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ARC-100 Plant Simulator

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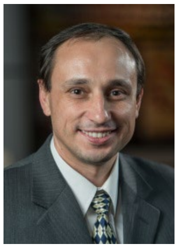

Anton Moisseytsev is a Principal Computational Nuclear Engineer in the Nuclear Engineering Division of Argonne National Laboratory. He has twenty years of experience in modeling and simulation of various systems, including design and analysis of the advanced reactors and energy conversion systems, safety analysis of nuclear reactors, and code development for steady-state and transient simulations of nuclear power plants. Anton is the primary author of the ANL Plant Dynamics Code and has been involved in the development of the supercritical carbon dioxide Brayton cycles at Argonne since 2002.

ABSTRACT

ARC-100, a 286 MWth sodium-cooled metal-fueled reactor coupled to a supercritical carbon dioxide Brayton Cycle, for a net output of 100 MWe, is being developed under the U.S. DOE Advanced Reactor Demonstration Program. Argonne National Laboratory is developing the Plant Simulator model. The simulator is based on two codes developed at Argonne: SAS4A/SASSYS-1 code for transient and safety analysis of liquid metal-cooled fast reactors, and Plant Dynamics Code (PDC) for dynamic and control analysis of sCO_2 cycles. The ARC-100 Plant Simulator is used to simulate operational transients and to investigate control of the entire plant. The emphasis is made on the coupled performance of the reactor and the power conversion system. For the reactor side, both passive and active control options are analyzed. Under the passive control, all control actions are applied on the sCO_2 cycle side, and the reactor follows the power demand from the cycle only by means of strong inherent characteristics of the ARC-100 core, without reliance on the operator action. The paper presents the results of the ARC-100 Plant Simulator for various operational transients, such as load following and shutdown/startup transients.

INTRODUCTION

Under the U.S. DOE Advanced Reactor Demonstration Program, ARC20 awards, ARC, LLC is developing an advanced ARC-100 reactor. ARC-100 is a 286 MW_{th} sodium-cooled metal-fueled reactor coupled to a supercritical carbon dioxide Brayton Cycle, for a net output of 100 MW_e. Argonne National Laboratory's participation in the ARC-100 project includes developing the Plant Simulator model. The goal of the Plant Simulator modeling is investigation of the behavior of the ARC-100 reactor, as an entire plant, during normal operation transients. The plant-level simulation includes modeling of the reactor side and the energy conversion system, with specific attention to interaction between these two parts of the plant during transients.

The simulation of the reactor side includes modeling of the primary and intermediate heat transport systems. The ARC-100 primary system consists of the metal-fueled reactor core, cooled by sodium, and all the primary sodium pools and components contained within the reactor vessel, such as intermediate heat exchangers (IHX) and primary pumps. The intermediate heat transport system (IHTS) utilizes intermediate sodium loops to transfer heat from the IHXs to the energy conversion system.

The ARC-100 energy conversion system uses supercritical carbon dioxide (sCO_2) Brayton cycle which includes intermediate sodium-to-CO_2 reactor heat exchanger (RHX), turbine and compressors, recuperative heat exchangers, and heat rejection heat exchanger (cooler). The ARC-100 sCO_2 cycle is a recompression Brayon cycle where the flow is split between two compressors to improve the efficiency of the low-temperature recuperator. The sCO_2 cycle investigated in this paper uses water cooling for ultimate heat removal from the plant. Currently, there is also a dry-air cooling option for the ARC-100 plant. These two options utilize different cooler heat exchanger concepts and thus can experience different behavior during the transients presented in this paper. However, both water-cooled and air-cooled sCO_2 cycle designs use the same CO_2 compressor-inlet conditions (32 °C and 7.62 MPa). Also, the normal operation transients investigated in this paper are relatively slow transients, such that any thermal delays imposed by the cooler HX are expected to have a minor effect on the transient response of sCO_2 cycle and entire plant.

In the analysis presented in this paper, the normal operation transients are simulated for the ARC-100 plant. These transients include normal power maneuvering (i.e., load following) and planned plant shutdown and startup. At the current stage of the ARC-100 concept development, the plant operation targets are not fully defined. Therefore, for the analysis presented in this paper, somewhat arbitrary power ranges, rates, and time scales have been imposed. For the load following, *a target of linear power change at 5%/min rate from 100% to 0% and back to 100% was selected*. For the shutdown and startup transients, the time scales (transient duration) are again selected arbitrary to provide sufficient time for power level changes. The present analysis only includes the thermos-hydraulic response of the ARC-100 plant, and does not consider any structural or material limitations.

COMPUTATIONAL TOOLS

The analysis presented in this paper is carried out using coupled SAS4A/SASSYS-1 code and Plant Dynamics Code (PDC). SAS4A/SASSYS-1 is used for the reactor side, including primary and intermediate sodium systems, while PDC is used for the sCO_2 cycle energy conversion system.

The SAS4A/SASSYS-1 code [1] is Argonne's liquid metal reactor analysis code system for modeling of liquid-metal reactors at the system level. The SAS4A/SASSYS-1 code couples reactor kinetics with thermal hydraulics calculations. In this work, the ARC-100 SAS4A/SASSYS-1 model developed for ARC-100 safety analysis [2] is utilized. This model includes the reactor core, with reactivity feedbacks, point kinetics, and decay heat, and components in both the primary and intermediate loops. The analysis presented in this paper uses the beginning-of-life variation of the ARC-100 SAS4A/SASSYS-1 model. The original ARC-100 SAS4A/SASSYS-1 model also includes simulation of reactor protection system (RPS) by SAS4A/SASSYS-1 control module. For the normal operation transients analyzed in this work, RPS is not expected to be activated. Therefore, the RPS part of the SAS4A/SASSYS-1 model is disabled in the current simulation. Instead, all reactor control actions are handled by SAS4A/SASSYS-1-PDC coupling as described below.

The Plant Dynamics Code (PDC) [3] has been developed specifically for the analysis of sCO_2

power cycles. It is based on an accurate representation of sCO_2 properties and their effects on the cycle and components, both for design and performance. Specifically for the transient analysis presented in this paper, the PDC features a multi-node compressible flow simulation of each heat exchanger with transient effects such as the thermal inertia of the wall mass, as well as a cycle-wide simulation such as turbomachinery off-design performance and the performance of the plant control system. These details allow the PDC to accurately simulate a wide range of thermal transients as well as interactions between individual components and the entire plant. PDC has been used in the past for analysis of sCO_2 cycle coupled to advanced reactors, including sodium-cooled reactors [4-8].

For this work, one significant modification to PDC was introduced regarding treatment of the turbomachinery components. In previous PDC calculations, the code's subroutines for turbine and compressor design and analysis were used. For ARC-100 sCO_2 cycle, the turbomachinery was preliminary sized by ConceptsNREC vendor. Therefore, the code was modified to skip the turbine and compressor design calculations and directly use the performance maps provided by the vendor. To be able to use the vendor maps at inlet conditions different from the design point in transients, the real-gas maps correction algorithm developed by ConceptsNREC [9] was directly modeled in PDC.

