ANL-GenIV-147

Investigation of Plant Control Strategies for the Supercritical CO_2 Brayton Cycle for a Sodium-Cooled Fast Reactor using the Plant Dynamics Code

Nuclear Engineering Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne, see www.anl.gov.

Availability of This Report
This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

Disclaimer
This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

ANL-GenIV-147

Investigation of Plant Control Strategies for the Supercritical CO_2 Brayton Cycle for a Sodium-Cooled Fast Reactor using the Plant Dynamics Code

by
A. Moisseytsev and J. J. Sienicki
Nuclear Engineering Division, Argonne National Laboratory

September 9, 2010

TABLE OF CONTENTS

Abstract 3
1. Introduction 4
2. Re-Optimization of the Control System for S-CO_2 Cycle for SFR 7
2.1. Minimum Cycle Temperature Control 8
2.2. Compressor Flow Split Control 11
2.3. Inventory Control 13
3. Plant Control Options 14
3.1. Option 1: Constant Intermediate Sodium Flow Rate and RHX-Inlet Temperature 14
3.2. Option 2: Autonomous Reactor Operation 19
3.3. Option 3: Linear Reactor Power and Flow Control 25
3.4. Comparison of the Control Options 32
4. Summary and Conclusions 34
Acknowledgements 37
References 38
Appendix A. Input Files for Dynamic Calculations with the Plant Dynamics Code 39

LIST OF TABLES

Table 1. Compressor-Inlet and Cooler Outlet Conditions for SSTAR and ABR-1000 7

LIST OF FIGURES

Figure 1. Steady-State Conditions for ABR-1000 S-CO_2 Cycle. 6
Figure 2. Water Flow Rate Control Parameter Optimization. 9
Figure 3. Water Flow Rate Control Parameter Optimization, Step 2. 10
Figure 4. Improved Stability with Flow Split Control. 12
Figure 5. Transient Results for Option 1. 15
Figure 6. Transient Results for Option 2. 20
Figure 7. Transient Results for Option 3. 27
Figure 8. Comparison of the Control Options. 33

Abstract

The development of a control strategy for the supercritical CO_2 (S-CO_2) Brayton cycle has been extended to the investigation of alternate control strategies for a Sodium-Cooled Fast Reactor (SFR) nuclear power plant incorporating a S-CO_2 Brayton cycle power converter. The SFR assumed is the 400 MWe (1000 MWt) ABR-1000 preconceptual design incorporating metallic fuel. Three alternative idealized schemes for controlling the reactor side of the plant in combination with the existing automatic control strategy for the S-CO_2 Brayton cycle are explored using the ANL Plant Dynamics Code together with the SAS4A/SASSYS-1 Liquid Metal Reactor (LMR) Analysis Code System coupled together using the iterative coupling formulation previously developed and implemented into the Plant Dynamics Code. The first option assumes that the reactor side can be ideally controlled through movement of control rods and changing the speeds of both the primary and intermediate coolant system sodium pumps such that the intermediate sodium flow rate and inlet temperature to the sodium-to-CO_2 heat exchanger (RHX) remain unvarying while the intermediate sodium outlet temperature changes as the load demand from the electric grid changes and the S-CO_2 cycle conditions adjust according to the S-CO_2 cycle control strategy. For this option, the reactor plant follows an assumed change in load demand from 100 to 0 % nominal at 5 % reduction per minute in a suitable fashion. The second option allows the reactor core power and primary and intermediate coolant system sodium pump flow rates to change autonomously in response to the strong reactivity feedbacks of the metallic fueled core and assumed constant pump torques representing unchanging output from the pump electric motors. The plant behavior to the assumed load demand reduction is surprising close to that calculated for the first option. The only negative result observed is a slight increase in the intermediate inlet sodium temperatures by about 10 °C. This temperature rise could presumably be precluded or significantly reduced through fine adjustment of the control rods and pump motors. The third option assumes that the reactor core power and primary and intermediate system flow rates are ideally reduced linearly in a programmed fashion that instantaneously matches the prescribed load demand. The calculated behavior of this idealized case reveals a number of difficulties because the control strategy for the S-CO_2 cycle overcools the reactor potentially resulting in the calculation of sodium bulk freezing and the onset of sodium boiling. The results show that autonomous SFR operation may be viable for the particular assumed load change transient and deserves further investigation for other transients and postulated accidents.

1. Introduction

The Plant Dynamics Code (PDC) [1] for the analysis of supercritical carbon dioxide (S-CO_2) Brayton cycle power converters has been under development at Argonne National Laboratory for several years. The Plant Dynamics Code has been used previously for control and transient analysis of the S-CO_2 cycle coupled to Lead-Cooled Fast Reactors (LFRs), such as SSTAR and STAR-LM [1-4]. Last year, modifications to the Plant Dynamics Code were made to allow application of the code to any reactor type [5]. This year, the code was used to investigate the control strategies and transient behavior of the S-CO_2 cycle coupled to a Sodium-Cooled Fast Reactor (SFR). An emphasis was made on the differences between the various reactor types and how those differences affect the cycle control.

As an example of an SFR system, the ABR-1000 reactor preconceptual design [6] was selected for the current analysis. The advantages of ABR-1000 system selection include the available S-CO_2 cycle model in the PDC code as well as the reactor dynamic model incorporated in the SAS4A/SASSYS-1 code [5] for which an input file has been developed for the ABR-1000. The ABR-1000 reactor preconceptual design incorporates many common features of a typical SFR including the two-loop configuration with an intermediate sodium loop as a mean of coupling the reactor to the balance-of-plant (BOP), forced circulation in both the primary and intermediate loops, and active reactor power control through the movement of the control rods. These three features present the most significant differences between the ABR-1000 reactor and the STAR LFRs analyzed previously in terms of the reactor control options. The STAR reactors dispense with an intermediate loop, work under natural circulation for the reactor coolant loop, and were designed for autonomous (i.e., no active reactor control) operation. Therefore, the goals of the current work were formulated to investigate the effect of the reactor side configuration and its control options on the S-CO_2 cycle behavior. In particular, the effects of active reactor power and coolant flow rate controls on the S-CO_2 cycle behavior under load following were investigated. The external variable for the transient was the grid load (demand) reduction from 100 % to 0 % at 5 %/min rate. The transients were run for 1,600 seconds of which 1,200 seconds were for the actual load reduction and 400 seconds – for the continuous operation at zero generator power. The following reactor side control options were considered in this work and were analyzed from the cycle behavior and control point of view:

1) ***Constant intermediate sodium flow rate and its inlet temperature at the Na-CO_2 reactor heat exchanger (RHX).*** Since the intermediate sodium temperature at RHX *outlet* would be varying according to the heat removal capability of the S-CO_2 cycle, this option is an equivalent to assuming an idealized active reactor control to maintain coolant temperatures and fixed coolant flow rates. The advantage of this option is that the transient can be modeled by the Plant Dynamics Code alone since no knowledge of the reactor response is necessary for the assumed idealized control.

2) ***Autonomous reactor operation.*** Under this option, it was assumed that the reactor power changes only in response to the change in the heat removal conditions on the S-CO_2 cycle by means of the internal reactivity feedbacks. The sodium pump torque in both the primary and intermediate loops is kept constant. Since no active control action is modeled for the reactor power and coolant pumps, this option is also referred to as "no reactor control" option in this report. This option would be the closest equivalent of the reactor control assumed in previous work for the S-CO_2 cycle for LFR.

3) ***Direct reactor power and flow rate control.*** Under this option, an active control of the reactor power and flow rate (through the primary and intermediate sodium pump torque) was simulated. It was assumed that both the reactor power and pump torques vary linearly at the same rate as the grid demand. Theoretically, this approach would provide constant temperatures in both primary and intermediate loops, as well as operating the S-CO_2 cycle at fixed efficiency.

These reactor side control options are also referred to as Options 1 through 3 in this report.

The goals of this work are investigation of the effect of various reactor control options, described above, on the S-CO_2 cycle behavior. Also, the effect of the S-CO_2 cycle performance at reduced loads on the reactor behavior and control are investigated. To better compare the results for the three options, an approach of minimal variation in the input parameters between the options was adopted. In particular, this precludes independent cycle control optimization for each option. The cycle control variation was limited only to necessary changes in order to generate and compare the results.

To investigate the transient behavior of the coupled reactor and S-CO_2 cycle system, an approach of simultaneous runs of the Plant Dynamics code (for the S-CO_2 cycle) and SAS4A/SASSYS-1 (for the reactor part) that was developed under this Project during FY 2009 is utilized [5]. When necessary, iterations on the parameters which provide the coupling of the two systems - intermediate sodium flow rate and its RHX inlet/outlet temperatures - are carried out.

In addition to the differences between the LFR and SFR systems described above, two more major differences are taken into account during the work described in this report. First, the temperatures for the SFR system are somewhat lower than those for the LFR resulting in lower S-CO_2 cycle design efficiency (40 % for the ABR-1000 compared to 44 % for SSTAR). Also, the size of the system, 1000 MWt (400 MWe) for ABR-1000 versus 45 MWt (20 MWe), would have an effect on the S-CO_2 cycle turbomachinery design and performance. (The S-CO_2 cycle heat exchangers are assumed to be of modular design such that their performance is not expected to be affected much by the size of the system.) As a result of these modifications, it was found necessary to re-optimize the S-CO_2 cycle control parameters, especially near the critical point. That re-optimization is described in the next chapter before the results of the control analysis are presented. Also, the differences between the SFR and LFR required re-generation of the turbomachinery

performance maps for the transient analysis of S-CO_2 cycle. In the current work, it is assumed that the ABR-1000 would operate synchronously with the grid such that only synchronous (i.e., fixed rotational speed) turbomachinery maps were generated and used for the analysis of the ABR-1000 S-CO_2 cycle.

The steady-state conditions of the ABR-1000 S-CO_2 cycle are shown in Figure 1. The conditions in Figure 1 define the starting point of the transient analysis. On the reactor side (not shown in Figure 1), the core inlet and outlet temperatures are 355 °C and 510 °C, respectively. The core power is the same as the RHX power (1000 MWt). The primary sodium flow rate is close to that of the intermediate sodium which is shown in Figure 1 on the Na side of the RHX.

