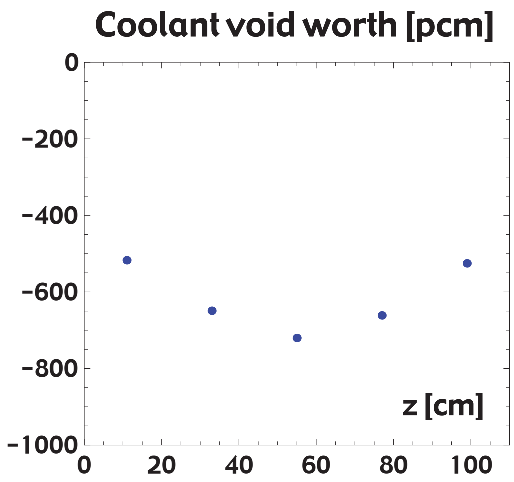

Figure 2: Axial distribution of void worth (pcm/22 cm slice).

3. Transient analysis

Using the safety parameters listed in the previous section, single channel simulations of un-protected transient over-power (UTOP) and loss of flow (ULOF) were carried out. In Figure 3, the power evolution during an un-protected insertion of 0.5 dollar at BOL is displayed, as predicted by SAS and BELLA. The agreement is excellent.

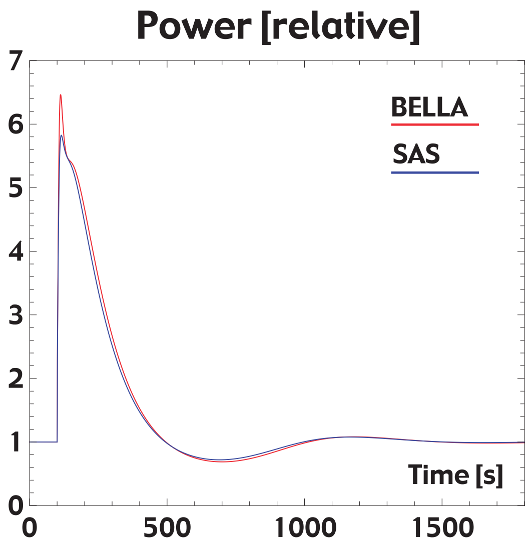

Figure 3: Predicted power evolution in the 3MWe SEALER core, following an un-protected reactivity insertion of 0.5$ at beginning of life.

Since BELLA is a lumped parameter point dynamics code, direct information about the peak temperature is not provided by the code. In Figure 4, the peak fuel and clad temperatures during the UTOP accident, as calculated by SAS are shown.

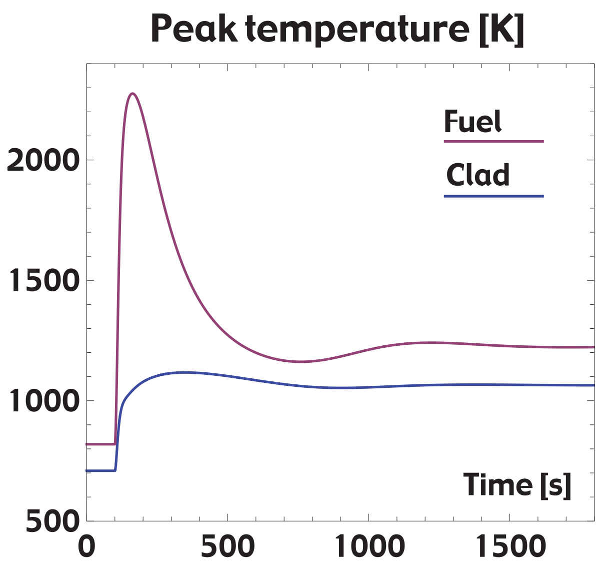

Figure 4: Peak fuel and clad temperatures in the 3MWe SEALER core following an un-protected reactivity insertion of 0.5$ at beginning of life (SAS data).

The margin to failure of the oxide fuel (3100 K) remains above 800 K at all times. At BOL, the rapid creep rupture temperature of the austenitic steel cladding is 1400 K, and a margin to failure of the cladding of about 300 K remains.

For the un-protected loss of flow simulation, a pump cost-down time of ten seconds was adopted. The resulting coolant temperatures at in- and outlet of the core are displayed in Figure 5. The initial rise in temperature yields a negative reactivity feedback which shuts down the reactor (Figure 6). As the system cools down, reactivity increases until re-criticality occurs 3000 seconds into the transient. The second shut-down takes place after 5000 seconds. This interesting phenomenon is due to the negative temperature feed-back of the fuel and coolant, and ensures that lead freezing will not take place. The magnitude of the oscillations is reduced over time, which eventually will lead to a new steady state at low power density.