The ARC-100 sCO_2 cycle heat exchangers (RHX, HTR, LTR, and cooler) are being designed by VPE, Inc. For this analysis, limited design information on the heat exchangers has been provided to Argonne. Using this information and assumptions on other design parameters required for the PDC simulation, the heat exchanger models were developed and validated by matching the HX performance at the design conditions.

Figure 1 shows the ARC-100 sCO_2 cycle as it is modeled in PDC with all included components and connections. Figure 1 also presents the results of the steady-state calculation in PDC, including temperatures, pressures, flow rates, and heat duties along the cycle. Although not explicitly shown in Figure 1, all ARC-100 turbomachinery components, - turbine and two compressors - are located on the common shaft. This design feature will be important for the transient simulation.

The SAS4A/SASSYS-1 and PDC codes were coupled for the analysis presented in this paper. The coupling is carried out at the Na-to-CO_2 reactor heat exchanger. SAS4A/SASSYS-1 calculates the intermediate sodium temperature and flow rate at the RHX inlet. All calculations for this heat exchanger are done in PDC, and the results in terms of sodium outlet temperature are provided back to SAS4A/SASSYS-1. This communication between SAS4A/SASSYS-1 and PDC occurs on every time step. Detailes of the SAS4A/SASSYS-1-PDC coupling are provided in Reference [10].

In addition to the RHX calculations, the SAS4A/SASSYS-1-PDC coupling is also used to calculate and impose the reactor side controls. These controls are applied to the primary and intermediate sodium pumps and core external reactivity, as discussed below.

ARC-100 PLANT CONTROLS

Figure 2 shows the ARC-100 plant control mechanisms simulated in this work, both on the reactor and the sCO_2 cycle sides. All controls simulated in this work are set up using proportional, integral, and differential (PID) controllers, with PID coefficients provided by user in the input files.

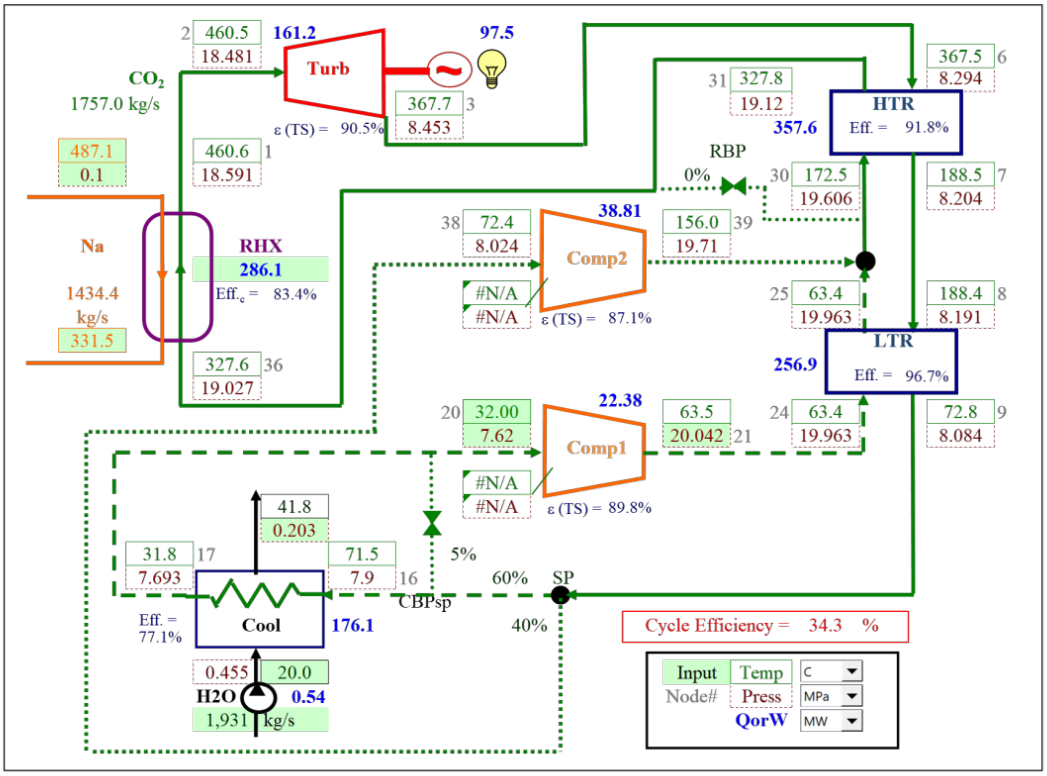

Figure 1. PDC Model of ARC-100 sCO$_2$ Brayton Cycle

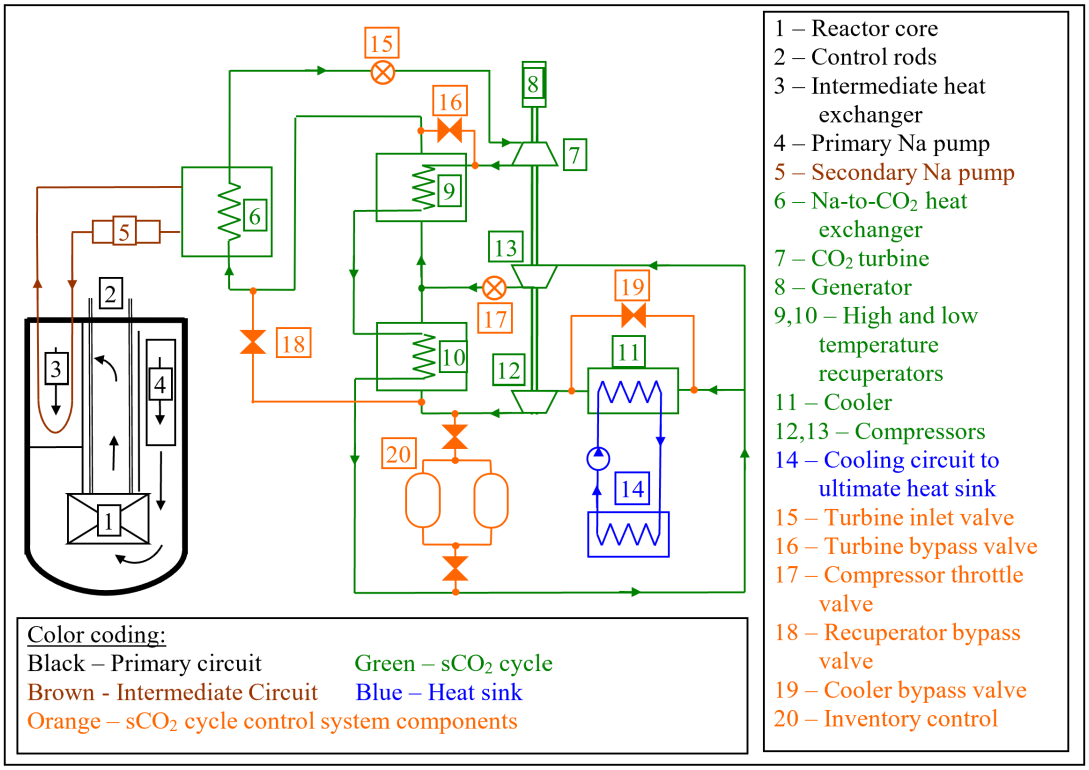

Figure 2. ARC-100 Controls

The reactor side controls include:

- *Control rods in the core for reactor power control*, which is used to control core-outlet temperature. For all simulations presented in this paper, unless otherwise explicitly stated, this core reactivity control is used to maintain core-outlet temperature at the design level of 510 °C. The external reactivity is only one component of the core net reactivity; in all simulations, the core reactivity feedbacks will be present and will also affect the net reactivity and core power. The core power would also be affected by the decay heat which is calculated by SAS4A/SASSYS-1. Both the reactivity feedbacks and decay heat use the same modeling and inputs utilized for the ARC-100 safety analysis [2].