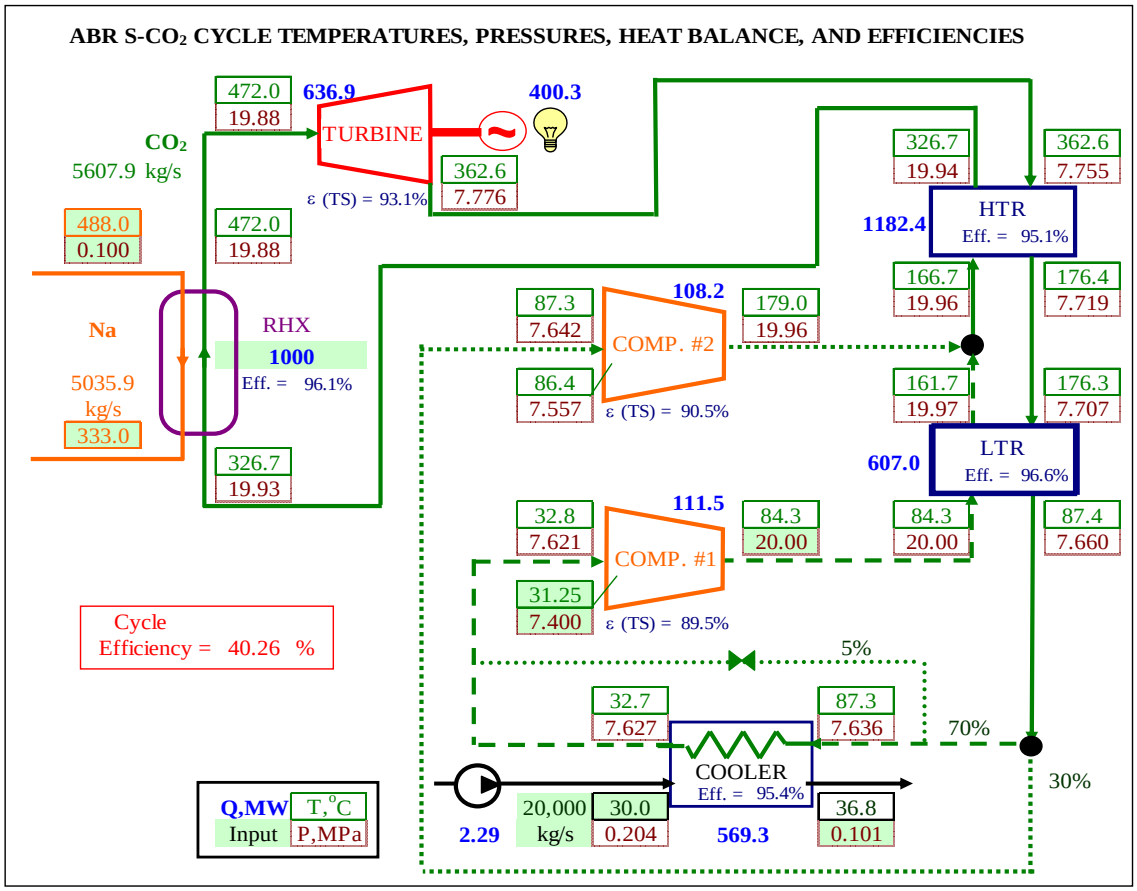


Figure 1. Steady-State Conditions for ABR-1000 S-CO_2 Cycle.

2. Re-Optimization of the Control System for S-CO_2 Cycle for SFR

The S-CO_2 cycle control system parameters, such as proportional, integral, and differential (PID) control coefficients, were selected in previous work to provide an optimal system response in transients. During this work however, it was discovered that significant changes to the system, described in the Introduction, warranted re-optimization of at least some control parameters. In particular, the size of the main compressor affected its design such that the flow speeds at the first stage inlet were different for SSTAR and ABR-1000. As a result, even with the same first stage inlet conditions (fixed in both cases just above the critical point), the compressor-inlet conditions were slightly different for these designs as demonstrated in Table 1. Also, the cooler-outlet conditions are slightly different for these two systems. Even though the difference in cooler-outlet and compressor-inlet temperatures for SSTAR and ABR-1000 is only about 1 °C, close to the critical point that difference is expected to provide significant variation in properties which is expected to reflect on the transient behavior of these two components.

Table 1. Compressor-Inlet and Cooler Outlet Conditions for SSTAR and ABR-1000

Component	Parameter	SSTAR	ABR-1000
Compressor #1	Type	Centrifugal	Centrifugal
	Power, MW	4.71	111.46
	Rotational speed, rev/s	180	30
	First stage inlet temperature, °C	31.25	
	First stage inlet pressure, MPa	7.400	
	Outlet pressure, MPa	20.00	
	Outlet temperature, °C	84.5	84.3
	Inlet temperature, °C	**33.85**	**32.79**
	Inlet pressure, MPa	**7.775**	**7.621**
	Efficiency (T-S), %	87.4	89.5
Cooler	**Outlet pressure, MPa**	**7.778**	**1.627**
	Outlet temperature, °C	**33.6**	**32.7**

As a result of the different conditions near the critical point, changes to the minimum cycle temperature control and flow split control were introduced for the new S-CO_2 cycle. In addition, changes to the inventory control were necessary to account for the changing inventory of the S-CO_2 cycle. These modifications to the S-CO_2 cycle control are described below. The cycle control was re-optimized using Option 1 for the reactor control (constant flow rate and inlet temperature for the intermediate coolant).

2.1. *Minimum Cycle Temperature Control*

Due to the differences in the cooler-outlet conditions, the application of the minimum temperature control with the parameters optimized for the SSTAR S-CO_2 cycle to the ABR-1000 resulted in an oscillating behavior of the minimum cycle temperatures. To eliminate the oscillations, the minimum cycle temperature control, consisting of the cooler bypass and cooling water flow rate controls, was re-optimized for the new system. The optimization was carried out based on the system response to a 10 % step change in grid load.

Figure 2 shows how the variation of the proportional (P), differential (D), and integral (I) control parameters affect the system response to the 10 % load change transient in terms of minimum cycle temperature. The last plot in Figure 2, P/D/I = 0/1/0, shows very fast and effective response. However, further analysis of the parameters not shown in Figure 2, such as cooler bypass flow fraction, suggested that additional improvements are still needed.

Figure 3 demonstrates the system response to the same transient with further improvement of the control coefficients. In this case, the cooler bypass valve open fraction, which is proportional to the bypass flow fraction, is shown together with the minimum cycle temperature. (In case of the last set of parameters in Figure 2, P/D/I = 0/1/0, the flow fraction does not return to the steady state value.) Based on the results in Figure 3, the water flow rate control parameters of P/D/I = 1/10/0 are selected as optimal for further analysis.

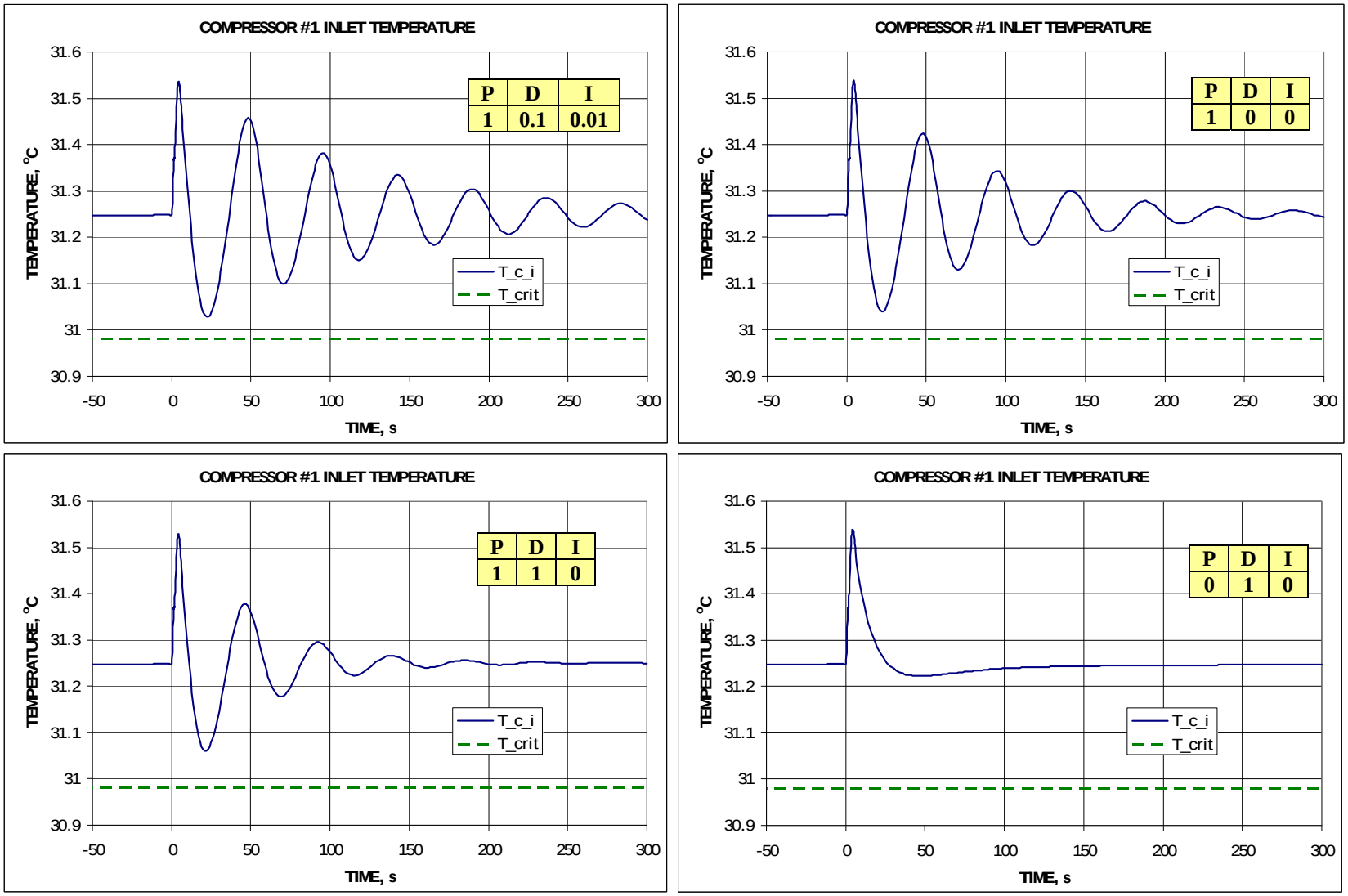


Figure 2. Water Flow Rate Control Parameter Optimization.

