Assessment of Pump Coastdown and Reactor Protection Scram Delays during Station Blackout Conditions

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Assessment of Pump Coastdown and Reactor Protection Scram Delays during Station Blackout Conditions

T. Kim, T. Sumner, T. Fanning
Nuclear Science and Engineering Division
Argonne National Laboratory

April 26, 2019
ABSTRACT

This report presents an assessment of the impact of pump coastdown time and reactor protection scram delays for the Versatile Test Reactor (VTR) during Protected Station Blackout (PSBO) conditions. While previous simulations for the VTR assumed centrifugal pumps in the primary system, the current pre-conceptual design uses electromagnetic (EM) pumps. Because there is uncertainty as to what the parameters of the EM pump design will be, this report focuses on the impact of the flow coastdown and the reactor protection scram delay, not on the needs of the pump design.

PSBO transient simulations were performed using the SAS4A/SASSYS-1 fast reactor safety analysis code (version 5.2.3). The model used in the simulations is based on the FY18 SAS4A/SASSYS-1 model. A change to the model was made to replace the centrifugal pump model with an electromagnetic pump model with a motor generator as a coastdown mechanism.

The results of the PSBO transient simulations were assessed against the criteria used in Reference 2 with an additional 50°C for conservatism to account for uncertainties. The results show that as the delay before scramming the rods increases, the moment of inertia of the coastdown mechanism must increase to satisfy the criteria. By increasing the moment of inertia to extend the flow coastdown, temperatures can be kept below the desired limits with reactor protection scram delays between 3 and 10 seconds.
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1 Introduction

This report presents an assessment of the impact of pump coastdown time and reactor protection scram delays for the current pre-conceptual Versatile Test Reactor (VTR) during Protected Station Blackout (PSBO) conditions. While previous simulations for the VTR assumed centrifugal pumps in the primary system, the current pre-conceptual VTR is designed to use electromagnetic (EM) pumps with mechanisms such as motor generators to extend the flow coastdown time. Because there is uncertainty as to what the parameters of the EM pump design will be, this report focuses on the impact of the flow coastdown, not on the design of the coastdown mechanism.

PSBO transient simulations were performed using the SAS4A/SASSYS-1 fast reactor safety analysis code (version 5.2.3) [1]. The model used in the simulations was based on the model developed to represent the VTR core design and a functional heat transport system layout developed in FY18 [2]. A change to the model was made to replace the centrifugal pump model with the electromagnetic pump and a motor generator (GEH-EM pump).

PSBO transients with a matrix of different flow halving times (t_{1/2}) and reactor protection scram delays were simulated to evaluate their effect on the peak fuel temperature, peak cladding temperature, and peak coolant temperature. The proposed criteria for Anticipated Operational Occurrences (AOOs) that were described in Reference 2 are as follows:

- Cladding temperatures must remain below 649°C,
- Bulk coolant temperatures must remain below 649°C, and
- Subcriticality must be established and maintained.

These criteria, which are roughly based on the criteria used for the original PRISM PSID [4], should be considered preliminary and are subject to change based on the results of ongoing probabilistic risk assessment and future uncertainty quantification efforts. Final safety requirements will take into account the expected probability of each scenario and the potential consequence of those scenarios.

In this report, the results of the PSBO transient simulations were assessed against the criteria used in Reference 2 with an additional 50°C to account conservatively for uncertainties. Therefore, the criteria used in this report are as follows:

- Cladding temperatures must remain below 599 °C,
- Bulk coolant temperatures must remain below 599 °C, and
- Subcriticality must be established and maintained.
The PSBO transient simulation results show that as the reactor protection scram delay increases, the pump coastdown must be extended to satisfy the criteria. By increasing the inertia of the coastdown mechanism to extend the flow coastdown, temperatures can be kept below the desired limits with the reactor protection scram delays between 3 and 10 seconds.

2 The SAS4A/SASSYS-1 Model

The PSBO transient simulations of the VTR were performed using the fast reactor safety analysis code SAS4A/SASSYS-1 (version 5.2.3) [1]. The model used in the simulations was based on the model developed to represent the VTR core design and a functional heat transport system layout described in ANL-VTR-4 developed in FY18 [2].

Prior to the PSBO transient simulations, a change to the model was made, which was to replace the primary pump option for a centrifugal pump (homologous pump) with an electromagnetic pump model using a motor generator (GEH-EM pump). An EM pump-motor generator combination can be modeled using an electromagnetic pump option in SAS4A/SASSYS-1 (IEMPMP=-2), which was developed using head and efficiency data obtained by General Electric Hitachi (GEH) for their ARIES-P code [3]. The number of the primary pumps was changed from two to four to reflect the current design.