- *Primary and intermediate sodium pumps for flow control*, which are used to control primary and intermediate cold leg temperatures, respectively. The pump control is implemented by changing the pump motor torque for the homologous sodium pump model[1], where the actual pump head (and flow) are calculated internally in SAS4A/SASSYS-1 using the motor torque, pump inertia, and flow conditions. Similar to the core inlet temperature, the default target temperatures for the sodium flow controls are the steady-state design temperatures of 355 °C for primary cold leg at the IHX outlet and 331.5 °C for intermediate cold leg at the RHX outlet.

The reactor-side controls shown in Figure 2 and described above are used in “active control” reactor operation mode when all controls are activated. At the same time, the ARC-100 design allows, at least theoretically, operation in so-called *no-control mode*. In this regime, no control action is implemented on the reactor side and instead the reactor is allowed to self-regulate based on the strong inherent reactivity feedbacks of metal-fueled sodium-cooled ARC-100 core. These reactivity feedbacks, including Doppler, core radial and axial expansion, and control rod driveline expansion, have been shown to be sufficiently strong to control reactor power in the unprotected accidents when RPS is assumed to fail [2]. Likewise, under no-reactor-control option, no action will be applied on primary and intermediate sodium pumps. The pump motor torques will be maintained at 100%, which will result in approximately full design flow rates. Small variation in flow are expected due to changing natural circulation component under varying loop temperatures.

The sCO_2 cycle control mechanisms, as modeled in PDC, are also shown in Figure 2. Some of these controls are used for generator output adjustment in transients, while others are utilized for specific temperature control, as described below.

- *Turbine throttling control* is a single valve located upstream of the turbine. Normally, the valve is fully open. With partial closing of the valve, the flow to the turbine is restricted, resulting in turbine producing less power and therefore reducing the plant output during load following.

- *Turbine bypass control* acts by diverting some flow to bypass the turbine and send it back to compressors. By doing this, the flow rate in turbine is decreasing, thus decreasing useful power output from the turbine. At the same time, flow rate in compressors increases, also increasing power demand by the compressors. Both these actions result in a decrease in the net generator output to the grid.

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[1] The SAS4A/SASSYS-1 model in this analysis uses homologous pump model to represent ARC-100 electromagnetic pumps.

- *Inventory control* acts by reducing the cycle pressures by removing part of working fluid inventory from the cycle. As shown in Figure 2, this removed inventory can be stored in external tanks, and later returned to the cycle. For gas cycles, both turbine and compressor works are proportional to their pressure ratios, such that decrease in pressures results in reduction in turbomachinery works, affecting the plant output. The limiting factor in inventory control range is the requirement to store the working fluid removed from the cycle in external tanks. This would require either large tanks or pressurization/cryogenic storage system (or both), adding cost to the plant. In this work, a passive system arrangement with inventory control system located between high (20 MPa) and low (7.6 MPa) pressure lines is modeled in PDC, and the control action is implemented by opening and closing the inlet and outlet valves.

- *Cooler bypass and water flow rate controls* are both utilized in the ARC-100 sCO_2 cycle to control the main compressor inlet temperature. Since the compressor-inlet conditions are those closest to the CO_2 critical point, it was found in previous analyses that precise and fast control for these conditions is needed to ensure stable compressor operation. For these reasons, the traditional water flow control is augmented by cooler bypass control for the ARC-100 sCO_2 cycle. Water flow control provides long-term temperature control, with faster but limited action of cooler bypass. In all normal transient simulations presented in this paper, the target compressor-inlet temperature was maintained at 32.0 °C all the time (actual temperature varies in transients).

- *Compressor throttle control* is included in the PDC controls mostly for adjustment of flow split between the two compressors in off-design conditions. However, this control was not initiated in the transients presented in this paper, since there were no strong indication for flow split control requirement. For example, the surge/choke margins are very similar for both compressors in all transients and thus could not be improved by flow split variation between compressors.

- *Recuperator bypass control* is used in PDC for control of the CO_2 temperature at the RHX inlet by bringing colder CO_2 flow from recuperators inlet. As will be shown below, in most cases, reduction in sCO_2 cycle power output leads to increase in the RHX-inlet temperature (mostly, from reduced temperature change across the turbine, which is communicated back to RHX inlet in the HTR). Therefore, if it is desired to maintain sodium IHTS temperatures in transients, an active control on the CO_2 RHX inlet temperature is required. This control, though, has a negative effect on the cycle efficiency by reducing the useful heat transfer in the recuperators and thus (significantly) affecting the cycle efficiency at partial loads.

More information on how the controls are implemented in PDC can be found in Reference [3]. For all PDC controls, a limit on the control action (such as valve opening and closing rates) are implemented; however, these limits are selected somewhat arbitrary as the control valves are not designed for ARC-100 yet.

LOAD FOLLOWING TRANSIENTS

The goal of this analysis is to demonstrate the ARC-100 plant ability to “follow the load”, i.e., match the changing electrical grid demand at levels below the nominal plant output. Since the operating modes for the ARC-100 reactor plant are not yet finalized in this stage of reactor development, a generic goal of load change from 100% to 0% and back to 100% at 5%/min rate is selected for this analysis. Note that this power maneuvering is considered to be a rather aggressive schedule for nuclear reactors (current US reactor fleet operates in base load mode and does not participate in load following). In all simulations for this section, the turbomachinery shaft is assumed to be synchronously connected to the grid, such that the shaft speed is fixed to 100% of the design value.

To simulate the load following transients in PDC, a table of load demand, versus time, is provided as a user input. Table 1 provides the input used in the present simulation. Both decrease and increase in grid demand are simulated. At each stage, 100% power change is implemented over 1,200 s (20 min), i.e., at 5%/min rate. There is a 300 s (5 min) wait time between the down and up stages. PDC uses the input in Table 1 as the target for the net plant output. It then calculates the actual plant output at every time step and applies a selected control action to adjust the plant output to match the demand.

Table 1. Grid Demand Input for Load Following Transients

Time, s	Grid Demand
0	100%
1,200	0%
1,500	0%
2,700	100%

In this work, four transient variations for load following have been simulated, and are discussed in the subsections below. In each variation, one control is implemented to adjust the plant output, while other controls are used to maintain boundary conditions (like water flow rate and reactor power controls) as discussed in previous section. The success of each control is judged by how closely the grid demand is matched by plant net output (this was achieved in all transients). Then, the selected control approaches are compared by key figures, such as cycle efficiency and reactor temperatures at partial loads.

The main limiting factors in the simulation are the ability to maintain operation of the components and the entire plant. For turbomachinery, it means avoiding surge and choking conditions. For the reactor side, it’s ability to not exceed the peak reactor temperatures. Note that, as it was discussed above, only thermo-hydraulic limitations are considered in this work, - structural limits will be investigated in future analyses.