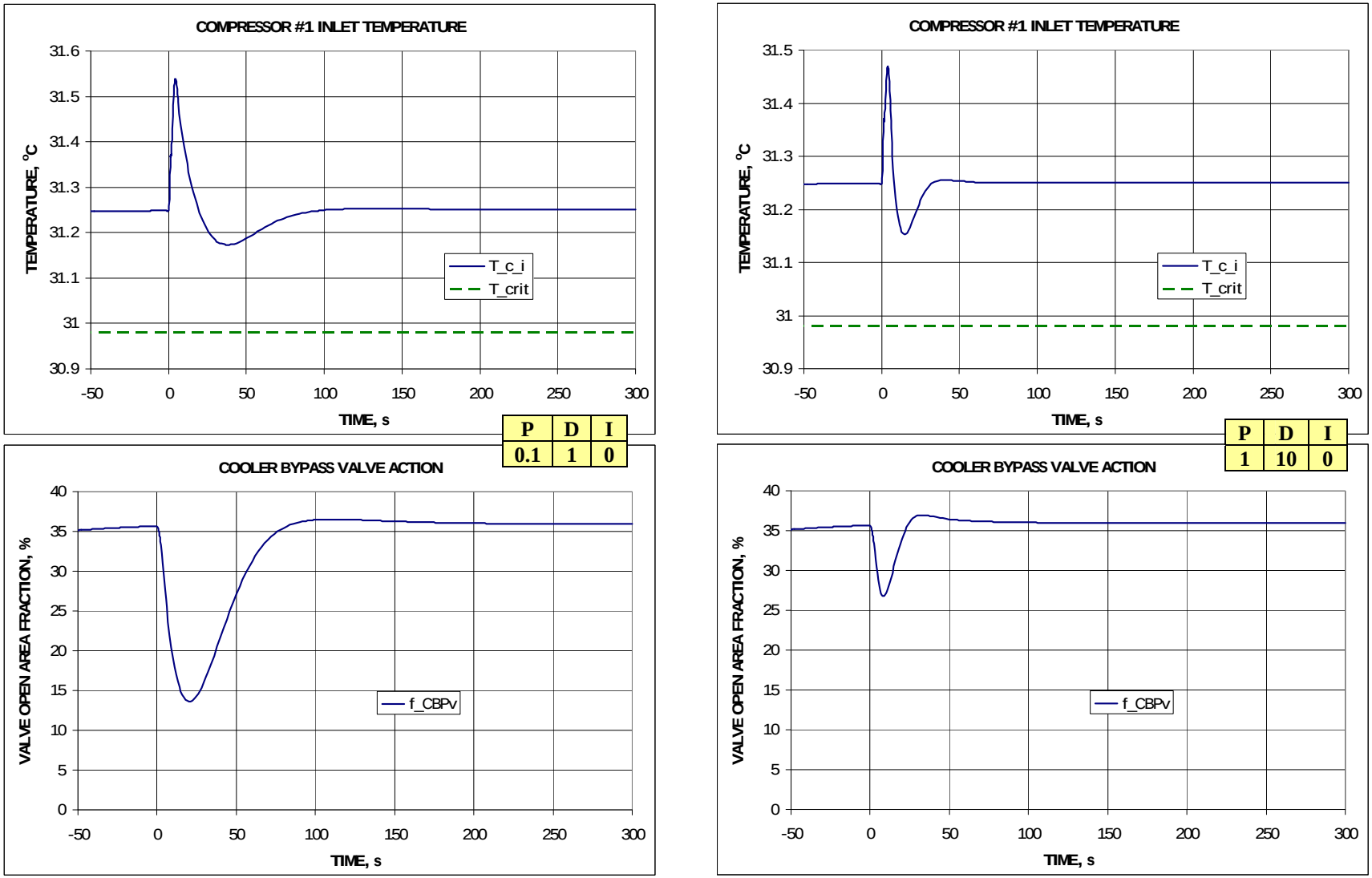


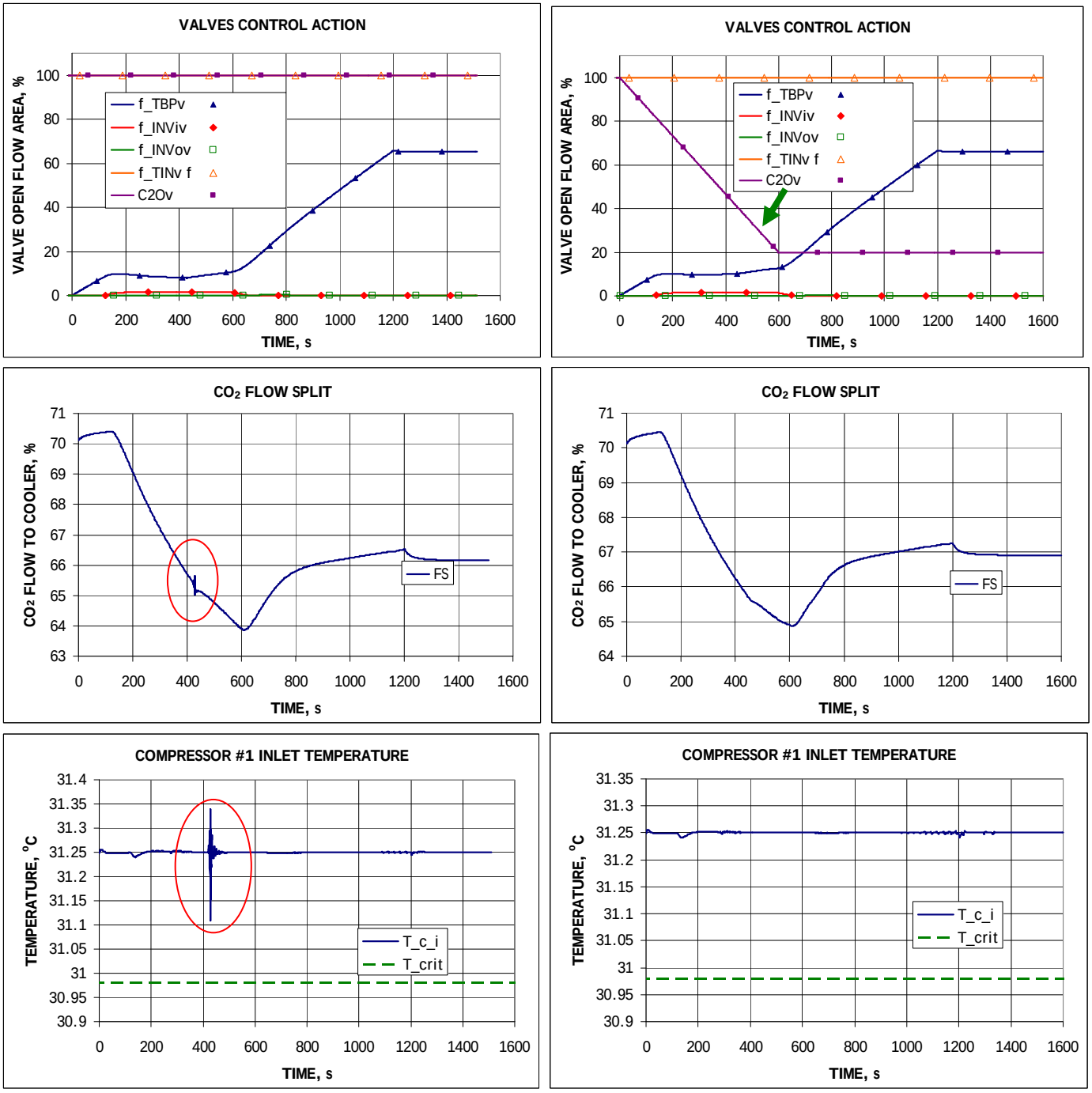
Figure 3. Water Flow Rate Control Parameter Optimization, Step 2.

2.2. *Compressor Flow Split Control*

Previous control strategy for the S-CO_2 cycle (for the LFR) implemented no control on the flow split between the two compressors. The flow split was allowed to vary according to the relative performance of the compressors (i.e., pressure-flow characteristics) at reduced loads. That strategy resulted in some oscillations observed in previous work [7] at certain compressor inlet/outlet conditions. Similar oscillations are observed for the ABR-1000 S-CO_2 cycle control analysis carried out for this work.

To eliminate (or reduce) the oscillations, a strategy is selected to avoid the compressor conditions causing oscillations during the transients. One of the possible ways to control the compressor conditions is to alter the conditions by means of the changing flow rates through each compressor, i.e., by changing the flow split between the compressors. Limited flow split control is now implemented for the cycle analysis by manually setting the compressor #2 throttling valve to some value (20 % open) at reduced loads. That control addition is shown to be effective in eliminating the oscillations. Figure 4 demonstrates that the addition of the Compressor #2 outlet valve (C2Ov) action eliminates the oscillations (just after 400 s). At the same time, the effect of such a control action is small enough such that the control results are not affected significantly by this action. Figure 4 shows that the flow split is not affected significantly by the selected valve action and follows the same shape throughout the transient. The results in Figure 4 (as well as other results not shown in Figure 4) demonstrate that this control action is introduced just to avoid unfavorable compressor conditions; it is not intended to actively control the flow split (even though it is still called flow split control).

In the simulations presented below in this report, the flow split control is set by manual closing of the C2Ov valve to 20 % open in 600 s. That manual control could easily be converted into an automatic mode by relating the valve open area to the grid demand (both the grid load and the valve closing are linear in the following simulations). Because an introduction of the automatic control would require code modification and because of the relatively small effect of this control action on the overall system behavior, it is judged that manual operation of the C2Ov is sufficient for the purposes of this work. Again, relating the valve position to the load demand should be straight forward and could be done in the future, if necessary.



a) No Flow Split Control Action

b) Flow Split Control Action

Figure 4. Improved Stability with Flow Split Control.

2.3. *Inventory Control*

The inventory control is programmed in the Plant Dynamics Code as a table of the CO_2 mass removal from the cycle (in kg) versus the grid load. For the SSTAR S-CO_2 cycle, that table was obtained during the quasi-static control analysis. However, no such analysis was carried out for the ABR-1000. Since the effect of the CO_2 mass removal is proportional to the total CO_2 inventory in the cycle and, therefore, to the power, the inventory control table had to be modified for the ABR-1000. With the lack of detailed quasi-static calculations for inventory control, a simplified control table is adopted for the ABR-1000 where a fixed CO_2 mass is removed from the cycle for every 10 % load change. The amount of the CO_2 mass removal is found based on the condition of keeping the turbine bypass flow approximately constant in the range of the inventory control. That simplified approach is found to be satisfactory for the S-CO_2 cycle control results for the ABR-1000, as demonstrated by the results in the next section.