A basic investigation on the functionality of the GEH-EM pump was conducted using the model of ANL-VTR-4. Because the data used to develop this model was limited to the positive flow/positive head quadrant, this model does not work with flow reversal, which can occur when the pumps trip at different times. The GEH-EM pump model is only applicable to the range of data that were used when developing the model, and does not work properly outside of the range of data.
3 Results

As described in previous section, the functional layout of VTR from FY18, which is documented in ANL-VTR-4 [2], had mechanical pumps in the primary system. Safety analyses will be performed in the future for the new VTR heat transport system layout, which uses EM pumps in the primary system. The parameters of the EM pump have not been determined yet. Therefore, in this report, various Protected Station Blackout scenarios were simulated to evaluate the impact of the flow coastdown and the reactor protection scram delay.

The Protected Station Blackout accident is initiated by an assumed loss of electrical power to all plant systems, causing primary and intermediate sodium pumps to trip and the primary heat rejection path through the sodium-to-air heat exchangers (SAHXs) to be lost. The loss of electrical power causes the shutdown heat removal system (SHRS) air dampers to open automatically via failsafe, before the reactor protection system (RPS) has a chance to activate them. Once elevated system conditions are detected, the reactor protection system responds with the series of actions as described in Reference 2 (ANL-VTR-4).1

Various PSBO transient cases with a matrix of different initial flow halving times and reactor protection scram delays were simulated in order to evaluate their effect on the peak fuel temperature, the peak cladding temperature, the peak coolant temperature, the core flow rate, and the pump head. In the PSBO transient simulations, it is assumed that the primary and the intermediate sodium pumps trip at 100 seconds from the beginning of the transient calculation. For all plots in this report, the moment of pump trip is marked as 0 seconds. All pumps are assumed to have normal coastdown, and the cut over voltage fraction ($V_{fr}$) is assumed as 60%. The initial flow halving time was changed by increasing or decreasing the inertia of the coastdown mechanism, resulting in initial halving times ranging from 1.7 seconds to 15.9 seconds. The reactor protection scram delay was changed from 1 second to 15 seconds after the pump trip. It is assumed that the scram occurs over 2 seconds and the reactivity worth by control rods is -5$, which is less than a scram is expected to insert but more than enough to terminate the fission process. Table 3.1 summarizes the calculation matrix.

1 The shutdown heat removal system (SHRS) was used in the previous VTR design from FY18. The current VTR design uses a reactor vessel auxiliary cooling system (RVACS).
# Table 3.1. PSBO transients calculation matrix

<table>
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<tr>
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Initial flow halving time is closely related to the moment of inertia. The change in the initial flow halving time for a reactor protection scram delay of 5 seconds can be found in Figure 3.1. The initial flow is 1570.8 kg/s for all cases and the initial flow halving time increases with increasing moment of inertia. The estimated initial flow halving time and corresponding moment of inertia are summarized in Table 3.2. Based on previous experience, an initial flow halving time between 5 and 10 seconds (marked as bold in Table 3.2) is anticipated for the design, and thus the assessment focused on this flow halving time range.

It should be emphasized that the halving times resulting from the inertias in Table 3.2 correspond to the previous HTS design and several currently assumed pump model input parameters. The reader should not conclude a specific inertia value to obtain a desired halving time. Rather, the flow halving time is the more important parameter for this analysis. Therefore, only halving times are presented for the remainder of this report.
Table 3.2. Initial flow halving time and moment of inertia

<table>
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<th>Moment of inertia (kgm²)</th>
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<td>15.9</td>
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</table>

In case of 5 seconds for the reactor protection scram delay, the cladding temperature and coolant temperature with different initial flow halving times during the first 10 seconds after the pump trip are shown in Figure 3.2. Cladding and coolant temperatures increase to their peak temperatures, and sharply decrease after the RPS initiates a control rod scram at 5
seconds. As shown in Figure 3.2, the clad temperature meets the criteria (599 °C) when the flow halving time is 6.3 seconds or more, and the coolant temperature meets the criteria (599 °C) when the flow halving time is 4.8 or more.

Figure 3.3 illustrates the cladding and coolant temperatures with different initial flow halving times during the first 300 seconds after the pump trip. This shows that the clad and coolant temperatures increase again to their second peak after the sharp drop due to the decrease of pump flow. However, the second peaks meet the criteria for all cases. Afterwards, the clad and coolant temperatures go to equilibrium state.

Figure 3.4 illustrates the power-to-flow ratio with different flow halving times for the reactor protection scram delay of 5 seconds during the first 10 seconds after the pump trip (a) and 300 seconds after the pump trip (b). The power-to-flow ratio increases quickly after the pump trip. It keeps increasing until the control rod scram is actuated at 5 seconds. Based on previous experience, a maximum power-to-flow ratio threshold of 110-120% is reasonable. The power-to-flow ratio would increase even after the threshold is exceeded due to instrumentation delays and actuation delays. The maximum power-to-flow ratio reached ranges between 1.3 and 1.5 when the flow halving time is between 4.8 and 9.5 seconds.