The results of the load following analysis are summarized in Figure 3 below, which compares the main characteristics of ARC-100 plant during load following under various control approaches. The specific results and major highlights for each simulated control approach are discussed below.

Inventory Control with No Reactor Control

The load following by inventory control was simulated in two phases. On the first phase, the inventory inlet valve was manually open to a small fraction to record: a) CO_2 mass removal from the ARC-100 cycle and b) net generator output associated with that mass change. From that phase, a table of plant output versus mass reduction was generated. That table was then used in the second phase with fully automatic control for load following. Only these results are shown in Figure 3. In addition to the inventory control action, a small variation in the turbine bypass was implemented for fast fine-tunning of the net plant output. The turbine bypass control is simulated to act between 100% and 95% loads, with inventory control acting for loads 95% and below.

In this variation of inventory control, no control action was implemented on the reactor side. Instead, the reactor power was left to adjust itself based on strong ARC-100 core reactivity feedbacks. Those feedbacks respond to the changes in heat removal rate by the sCO_2 cycle during load following and corresponding changes in the core-inlet temperature. As demonstrated in Figure 3 ("INV" lines), the ARC-100 feedbacks are strong enough that even without any active core power control, the core-outlet temperature only changes by +1/-2 °C during the entire 100%-0% load range, and only increase by <10 °C during the up transient from 0% to 100% loads. Consequently, peak reactor temperatures do not show any significant increase during load following.

In this transient simulation, it was shown that inventory control (even without reactor control) is capable of matching load demand from 100% to 0% and back to 100%. However, in order to achieve this range, a very large inventory tank, with volume of 500 m^3, was needed. A smaller tank would limit the attainable range of the inventory control. On the other hand, if the tank volume is the only restriction, then it could be overcome by active inventory control system, for example by using charging pumps or active cooling.

As the results in Figure 3 show, the inventory control emerging as preferable control mechanism as it results in the highest cycle (and plant) efficiency at partial loads. The disadvantages of this control (aside from the tank requirements) are the largest increase in the CO_2 RHX-inlet temperature, beyond the steady-state design limit.

Also, the simulations have shown that both compressors operate at choke conditions shortly after the control action is activated. This result, however, is a general trend for all control options considered in this work, partly because of very small choke margins (10% or less) at the design point.

Inventory Control with Active Reactor and Recuperator Bypass Controls

Although previous results showed that ARC-100 load following can be achieved by inventory control without any reliance on the reactor control, activation of reactor reactivity feedbacks for self-regulation in those calculations required a significant increase in the RHX-inlet temperature in CO_2 side. As shown in Figure 3 ("INV" lines), this temperature increase is communicated all the way to the core-inlet temperature, with noticeable increase in the reactor cold leg temperatures, both on primary and intermediate sides. The increase in the reactor primary side cold-leg temperature (see IHX-outlet temperature plot) may be problematic, since it is closely related to the reactor vessel temperature and increase of more than 100 °C beyond the nominal design level is not a desirable outcome for normal reactor operation.

To preclude the increase in the reactor-side temperature, the load following calculations with the inventory control are repeated, this time with active reactor control. In this mode, both the reactor power and flow rates are actively controlled to maintain reactor-side temperatures. The results of simulation, however, have shown that in order to maintain reactor temperatures close to steady-state level, a recuperator bypass control is needed to preclude CO_2 RHX-inlet temperatures from rising. These results are shown in Figure 3 with "INV+Rx+RBP" lines.

Overall, while all other results are close to the INV lines, the introduction of active reactor control indeed allows to significantly reduce variation in reactor (and CO_2 RHX-inlet) temperatures during load following. At the same time, because of the negative effect of the recuperator bypass, the cycle efficiency at partial loads is significantly reduced, compared to just inventory control results.

This transient was also simulated for the entire load schedule Table 1 for both down and up parts. Again, the main difference from pure inventory control is significantly smaller variation in reactor temperatures – for example, core-outlet temperature stays within ±1 °C of the design value for the entire transient.

Turbine Bypass Control

The turbine bypass control was also capable of following the load for ARC-100 plant between 100% and all the way to 0%. In this work, only down transient was simulated as up transient is usually very symmetric for this control. As demonstrated in Figure 3 ("TBP" lines), consistent with previous PDC analyses, turbine bypass control shows the lowest efficiency at partial loads. Very little change in reactor power (and conditions) and heat transfer in RHX is calculated, as the control effectively just decreases useful turbine work and increases parasitic compressor work. As a result, the cycle efficiency decrease is almost linear with load. Because this control acts on flow and pressures, this action results in smallest temperature changes on both the reactor and CO_2 cycle sides. Still, even with this control, choke conditions are encountered for both compressors from about 90% loads down.

Turbine Inlet Throttling Control

Turbine inlet throttling control ("TIN" lines in Figure 3) can also be used for ARC-100 load following. Again, the calculations have shown that any load between 100% and 0% can be achieved by this control action. However, two serious issues are identified for the throttling control in Figure 3. First, as in previous works, throttling flow upstream of the turbine increases pressures upstream of that valve. Meaning that all pressures from the main compressor outlet to RHX CO_2 side increase beyond their design values of 20 MPa. In this analysis, pressures up to 28 MPa have been calculated at low loads. Therefore, if this control is to be used for normal plant operation, all high pressure components need to be designed for at least this pressure (better, with some margin) increasing the cost of the plant. The second issue encountered with turbine throttling control for ARC-100 plant is that compressor surge is predicted for each of the compressors (although not at the same time) during the transient. This issue may be dealt with by compressor redesign to increase range (likely, at the expense of efficiency at the design point) or by activation of the compressor surge control (at the expense of cycle efficiency at partial loads). Overall, for these two issues, the turbine throttling control is *not* recommended as a control mechanism for ARC-100 load following.

From all the results in Figure 3, the following observations can be made. First, all selected controls mechanisms were able to achieve the load following targets for ARC-100 plant from 100% to 0% grid outputs at 5%/min rate. Inventory control emerges as the preferred option due to the highest efficiency at partial loads.

For ARC-100 reactor and with inventory control on the sCO_2 cycle side, the load following goals can be met with both active and no-control approaches on the reactor side. Due to strong reactivity feedbacks of the ARC-100 core, power self-regulation is sufficient to preclude increase in the hottest reactor temperatures. Still, the reactor cold-leg temperatures need to increase significantly to trigger the reactivity effects. This increase in cold leg temperatures can be eliminated with the active reactor control, assisted by the recuperator bypass control, such that the load following can be realized with almost fixed temperatures (at least on the reactor side). That benefit, however, comes at the expense of somewhat lower cycle efficiency at partial loads (mostly dictated by the recuperator bypass action).

