Station Blackout Transient Analyses for VTT's SMR Design LDR-50

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ABSTRACT

VTT Technical Research Centre of Finland is developing a small district heating reactor that operates at low temperature and pressure with natural convection. The design features an innovative passive decay heat removal function that works without any mechanical moving parts. This paper presents variations of station blackout transient analyses done with Apros simulation software. The station blackout transient sets boundary conditions for the design. The variations include a normal case, in which the reactor trip is successful, and two cases in which the scram fails: at the beginning and end of cycle. The pool, which functions as the final heat sink, was assumed to contain spent nuclear fuel as additional heat source. The transients were calculated until the pool reached boiling point. During the station blackout transients, both primary temperature and pressure remained at safe levels and the containment removed decay heat efficiently. The pool reached 100 °C in 22 days in the case with scram and 12 days in the cases without scram. The primary pressure and temperature peaked at the highest in the case without scram at the end of cycle.

1 INTRODUCTION

In 2020, VTT Technical Research Centre of Finland started developing a small reactor for low temperature applications. The LDR-50 (Low Temperature District Heating and Desalination Reactor) design relies on well-established LWR technology and passive safety features.

The basic concept and results from the first analyses were presented at ICONE-28 conference [1-3]. This paper covers variations of a station blackout (SBO) transient done with Apros simulation software. Since the preliminary analyses, the design geometry has changed and the Apros model has been modified, which affects the transient results.

2 LDR-50 DESIGN

A schematic representation of the LDR-50 module can be seen in Figure 1. The whole primary circuit is enclosed inside the reactor vessel in the integrated design. The reactor vessel is located inside a containment vessel that is submerged in a pool. The primary circuit is connected to the district heating network via secondary circuit and two heat exchangers.

The primary coolant circulation is driven by natural convection with the core outlet temperature being about 150 °C at maximum. The reactor is pre-pressurized with nitrogen, and the primary pressure follows the core outlet temperature.

The containment vessel acts as the outermost release barrier as well as a passive decay heat removal system. The containment space is partially filled with water. During normal operation, the containment water temperature remains below boiling point. At this point heat losses to the pool remain small. If, however, the primary cooling path through the heat exchangers is lost and the downcomer temperature begins to increase, the containment water eventually reaches boiling point. This opens an efficient heat transfer path to the pool as the water boils and condenses again in the cooler wall against the pool. The containment function is demonstrated in Figure 2.

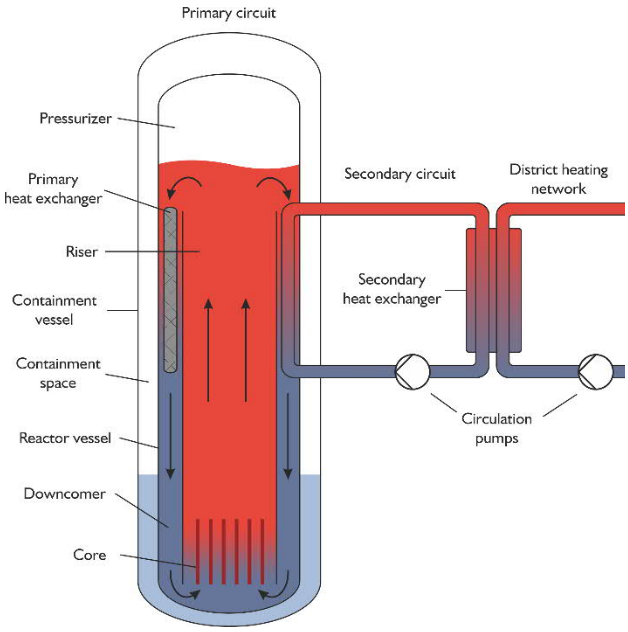

Figure 1: Schematic picture of the LDR-50 module.