The range of the inventory control in previous analysis was primarily defined by the available inventory control tank volume. It was shown for SSTAR that an inventory tank with a volume about equal to the total volume of high temperature recuperator (HTR) provides the inventory range from 90 % load to about 40 % load. For the ABR-1000, the total HTR volume is about 80 m^3 (not including headers). Further calculations, presented below in this report, show, however, that the inventory tank volume should be greater than that. It is estimated that the tank volume should be about 120 m^3 (or about 1.5 times the HTR volume) in order to provide the range for the inventory control of 90 % to 50 % load. That range is judged to be adequate for this study, so the inventory volume is assumed to be 120 m^3 (or greater) with the inventory control table defined in the range of 50 % - 90 % load.

With the exceptions described above, no other modifications to the control mechanisms and strategy for the S-CO_2 cycle are implemented in this work. The complete list of the control parameters is provided in Appendix A, along with the rest of the input data for the Plant Dynamics Code.

3. Plant Control Options

The results of the control analysis for the S-CO_2 cycle and the reactor (where applicable) parts of the ABR-1000 system are presented below for each of the three alternative control options (see Introduction).

3.1. *Option 1: Constant Intermediate Sodium Flow Rate and RHX-Inlet Temperature*

The results of the transient S-CO_2 cycle control simulation with fixed intermediate sodium conditions at the RHX inlet (Option 1) are shown in Figure 5. The S-CO_2 cycle automatic control is able to follow the load very closely (W_gen and W_grid curves on the first plot overlap during the entire transient). The heat removal rate in the RHX and, therefore, the cycle efficiency, are related to the acting control mechanism. For turbine bypass control (above 90 % and below 50 % load), the cycle efficiency drops linearly with the load and the heat removal from RHX stays approximately constant. For inventory control, the cycle efficiency is more or less maintained at the same level such that the heat removal from the RHX closely follows the grid load.

The S-CO_2 cycle low pressure falls below the critical value when inventory is removed from the cycle. It increases back to almost the critical value when turbine bypass control operates below 50 % load. The high CO_2 pressure decreases first with inventory control and later from the cooling down of the cycle temperatures. After about 500 s, the Compressor #2 outlet pressure increases above that of Compressor #1, due to the C2Ov throttling action, such that it becomes the highest pressure of the system (but still stays significantly below the maximum cycle pressure at steady state conditions).

The compressor flow rates decrease with inventory control but increase with turbine bypass control. The turbine flow rate decreases with both inventory control and turbine bypass control. This flow rate behavior provides the primary reason for the reduction in the generator power. It also explains why the efficiency drops with turbine bypass control (due to increased compression work).

Overall, the system response is close to that calculated previously for other systems with a S-CO_2 cycle.

The assumption of fixed sodium temperature and flow rate at the RHX inlet eliminates the need for simultaneous simulation of the reactor and BOP sides. The Q_RHX_Rx curve on the second plot in Figure 5 defines what the heat generation on the reactor side (taking into account the thermal inertia) should be as a function of time in order to maintain the same inlet temperature.

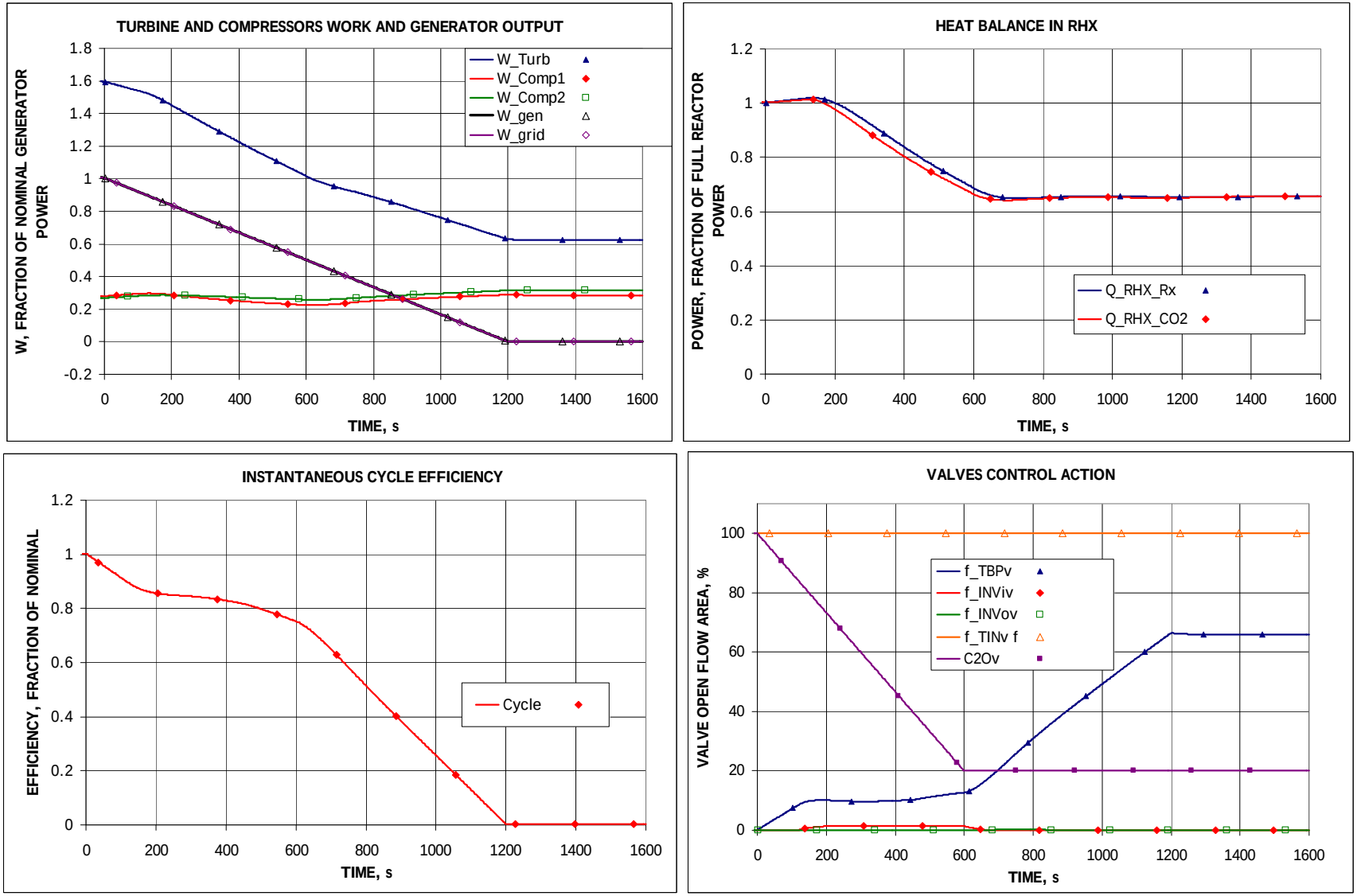


Figure 5. Transient Results for Option 1.

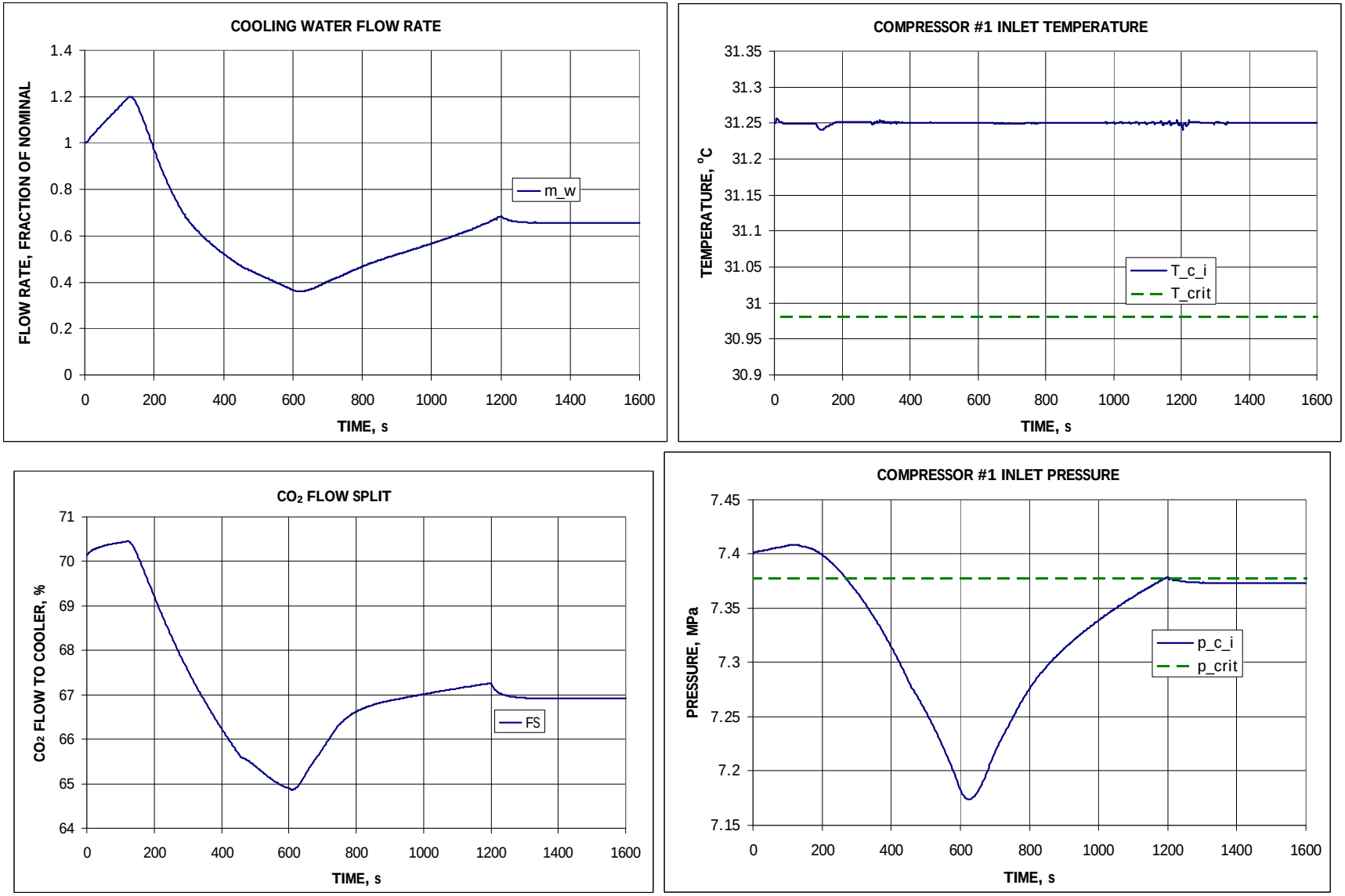


Figure 5. Transient Results for Option 1. (Continued)