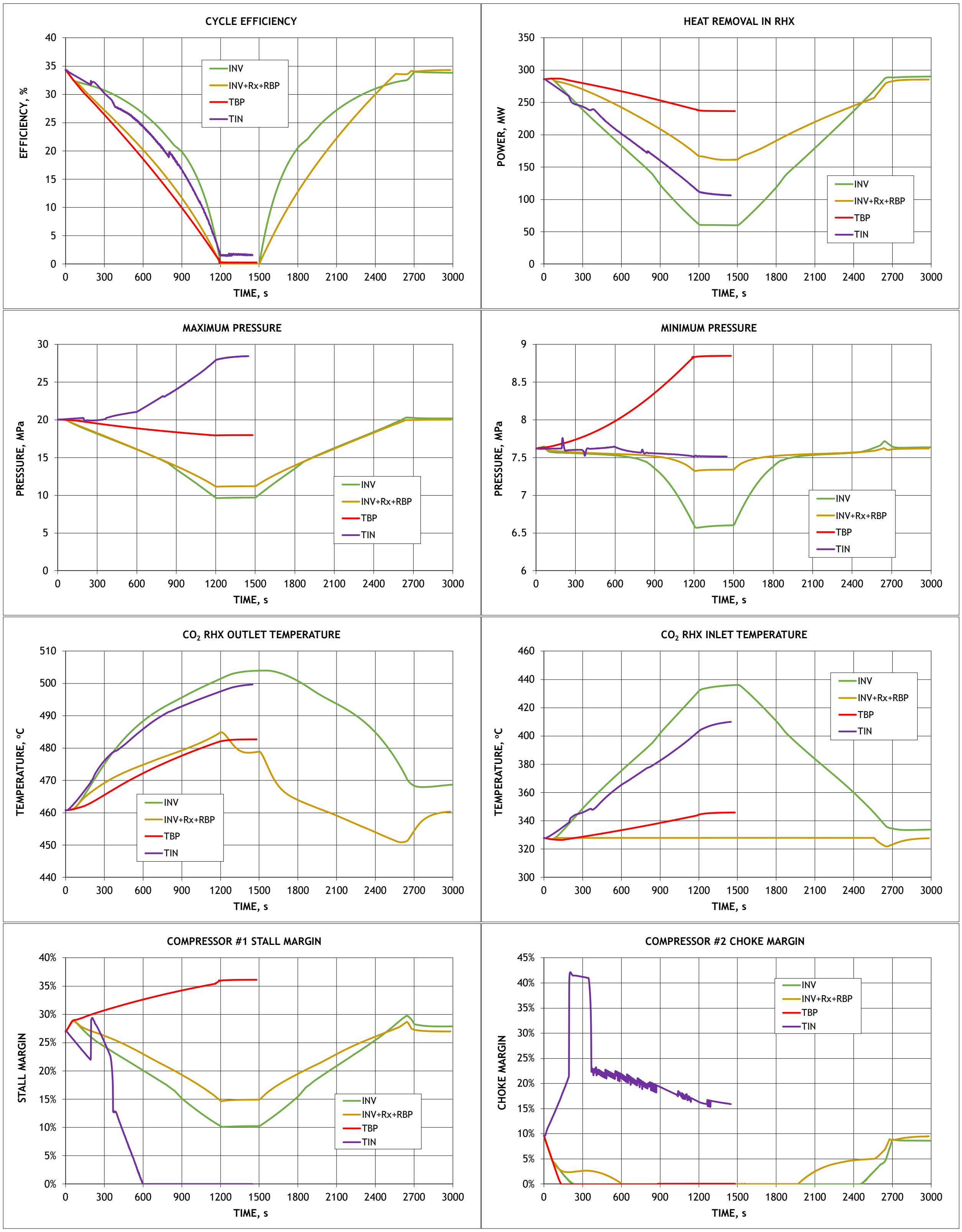

Figure 3. Transient Results of Load Following Analysis

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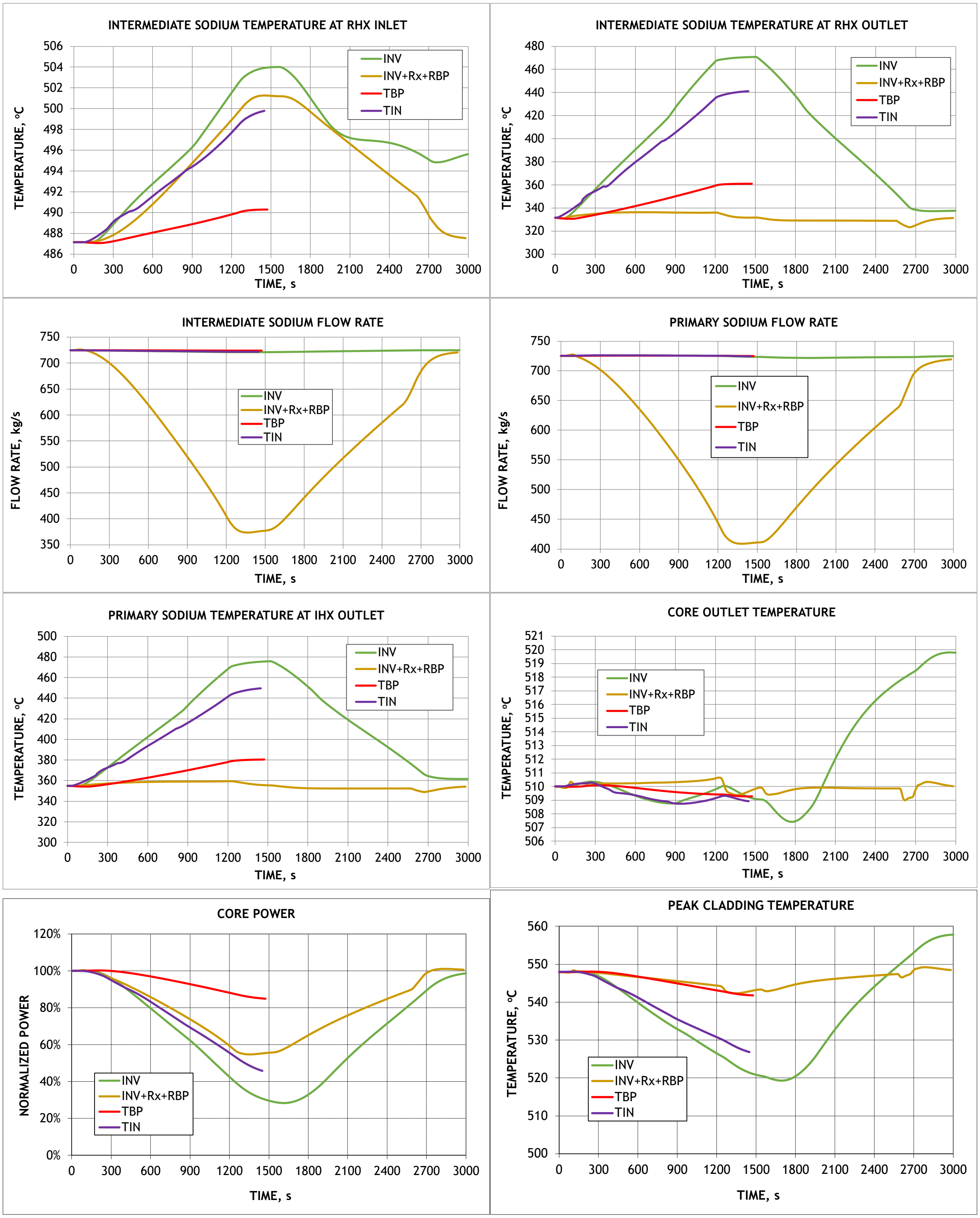