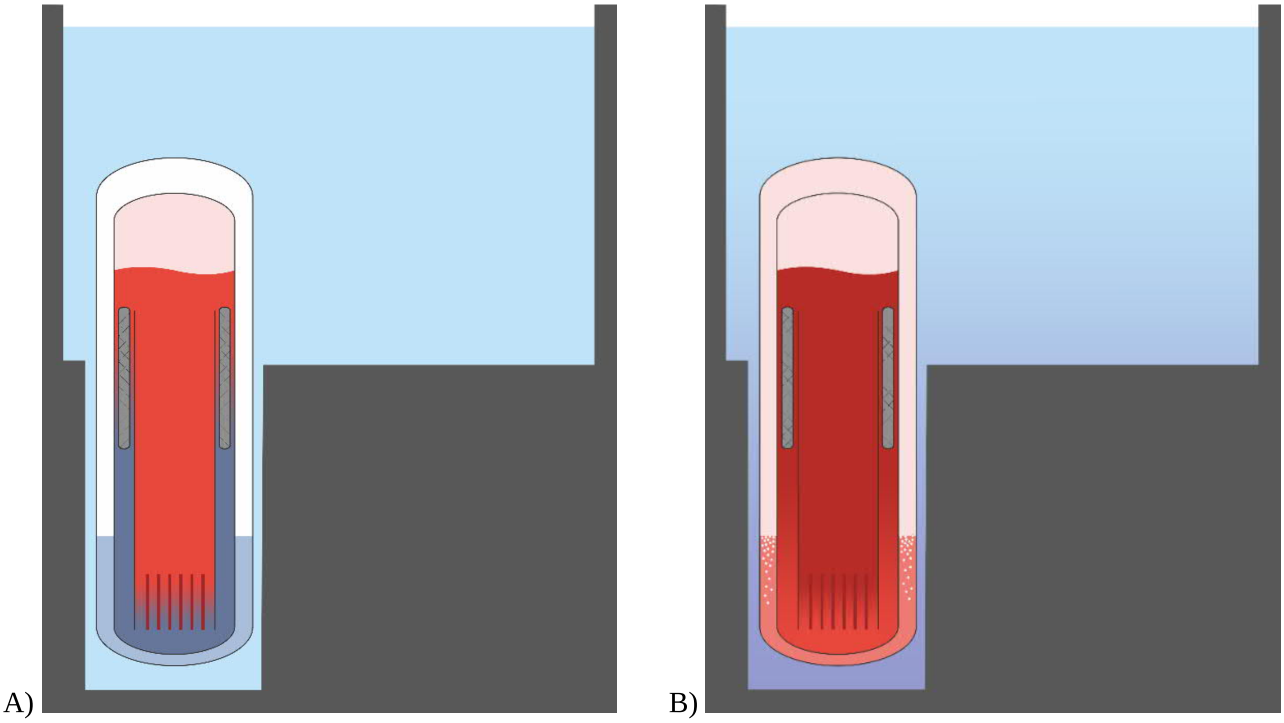

Figure 2: A) In normal operation, the containment water temperature is below boiling point and heat losses to the pool remain small. B) If the primary cooling route through heat exchangers is lost, the containment water starts to boil opening an efficient heat transfer path to the pool.

3 APROS SIMULATIONS

Apros is a process simulation software developed by VTT and Fortum [4]. It is used widely for modelling nuclear power plants, conventional power plants as well as other industrial processes.

3.1 Apros model

The nodalization of the LDR-50 Apros model is presented in Figure 3. The model is described in more detail in [1]. The 1D-model includes the primary and secondary circuits, containment vessel, pool, and heat transfer between the structures. There is no heat transfer out of the pool, which is a conservative assumption. The district heating network and shutdown cooling system are modelled with boundary conditions.

Point kinetics model was used in these simulations. The point kinetics parameters were produced with the Kraken reactor simulator [5]. Both beginning of cycle (BOC) and end of cycle (EOC) conditions were considered. The model uses simplified ANSI/ANS-5.1-1979 standard for decay heat.