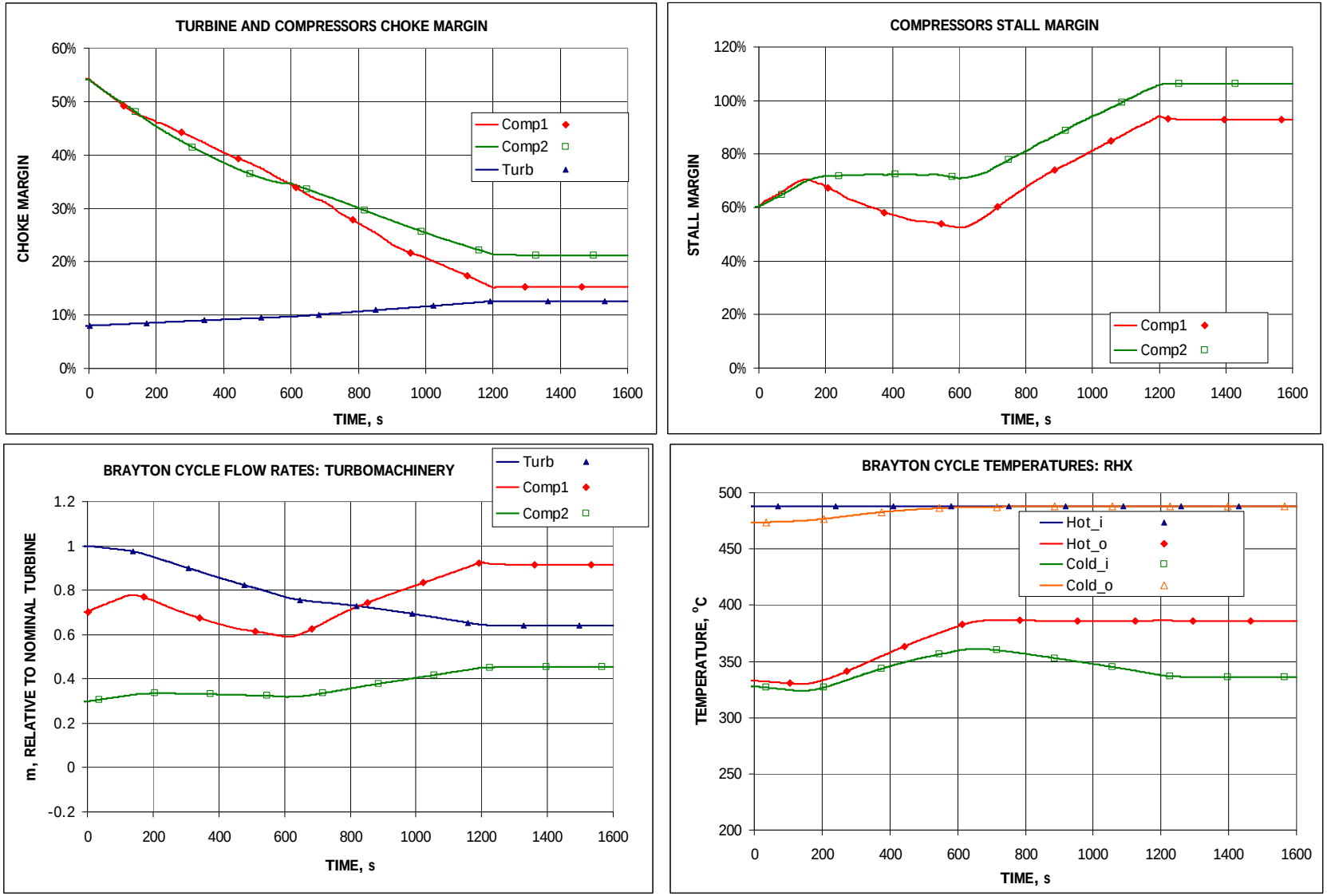


Figure 5. Transient Results for Option 1. (Continued)

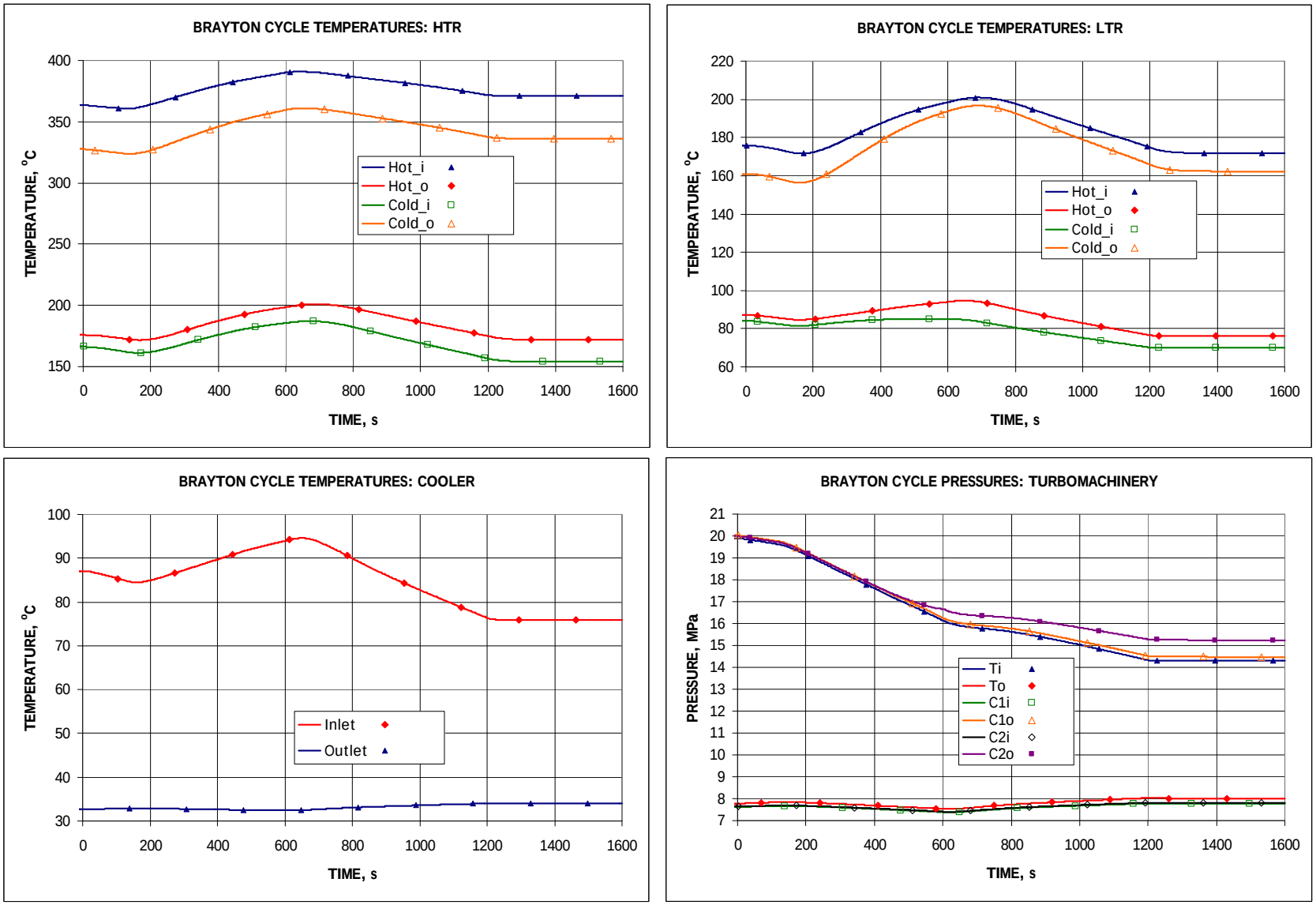


Figure 5. Transient Results for Option 1. (Continued)

3.2. *Option 2: Autonomous Reactor Operation*

Under this option, no active control on the reactor side is implemented. The reactor power is allowed to change by means of the reactivity feedback coefficients in response to the changing sodium temperatures. The primary and intermediate sodium flow rates are also allowed to change in response to temperature variations but with constant pump torques. Since the reactor power is changing in this scenario by virtue of the core reactivity feedbacks only, a detailed simulation of the core transient feedback is necessary in this case. Therefore, the simultaneous and iterative operation of the Plant Dynamics Code for the S-CO_2 Brayton cycle and SAS4A/SASSYS-1 for the reactor with the intermediate loop is utilized to obtain the results for this control option.

The results of the transient simulation for Option 2 are shown in Figure 6. The response of the S-CO_2 cycle is very close to results of Option 1 (Figure 5). Both of the reactor-side variables which affect the S-CO_2 cycle performance, namely, the intermediate sodium temperature at the RHX inlet and its flow rate, do not change significantly compared to the previous option. The flow rate changes by only about 2 %. The RHX inlet temperature increases by about 10 °C at most.

The response on the reactor side is defined by the heat removal by CO_2 in the RHX and the reactivity feedback coefficients of the reactor core. In the turbine bypass control action range (before 120 s and after 600 s with some delay due to thermal inertia), the heat removal rate by CO_2 does not change much such that the reactor temperatures are about constant. As the result, the net reactivity is zero and the reactor power does not change. When the inventory control is applied to the S-CO_2 cycle, the heat removal by CO_2 in the RHX is reduced leading to an increase of the intermediate sodium cold leg temperature and later of the core inlet temperature. Through the net negative overall reactivity feedback of ABR-1000 core, the higher core inlet temperature is translated into negative net reactivity and, therefore, a lower reactor power. Eventually, the reactor power matches the heat removal rate in the RHX such that the temperatures equalize at the new level and the net reactivity is zero. The level at which the reactor temperatures equalize is a function of the reactivity feedbacks (or combination of various feedbacks components). The results in Figure 6 demonstrate that due to the favorable reactivity feedbacks of the ABR-1000 core, the core outlet temperature does not change much during load following.