Figure 3. Transient Results of Load Following Analysis (continued)

SHUTDOWN AND STARTUP SIMULATION

The ARC-100 Plant Simulator was also used to calculate the normal (i.e., not emergency) plant shutdown sequence. The goals of this analysis were to find the control action to bring the plant to “hot standby” conditions. The hot standby conditions for sodium cooled reactors like ARC-100 are defined as those at very small power and temperatures around nominal core-inlet temperature (355 °C) to maintain the primary and intermediate sodium coolant in molten state. Nominally, the hot standby will be followed by transition to cold standby, where sodium temperatures are decreased even further to be even closer to sodium freezing temperature. However, once hot standby conditions are reached and the reactor power is reduced to (almost) zero, the reactor might not need to rely on the sCO_2 cycle for heat removal and the cycle could be disconnected from the reactor. At that point, the ARC-100 Plant Simulator model developed here for coupled reactor and sCO_2 sides is no longer applicable and thus could not be used for that simulation.

It is noted also that the discussion above is also applicable to the plant startup sequence, which would be in reverse of the shutdown process. Again, anything prior to reaching the hot standby conditions might not be used for simulation with the model developed in this work. For these reasons, only transients down to hot standby (for shutdown) are simulated in this work. Also, the analysis presented here is done for the planned plant shutdown, with the assumption that the plant startup sequence from hot standby will be just a reverse of the shutdown transient. To make this assumption valid, during the shutdown simulations only gradual and reversable control actions are considered. For example, any “trip” actions, such as reactor scram, are not included in the present simulation.

The shutdown transient discussed in this paper is initiated from the end point of load following down to 0% discussed in previous section. For this, the inventory control option with the active reactor control is selected because it provides reasonable plant efficiency at partial loads while precluding significant changes on the reactor temperatures. Figure 4 shows the sCO_2 cycle conditions by the end of load following transient at 1200 s when net generator output is reduced to zero. Note that at this point the heat transfer rate at RHX (and the reactor power) is 167 MW, which is approximately 58% nominal.

Starting from the conditions in Figure 4, the normal shutdown transient is simulated in several stages defined in Table 2, in addition to first stage of load following as described in the previous section. Once zero net generator output is reached, the plant can be disconnected from the grid. From the modeling perspective, this means that the generator frequency, and turbomachinery shaft speed, is no longer fixed by the grid and thus can be changed as needed.

The next stage in the plant shutdown is reduction in reactor power. This is achieved in the simulation by reducing the target core-outlet temperature to just a few degrees above the core inlet temperature. This would force the SAS4A/SASSYS-1/PDC codes to bring the reactor power down. For the entire duration of shutdown transient, the primary and intermediate sodium flow rates are fixed at values achieved by the end of the load following stage, which is about 60% nominal. Keeping the same flow rates ensures a simple relationship between target core power and target ΔT in the core. The reactor power reduction is accompanied by the sCO_2 turbomachinery shaft slow down, to keep the balance between heat production in the reactor and heat removal by the cycle. It was found that speed reduction to 55% approximately maintains heat balance in RHX.

After the reactor power is reduced to a low value, the plant shutdown continues on the sCO_2

cycle side (Stage 3 in Table 2). This is achieved by further reduction in turbomachinery shaft speed to 15%. At this stage, no additional control input is introduced on the reactor side.

For all shutdown simulations considered in this work and listed in Table 2, the time scales were somewhat arbitrarily selected to implement the specified control action and provide sufficient times for the system to gradually respond to these actions. The entire simulation is 10,000 s (~3 hours) with second and third stages being 2,000 s (~0.5 hr) and 4,000 s (~1 hr), respectively. Again, no structural considerations are included in the current work. Also, the control actions are implemented in a rather simplistic linear fashion. It might be possible to achieve better system response by more complex control action at each stage; however such optimization is deferred to future work.

Aside from controls described in Table 2, all other sCO_2 cycle controls are implemented as following. Inventory control action is terminated once the 0% plant output level is reached, and the inventory system remains isolated from the cycle for the remainder of the transient. Turbine (or compressor) throttling controls are not activated at all in this transient. Turbine bypass control remains active to maintain plant output. In this case, this means keeping net plant output at 0% for as long as possible. However, it is expected that at some point turbine power may not be sufficient to drive the compressors and thus external power would be needed. At that point, the turbine bypass valve would fully close and will remain closed for the remainder of the transient. The main compressor inlet temperature is still maintained at 32 °C by a combination of water flow rate and cooler bypass controls.

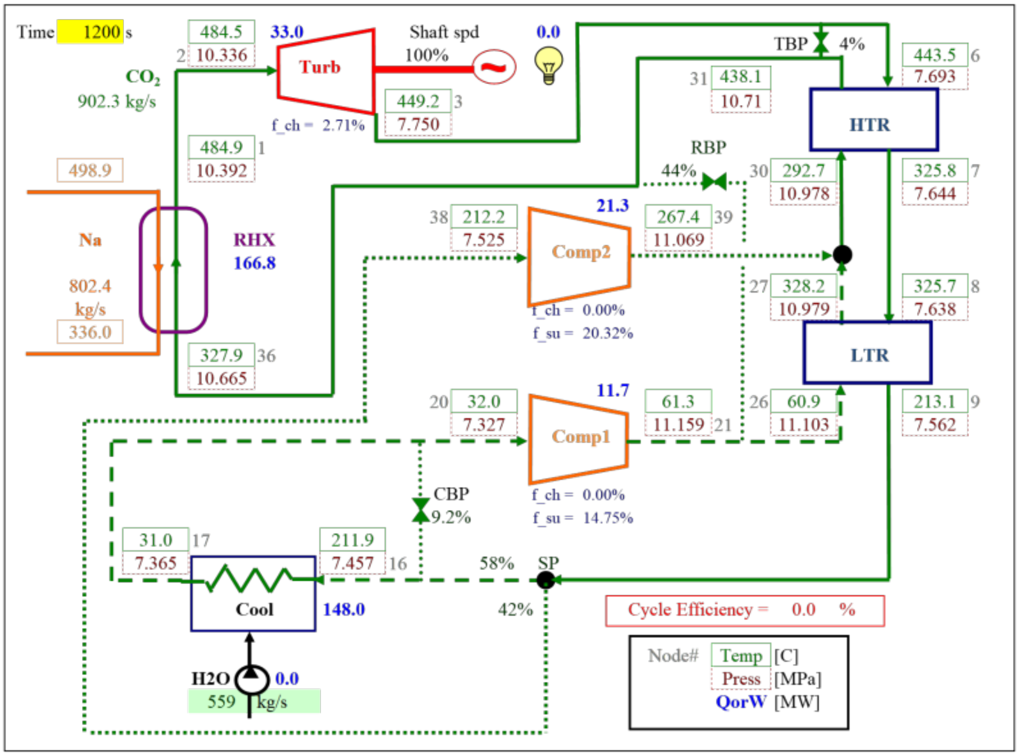

Figure 4. ARC-100 sCO_2 Brayton Cycle Conditions at the End of Load Following Stage

Table 2. Simulated ARC-100 Shutdown Phases

Time, s	Stage	Grid Connection	Cycle Control	Reactor Control
0-1,200	1. Load Following to 0%	Synchronous (6000 rpm)	Inventory + RBP	Tcold_IHTS=331.5 °C Tcold_pri =355 °C Tcore_out =510 °C
1,500	Grid disconnection			
1,500-3,500	2. Reactor shutdown	Asynchronous	Shaft speed to 55%	Tcore_out to 360 °C Fixed IHTS and primary flows (pump torques)
3,500-7,500	3. Brayton cycle shutdown	Asynchronous	Shaft speed to 15%	Maintain same
7,500-10,000	System stabilization		No action	No action

The results of ARC-100 plant shutdown simulation are shown in Figure 5, which includes all transient stages identified in Table 2. Figure 5 also shows the results for load following during first 1,200 s, but those are described in the previous section and thus are not discussed here.