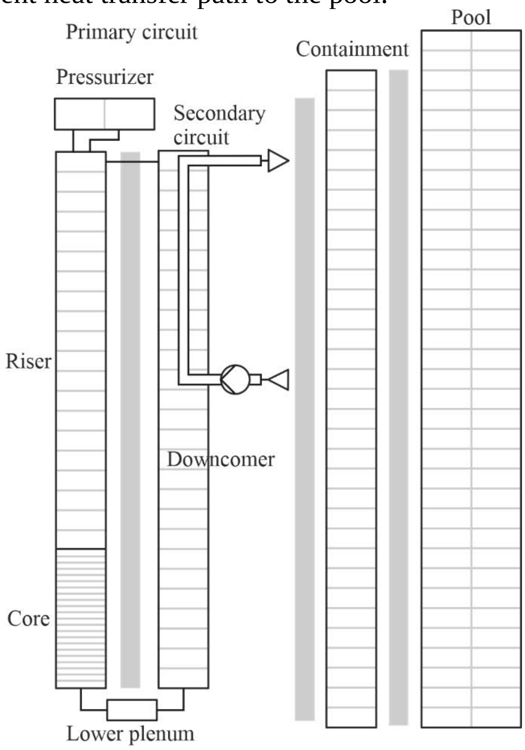

Figure 3: Nodalization of the LDR-50 Apros model.

3.2 Station blackout simulation

In station blackout, all sources of electricity are lost. The transient starts at the hottest possible state i.e., when the supply temperature to the district heating network is at maximum, 120 °C.

When the transient starts, the secondary circulation stops. The control rods drop in in the case with scram and stay at the nominal position in the anticipated transient without scram (ATWS) cases. Cooling of the pool stops. The calculation continues until the pool reaches 100 °C temperature.

It is assumed that the pool contains spent fuel from the past five fuel cycles. An average power of 88 kW was added as a constant power source into the pool. The pool volume is 1000 m^3.

4 RESULTS

Results from the station blackout simulations are presented in Figure 4.

In the case with scram, the reactor trips as soon as the transient starts and only decay heat remains. In the ATWS cases the reactor power decreases slowly as the temperatures in the primary circuit begin to increase. The core outlet temperature peaks highest in the ATWS EOC case at 179 °C. The difference between the ATWS cases is caused by weaker feedback effects in the EOC conditions. The pressure follows the temperature peaking at almost 14 bars, which is below the design pressure of 16 bars. The increased temperature difference between the downcomer and pool enhances heat transfer through containment to the pool, which eventually causes the primary temperature to decrease. When the temperature has decreased enough, the ATWS cases return to power and find an equilibrium where the reactor power is the same as heat transferred to the containment. This keeps the primary temperature and pressure almost constant. In the case with scram the primary temperature continues to decrease, until it starts to rise again after about four days. This is caused by weakened heat transfer to the pool as the pool temperature increases.

In the ATWS cases, the water in the containment reaches boiling point after about a week and continues boiling until the end of the simulation. This increases the containment pressure to about 2 bars. These results differ from the first SBO analyses presented in [1]. Apart from the new geometry, the current model uses a different heat transfer correlation in the containment and pool, which contributes to the differences. There are still a lot of uncertainties in the containment and pool modelling. However, the rate in which the pool temperature increases, which was one the main interest in these analyses, is about the same compared to previous simulations. The pool temperature reaches 100 °C in 22 days in the case with scram and about 12 days in the ATWS cases.

5 CONCLUSIONS

Station blackout transient analyses were conducted for VTT's district heat reactor design LDR-50. Both scenarios with and without successful reactor trip were considered.

The reactor survived the station blackout transients in all cases without any risk to reactor safety. The primary pressure remained below the design pressure in all cases. The primary temperature and pressure peaked at the highest in the ATWS EOC case. The containment transferred heat efficiently to the pool, which acts as the final heat sink. The pool temperature reached 100 °C in 22 days in the case with scram and about 12 days in the ATWS cases. The results indicate that there is a long grace period after a SBO transient before actions are needed.

There are still lots of uncertainties, such as the containment modelling, in the Apros model. Therefore, these results should not be taken as absolute but rather as approximates.