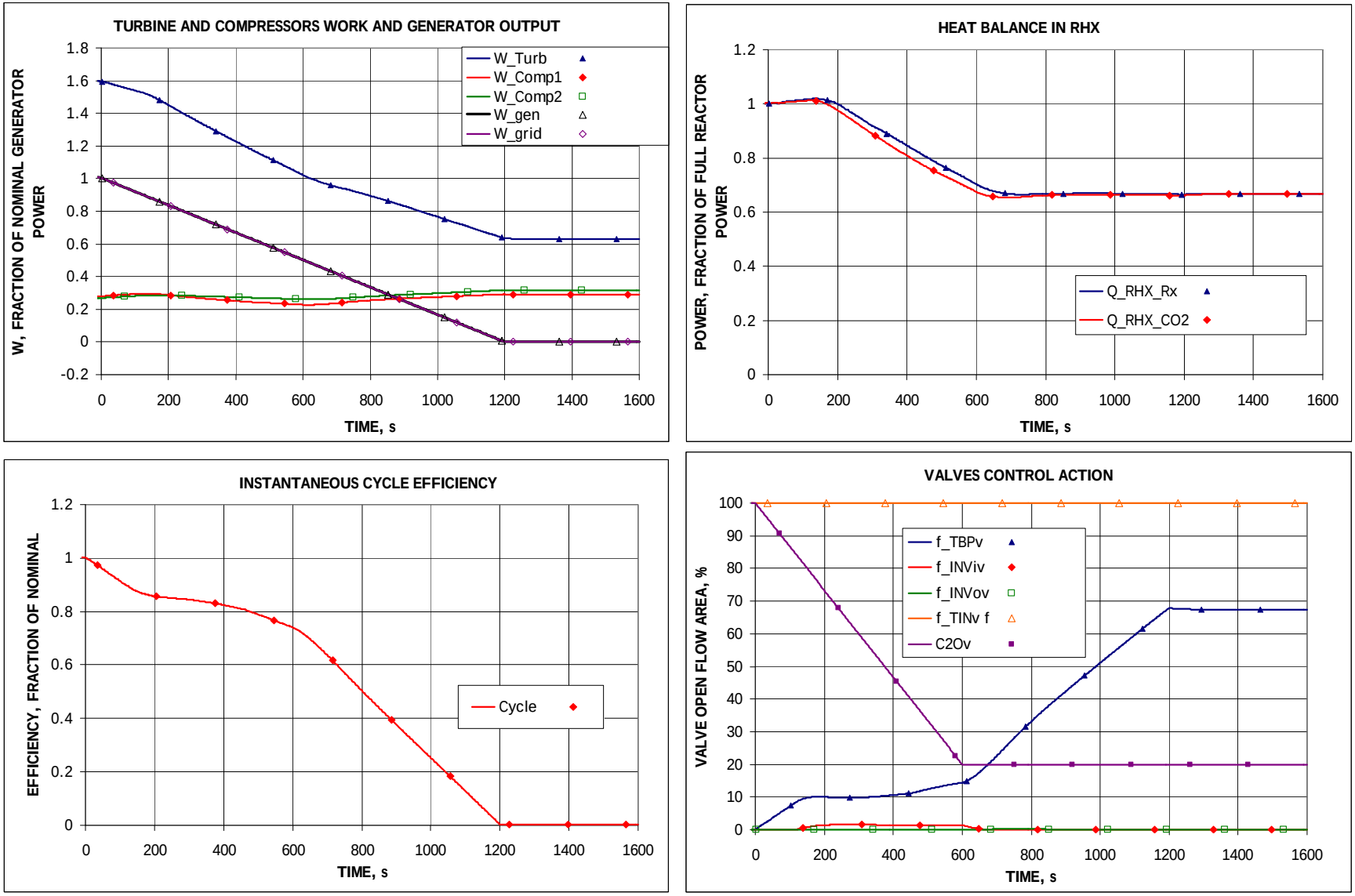
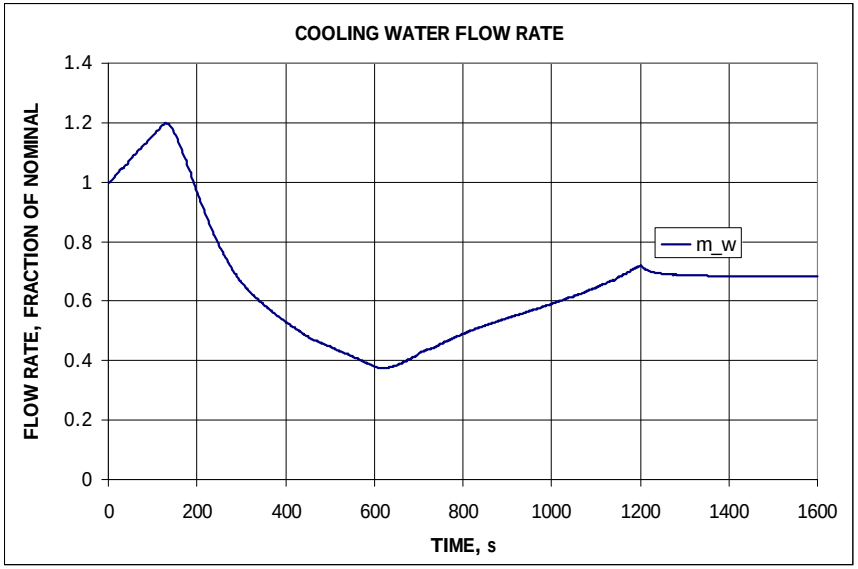
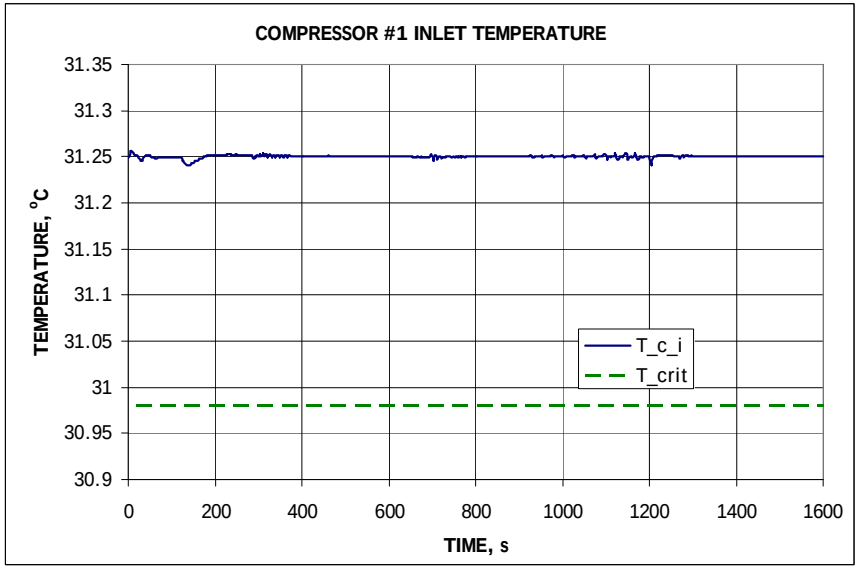
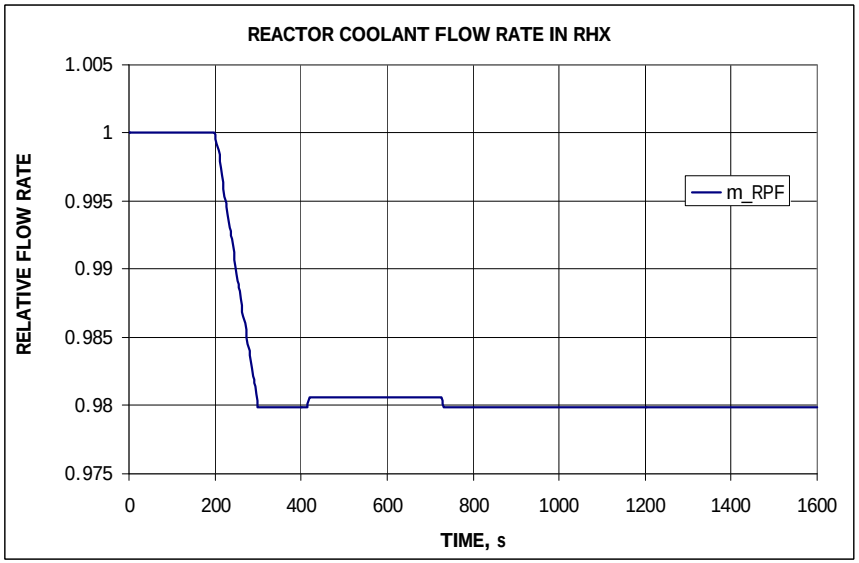


Figure 6. Transient Results for Option 2.