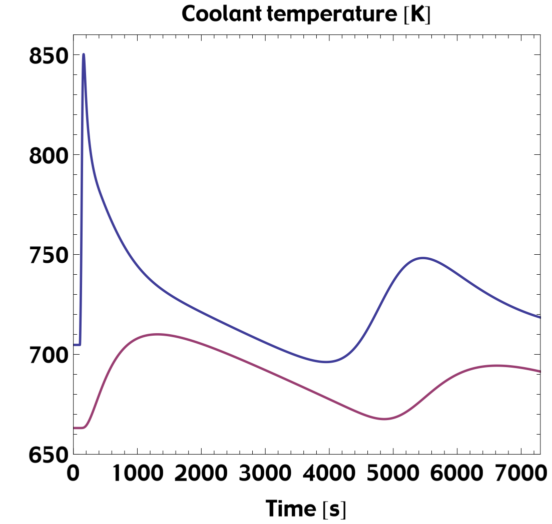

Figure 5: Coolant inlet (red line) and outlet (blue line) temperatures in the 3MWe SEALER system following an un-protected loss-of-flow accident, at beginning of life.

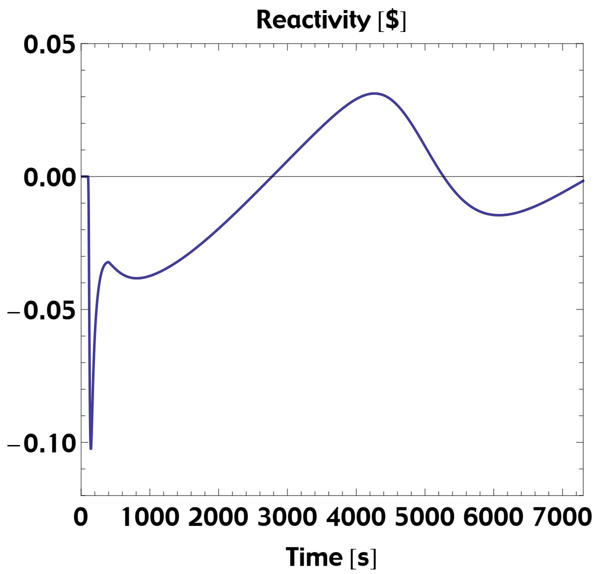

Figure 6: Reactivity evolution of the 3MWe SEALER core, following an un-protected loss-of-flow accident, at beginning of life.

Thanks to the spontaneous shut-down, the difference in temperature between hot and cold legs remains small. Hence, the natural convection flow rate is relatively modest, fluctuating between 15% and 7%, as shown in Figure 7. One may compare with the contribution of natural convection to the coolant flow rate under nominal operation, which is 12%.

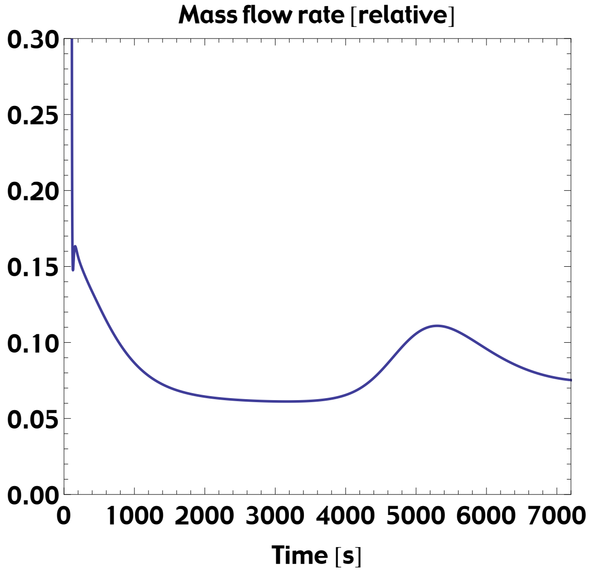

Figure 7: Coolant mass flow rate (relative to steady state operation) following an un-protected loss-of-flow accident at beginning of life.

At EOL, the coolant temperature coefficient is less negative, but the Doppler feedback is stronger. These differences do not have a major impact on the power and temperature evolution during the ULOF event, and the maximum coolant temperature is merely two Kelvin higher than at BOL.

4. Conclusions.

Transient analysis of the SEALER core shows that margins to fuel and clad failure remain large during un-protected control-rod withdrawal and loss of flow accidents. During, the latter, re-criticality permits to avoid coolant freezing. Next step in the safety analysis includes implementation of multi-channel models in SAS4A/SASSYS-1 and BELLA.

Acknowledgements.

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5. References

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