At the second stage (between 1,500 and 3,500 s), the reactor power and reactor hot side (core-outlet) temperatures are reduced. This action eventually propagates to the sCO_2 cycle where all temperatures start to reduce as well. In order to maintain heat balance in the RHX, the sCO_2 cycle turbomachinery speed is reduced, leading to reduction in sCO_2 flow rates throughout the cycle. The rate of shaft speed reduction, from 100% to 55% over 2,000 s, was selected to maintain reactor cold leg temperatures as close to a constant level as possible, which is demonstrated by the red line in the RHX temperature plots, as well as by the core-inlet temperature. Once the shaft speed reduction starts, the turbine power starts to decrease and thus the turbine bypass valve starts closing. The results in Figure 5 show that at 3,200 s the valve is fully closed, and the neutral power balance could not be maintained anymore. For this point on, the net plant output (W_2_grid) becomes negative, meaning that external power would be needed to drive the compressors.

Starting from 3,500 s, the reactor power reduction is completed, but the sCO_2 cycle shutdown continues with further decrease in the shaft speed. The results in Figure 5 demonstrate that when the shaft speed is reduced to 15%, both the RHX and reactor power reach ~3% level. This is the lowest power level achieved in this simulation, and roughly corresponds to the reactor decay heat level at this time and also emergency shutdown heat removal system capacity of ARC-100 reactor (these systems have not been activated in this work). With continuing decrease in the shaft speed, the CO_2 cycle flow rates continue to decrease as well, leading to reduction in turbomachinery power levels. The results in Figure 5 show that at 4,000 s, the turbine power reduced to zero and continue to decrease into negative values, meaning that turbine starts to operate as a compressor. The main reason for this is that the compressor's pressure ratio is smaller than cycle pressure drops, such that turbine experiences pressure ratios smaller than unity. Note that as the shutdown transient progresses, the turbomachinery components operate further and further from their design points, effectively in all variables, -speed, pressures, and inlet temperatures (only main compressor inlet temperature is maintained). As a result, the maximum power input to the compressors is calculated to reach 10 MW_e but stabilizes around 5 MW_e by the end of the transient.

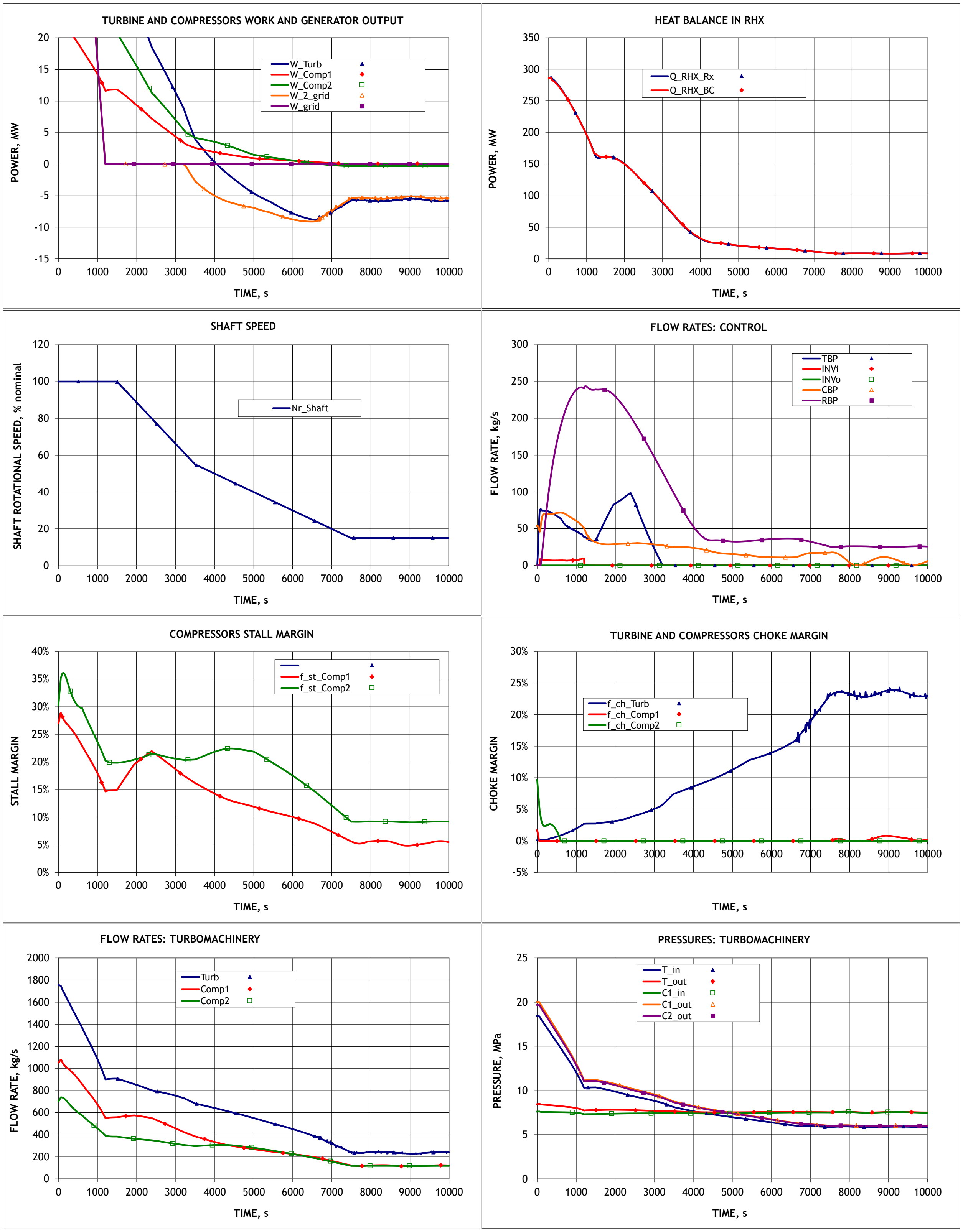

Figure 5. Transient Results of Plant Shutdown Simulation

(continues on next page)