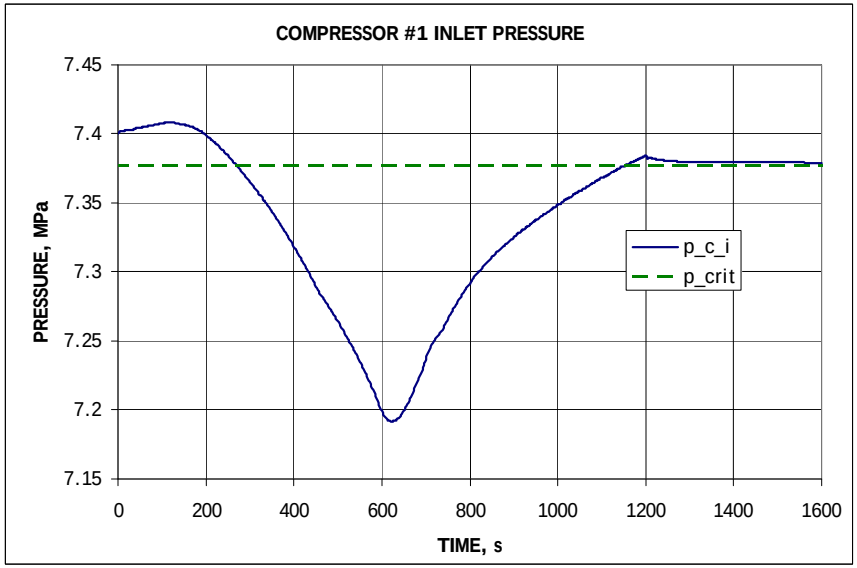


Figure 6. Transient Results for Option 2. (Continued)

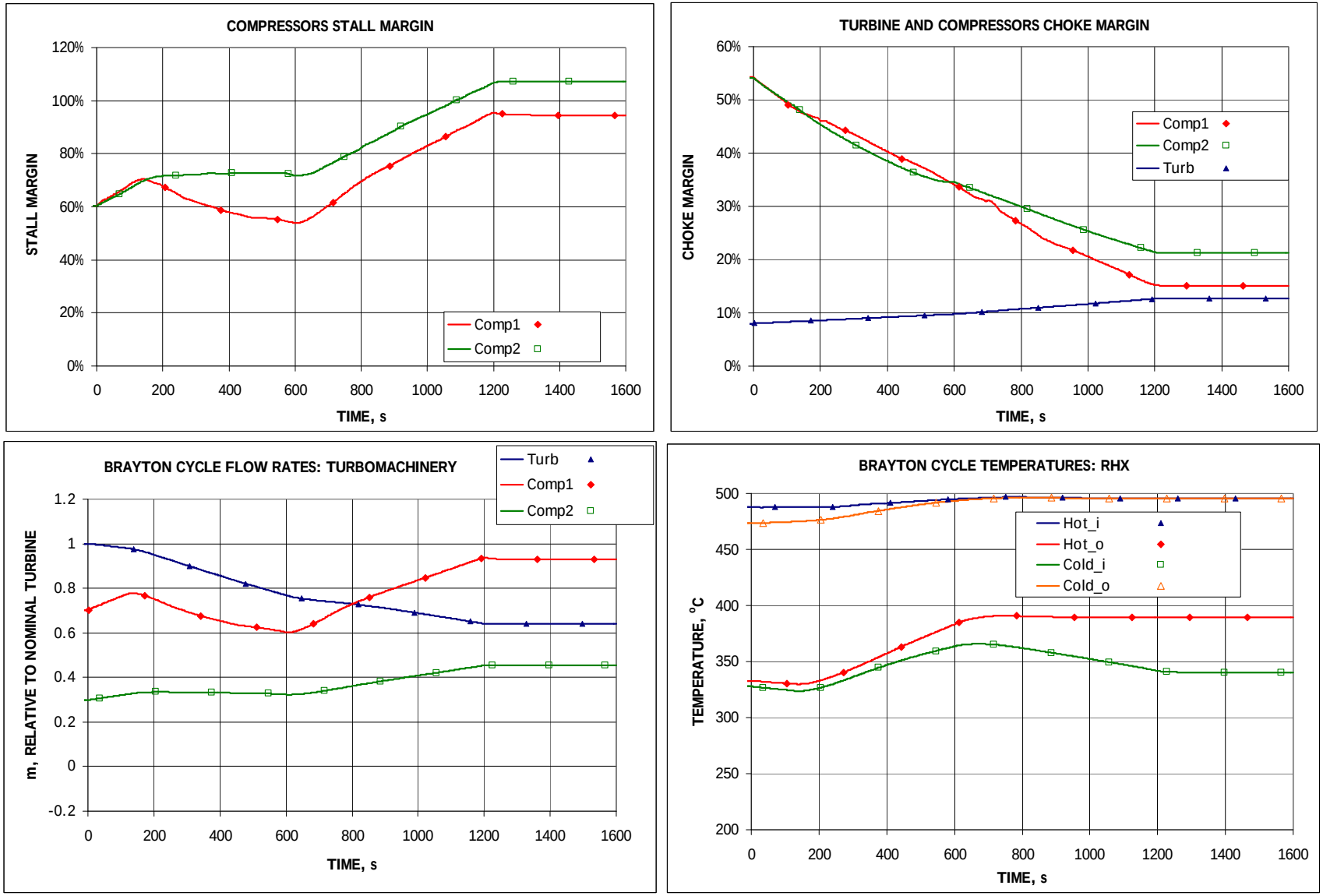


Figure 6. Transient Results for Option 2. (Continued)

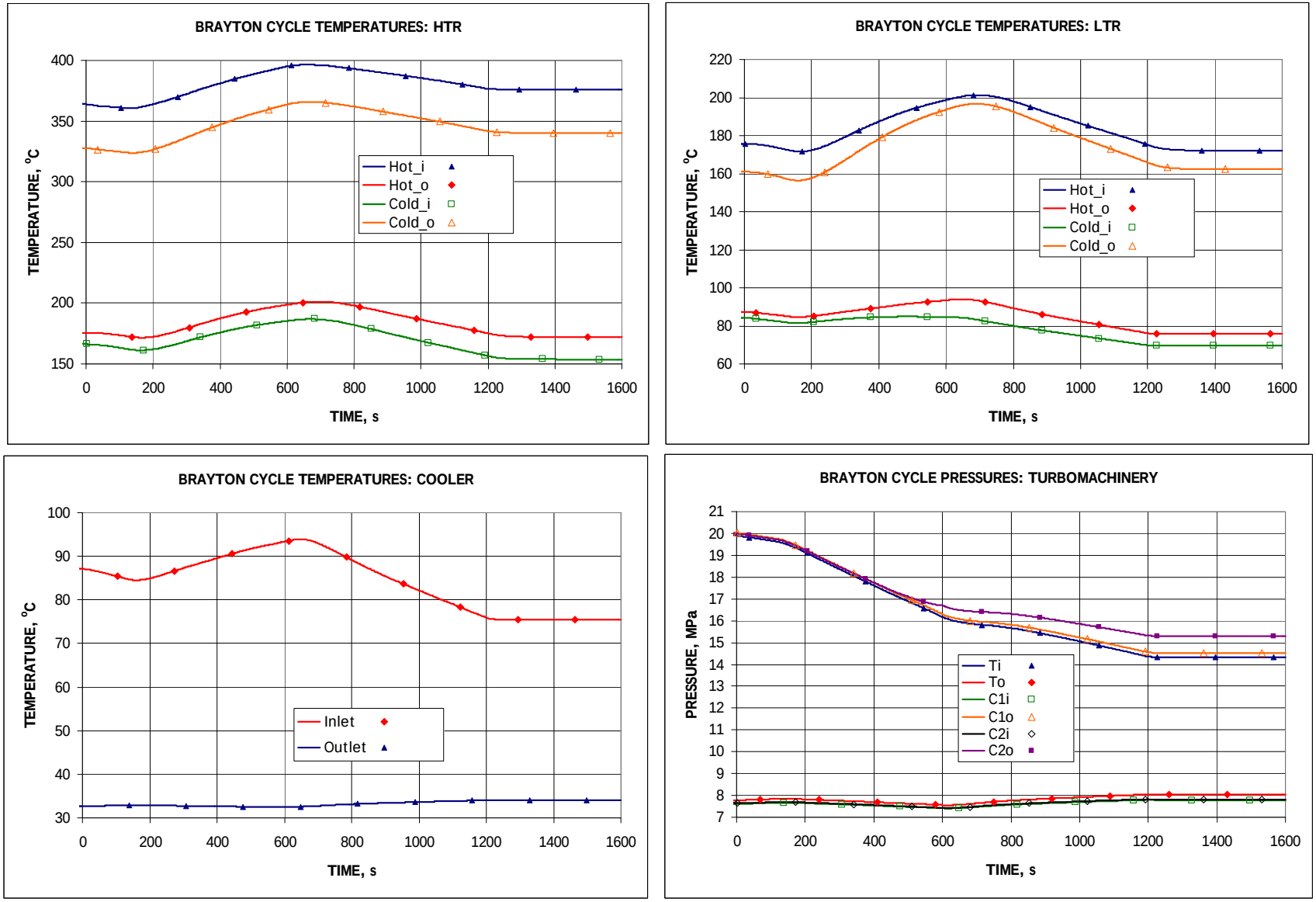


Figure 6. Transient Results for Option 2. (Continued)

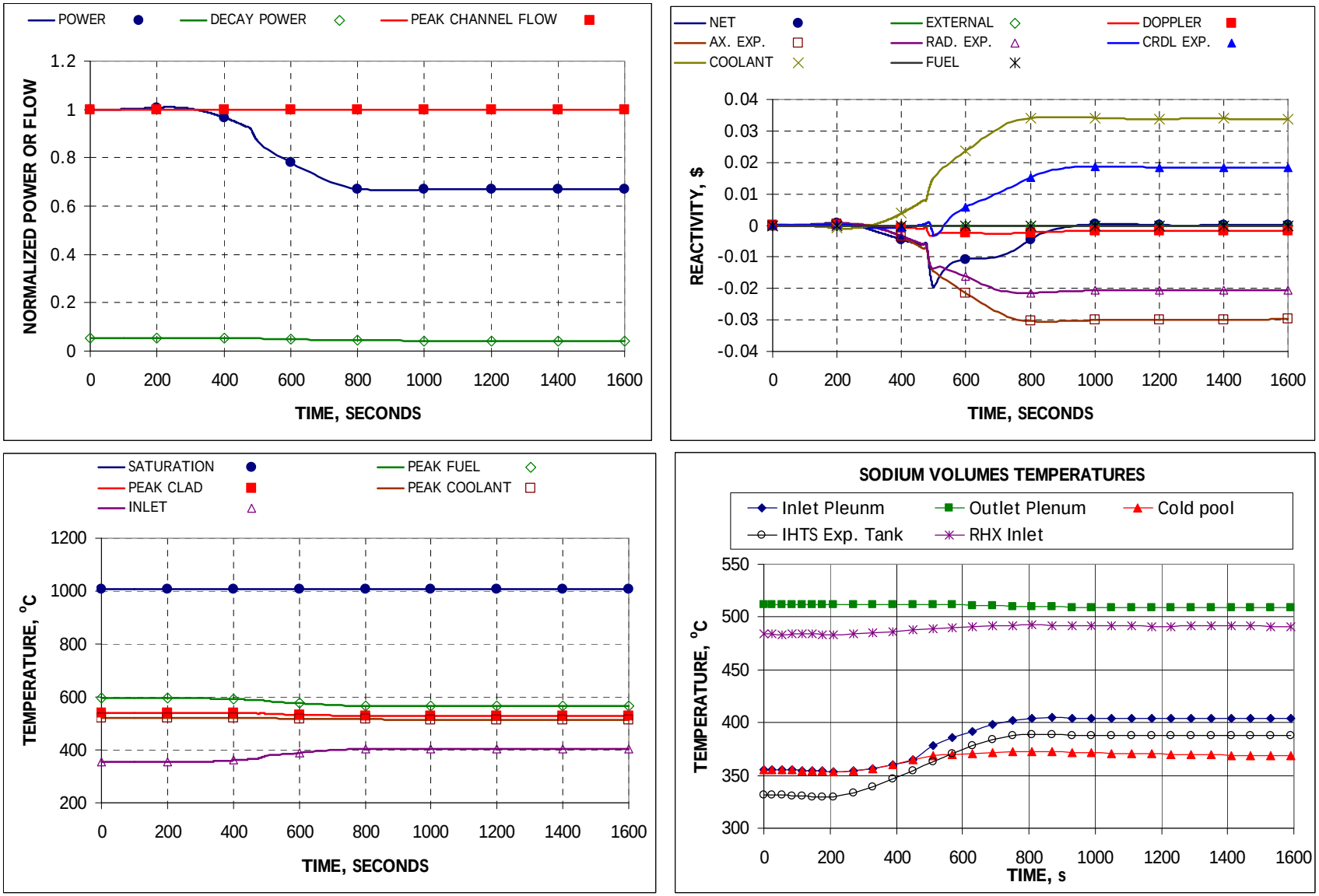


Figure 6. Transient Results for Option 2. (Continued)