Figure 3.2. PSBO transients with reactor protection scram delay of 5 s during the first 10 seconds after the pump trip: (a) clad temperature (b) coolant temperature
Figure 3.3. PSBO transients with reactor protection scram delay of 5 s during the first 300 seconds after the pump trip: (a) clad temperature (b) coolant temperature

Figure 3.4. Power-to-flow ratio during: (a) first 10 seconds (b) 300 seconds after pump trip

Figure 3.5 illustrates the cladding and coolant temperatures with different flow halving times during the first 300 seconds after the pump trip for the reactor protection scram delay of 1 second. Basically, the overall temperature behaviors are similar to those of the reactor protection scram delay of 5 seconds. Since the reactor protection scram delay is shortened, it blocks the temperature rise and limits the peak temperature value. Therefore, both peak clad temperature and peak coolant temperature decreased with decreasing the reactor protection delay.
scram delay. Both the clad temperature and the coolant temperature meet the criteria even for the flow halving time of 1.7 seconds.

![Clad Temperature vs Time](image1)

![Coolant Temperature vs Time](image2)

Figure 3.5. PSBO transients with reactor protection scram delay of 1 s during the first 300 seconds after pump trip: (a) clad temperature (b) coolant temperature

Figure 3.6 illustrates the cladding and coolant temperatures with different flow halving times during the first 300 seconds after the pump trip for the reactor protection scram delay of 3 seconds. The peak clad temperature and peak coolant temperature increased compared to those of reactor protection scram delay of 1 second. The clad temperature meets the criteria when the flow halving time is 4.8 seconds or more, and the coolant temperature meets the criteria when the flow halving time is 3.2 seconds or more.
As mentioned above, based on previous experience, an initial flow halving time between 5 and 10 seconds is expected. For these expected flow halving times, the effect of the reactor protection scram delay on the clad temperature was evaluated. Figure 3.7 shows the clad temperatures with flow halving times of (a) 4.8 seconds, (b) 6.3 seconds, (c) 7.9 seconds, and (d) 9.5 seconds for different reactor protection scram delay.

In case of 4.8 seconds of flow halving time, both the clad temperature and the coolant temperature meet the criteria when the reactor protection scram delay is 3 seconds or less. Even with 10 seconds of the reactor protection scram delay, the peak clad temperatures and the peak coolant temperatures meet the criteria without the additional 50°C for uncertainties that was used in Reference 2, which is 649 °C. In case of 6.3 seconds of flow halving time, both the clad temperature and the coolant temperature satisfy the criteria when the reactor protection scram delay is 5 seconds or less. In case of 7.9 seconds of flow halving time, both the clad temperature and the coolant temperature meet the criteria when the reactor protection scram delay is 7 seconds or less. In case of 9.5 seconds of flow halving time, both the clad temperature and the coolant temperature meet the criteria when the reactor protection scram delay is 10 seconds or less.
Figure 3.7. Clad temperature for various reactor protection scram delays: (a) $t_{1/2}=4.8$ s (b) $t_{1/2}=6.3$ s (c) $t_{1/2}=7.9$ s (d) $t_{1/2}=9.5$ s

Tables 3.3 and 3.4 summarize the peak clad temperatures and the peak coolant temperatures for all cases in the calculation matrix of Table 3.1. The green cells in the Table 3.3 and 3.4 indicate that the temperatures satisfy the criteria. It can be concluded that as the reactor protection scram delay increases, the initial flow halving time must increase to meet the criteria.

It should be noted that the last column of the tables shows the calculation results when there is no scram, that is, the results of the Unprotected Station Blackout (USBO) transient simulations. Interestingly, even in the cases of USBO, the peak temperatures are not much higher than those of PSBO transient simulations.
### Table 3.3. Peak clad temperatures for PSBO and USBO transients

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### Table 3.4. Peak coolant temperatures for PSBO and USBO transients

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4 Summary and Conclusions

This report presents an assessment of the impact of pump coastdown time and reactor protection scram delays for the pre-conceptual VTR design during PSBO conditions. The PSBO transient simulations were performed using the SAS4A/SASSYS-1 fast reactor safety analysis code (version 5.2.3) [1]. The model used in the simulations was based on the model developed to represent the VTR core design and a functional heat transport system layout in ANL-VTR-4 developed in FY18 [2]. A change to the model was made, which was to replace the primary pump option with a centrifugal pump to an electromagnetic pump with a motor generator as a coastdown mechanism.

PSBO transients with a matrix of different initial flow halving times and reactor protection scram delays were simulated to evaluate their effect on the peak fuel temperature, peak cladding temperature, and peak coolant temperature. The results of the PSBO transient simulations were assessed against the criteria used in Reference 2 with an addition of 50°C to account for uncertainties.

The PSBO transients simulation results show that as the reactor protection scram delay increases, the flow halving time must increase to satisfy the criteria. The pump motor-generator inertia can maintain temperatures below the allowable limits with initial flow halving times of 5 to 10 seconds. With these initial flow halving times, a scram could be initiated within 3-10 seconds and still maintain peak temperatures below the criteria.
References


4. PRISM Preliminary Safety Information Document, GEFR-00793, Chapter 15, Volume IV.
Nuclear Science and Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439-4842

www.anl.gov