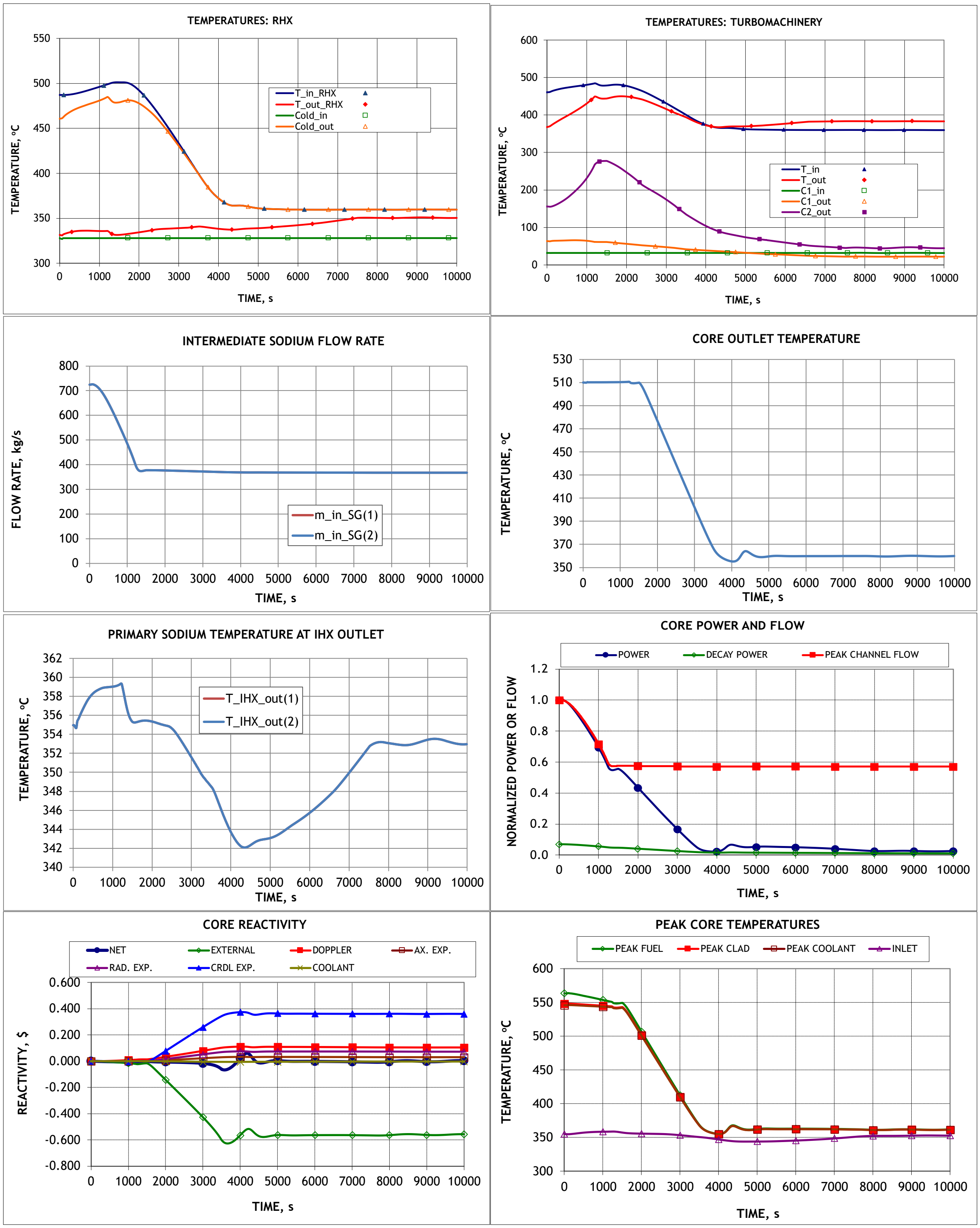

Figure 5. Transient Results of Plant Shutdown Simulation (Continued)

At the last stage, between 7,500 and 10,000 s, no control action is introduced, and the system stabilizes effectively at hot shutdown state. The reactor power and HX heat duties are very small, and the entire plant operates close to core temperatures of 350 °C or below. The slowly rotating turbine and compressor provide some, but small, flow rates in the system and very small pressure ratios. These conditions satisfy the target state for the plant shutdown simulation. Again, as the control action were introduced in a gradual fashion, it is expected that plant startup would follow the same transient progression, but in reverse order.

SUMMARY

In this work, ARC-100 Plant Simulator was created using coupled SAS4A/SASSYS-1 and PDC codes to simulate transient behavior of the ARC-100 sodium-cooled fast reactor with sCO_2 power conversion cycle. The Plant Simulator was used to calculate plant behavior for normal operation transients, including load following and normal shutdown and startup.

For load following analysis, a change in electrical grid demand from 100% to 0% and back to 100% at 5%/min rate was imposed and several options for the sCO_2 cycle and reactor control were analyzed and compared. For all control options, the load matching with the net generator output was demonstrated. The inventory control shows the best performance (cycle efficiency) at partial loads. At the same time, the range of the inventory control could be limited by the storage tank size. Both the turbine bypass and turbine throttling controls do not require additional equipment beyond the valves and, for bypass, connection lines. However, turbine bypass control resulted in the lowest cycle efficiency at partial loads. The identified issues with load following by the turbine throttling action include increase in the high side pressure, as well as operation of one or both compressors in stall/surge conditions.

The load following with the inventory control was also simulated with two reactor control options. Under full reactor control, the core power and primary and intermediate sodium flow rates are actively controlled. With active reactor-side controls, very small variations in the reactor temperature were calculated. However, in order to achieve this result, recuperator bypass control was needed on the sCO_2 cycle side, which resulted in a significant decrease in cycle efficiency. The no-control reactor operation mode relies on the ARC-100 core inherent reactivity feedbacks for power regulation. The transient results show that these feedbacks are strong enough to maintain the hot leg (highest) temperatures in the reactor. At the same time, activation of the reactivity feedbacks requires a significant increase in the cold-leg temperatures at partial loads, including the reactor vessel temperature.

For all load following transients, the limiting operating range of the two sCO_2 compressors has been identified as a possible issue. In all simulations, either one or both compressors were calculated to operate at the choke limit. In the case of turbine throttling control, a stall/surge limit was encountered. The turbine also operates very close to the choke limit in all transients, as well as at the design conditions. Additional work is recommended to explore increasing the operating range of turbine and compressors.

The nominal (i.e., not emergency) ARC-100 plant shutdown sequence was simulated in several stages. Starting from 0% plant output achieved by load following, the plant is disconnected from the grid. Next, the reactor power and hot-side temperatures are reduced, accompanied by gradual reduction in the sCO_2 turbomachinery shaft speed to maintain heat balance between the reactor and CO_2 cycle. Then, the plant shutdown continues, driven by further reduction in sCO_2 turbomachinery shaft speed and flows. It is calculated that at 15% shaft speed, the target hot shutdown conditions are achieved with low power levels and temperatures around nominal core-inlet temperatures. During the sCO_2 cycle shutdown, the turbine work continues to decrease and at some point it does not provide sufficient power to drive the compressors. From that point on, external power would be needed for the sCO_2 cycle, which is calculated to be in the 5-10 MW_e range. The plant shutdown simulation was implemented in a gradual fashion, such that it is expected that plant startup sequence would be very similar, but in reverse order.

For future work, the Plant Simulator modeling can also be extended to transients not considered in this work, such as accident and emergency conditions.

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