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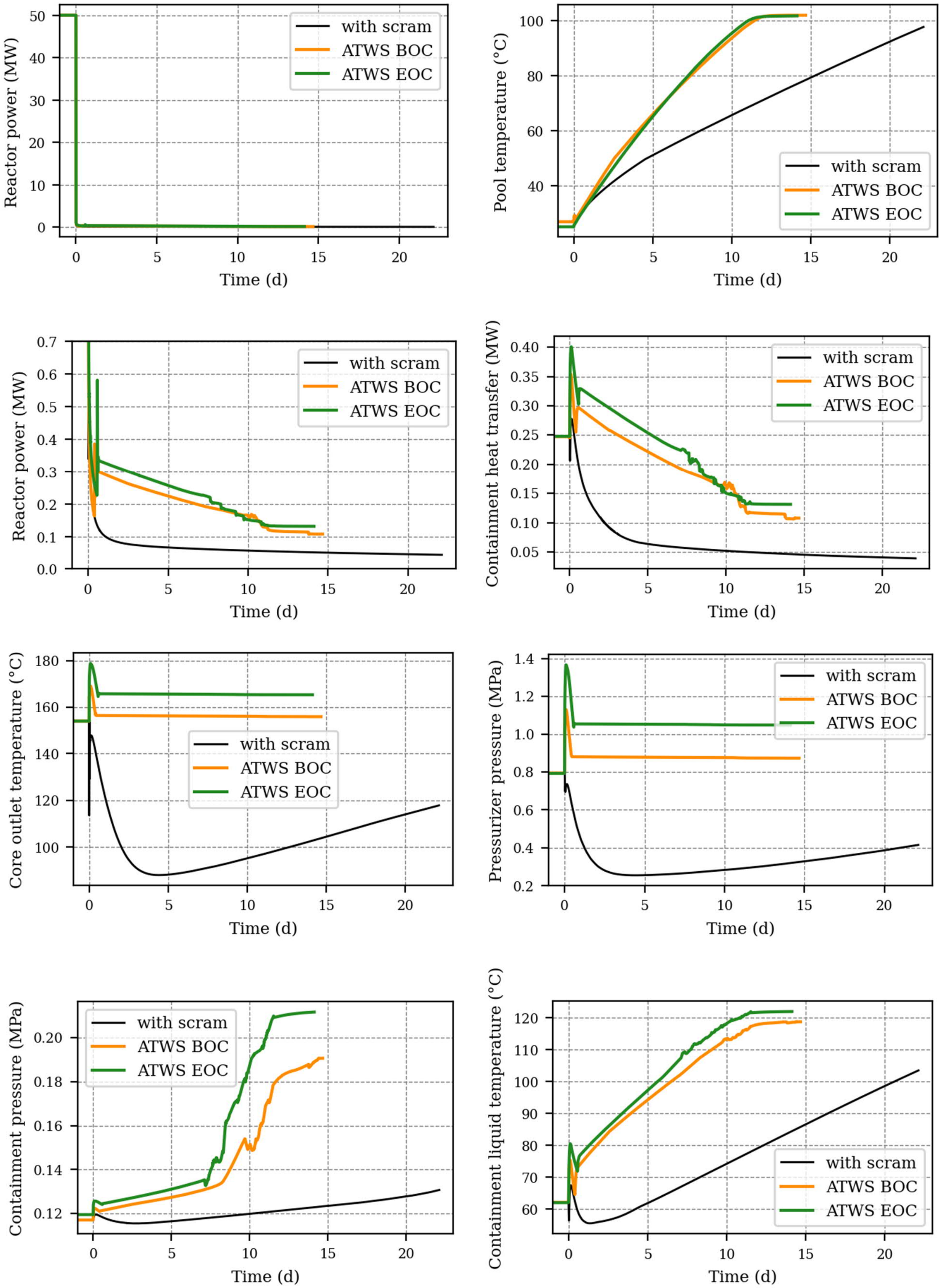

Figure 4: Results from the SBO simulations: total reactor power, pool temperature, containment wall heat transfer, core outlet temperature, pressurizer pressure, containment pressure, and containment liquid temperature.