3.3. *Option 3: Linear Reactor Power and Flow Control*

The reactor control options discussed above represent the type of the reactor control where the reactor power is dictated by the heat removal by the S-CO_2 cycle, either through autonomous reactor operation or a condition to maintain the intermediate sodium hot leg temperature. In this section, an independent reactor power control option is investigated. The reactor power is now controlled directly based on the grid demand (and not on the S-CO_2 cycle performance). It is assumed in this option that the reactor power is changing linearly with the same rate as a grid demand. The rational for this option is to reduce the power production in the reactor when the grid demand decreases. The reactor power reduction is selected to be the same as a grid load reduction, i.e., 5 %/min. In this case, the ratio of the grid demand (generator output) to the reactor power would be the same throughout the transient such that the cycle would operate at its design (maximum) efficiency.

In addition to the reactor power, the primary and intermediate coolant flow rates were also controlled in the same linear fashion. If the flow and power are reduced at the same rate, than the temperature difference across the core and other components on the reactor side remain at the design value. That behavior would be beneficial from the point of view of avoiding stresses in the reactor components and structures since it would reduce the thermal stresses in the reactor side components. The flow rate control is set by linear reduction of the primary and intermediate pump torques at the same rate of 5 %/min over 1,200 s.

The results of the calculations, however, show that the idealized system behavior described above cannot be achieved. Figure 7 shows the results of the converged solution of the transient simulation for the S-CO_2 cycle and reactor sides. As Figure 7 demonstrates, the system temperatures start to decrease from very early in the transient. This is due to the fact that the heat removal rate in the RHX by the S-CO_2 cycle is higher than the heat production on the reactor side. The heat production is mostly defined by the reactor power which is “programmed” to decrease linearly with time (with some thermal inertia provided by the coolant volumes and structures). The heat removal rate by the S-CO_2 cycle, as the results of previous simulations demonstrate, depends on the control mechanism used by the cycle. Initially, turbine bypass is used to control the cycle. Under this scheme, the heat removal rate by the cycle stays at about the design value. As a result of the heat imbalance between reduced power production and continued heat removal at basically the maximum rate, the temperatures start to decrease almost everywhere in the system. The temperature reduction on the S-CO_2 side leads, among other effects, to the reduction in CO_2 pressures. As a result, the ability of the S-CO_2 cycle to effectively convert the thermal energy into electricity (i.e., cycle efficiency) is decreasing with time. Initially the generator power is maintained at the grid demand level because the heat supplied to the cycle is still higher than the reactor power due to the thermal inertia of the system. However, at about 700 s, the reserve capacity of the cycle is not enough to maintain the grid demand and the generator output drops below the grid demand. When the reserve capacity is exhausted, the turbine bypass flow, which is present to compensate

for the initial reserve capacity, is reduced to zero and the ability to maintain the generator power is lost for the cycle.

Note that inventory control is never activated for this option. The inventory control is gradually phased out during the process of obtaining a converged solution between the cycle and reactor parts. Initially, the same inventory control table used in Options 1 and 2 is applied to the simulation. However, since inventory control serves the same purpose as turbine bypass control; i.e., to reduce the cycle output, turbine bypass flow would be even lower with an active inventory control than that recorded in Figure 7. Consequently, zero turbine bypass flow conditions are reached even earlier in the transient resulting in earlier loss of the cycle output control capability. To prolong operation with the generator output matching the grid demand, the inventory control has to be turned off eventually in this simulation.

The reduction of system temperatures leads to conditions for the calculated sodium temperature at the cold end of the RHX almost equal to that of the CO_2 entering the heat exchanger. Such conditions are equivalent to reaching the pinch point in a heat exchanger. It is known that the pinch point conditions have to be resolved with much higher accuracy on the temperatures and heat balance than normal conditions. Since the convergence criteria cannot be varied during the transient in the Plant Dynamics Code, reaching pinch point-like conditions results in the start of numerical oscillations after about 480 s into the transient. Also, the inability to properly resolve those conditions in the transient results in a mathematical solution where the sodium temperature at the RHX outlet is calculated to be lower than the CO_2 inlet. By 480 s the system temperature are decreasing (rather than staying at the design value as desired), so the system behavior already indicates that this control option is not advantageous relative to the other options.. Consequently, no significant effort was applied in an attempt to resolve the numerical instabilities after 480 s.

Due to the sodium temperature reduction, the sodium flow rates in both the primary and the intermediate sodium loops start to decrease more rapidly than the pump driving head (the pump torque is specified to decrease linearly with the same rate as power). That reduction in flow (and the thermal inertia of the system) assures that the sodium temperatures on the high side do not reduce as fast as the rest of the system temperatures. Moreover, after about 600 s the high sodium temperatures even start to increase. By about 800 s, when the calculated sodium low temperatures approach the freezing temperature (about 100 °C), the sodium flow rate drops to almost zero resulting in very high sodium temperatures on the hot side and the onset of sodium boiling is predicted at about 800 s.

The combination of rapid temperature reduction, lost ability to control the cycle output, together with possible sodium freezing in the cold legs and the sodium boiling in the core make this control option very unfavorable. It has therefore been shown that independent variation of the reactor power and primary and intermediate coolant flow rates to match an anticipated load reduction is not recommended for a SFR coupled to a S-CO_2 cycle system.

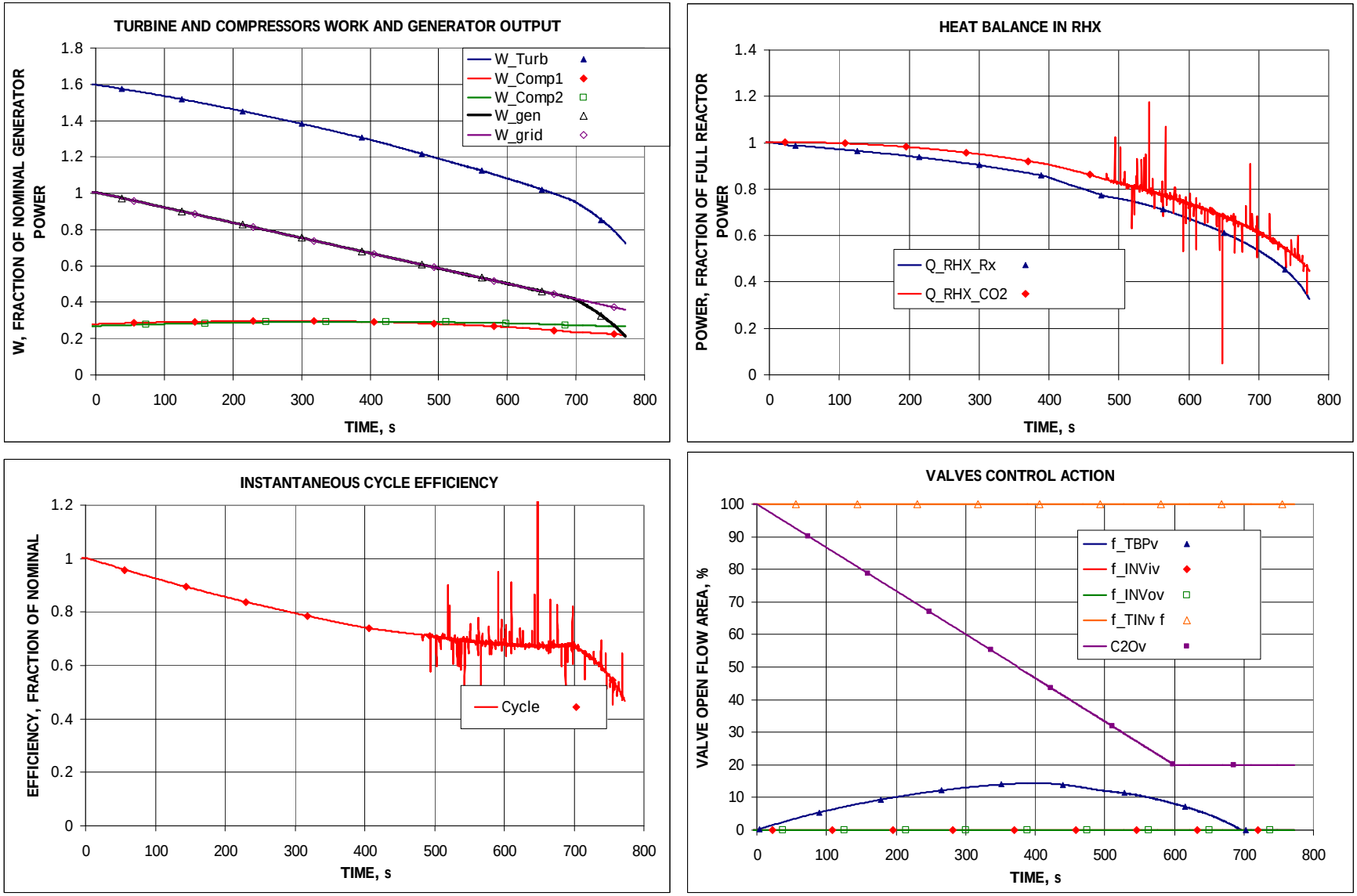


Figure 7. Transient Results for Option 3.

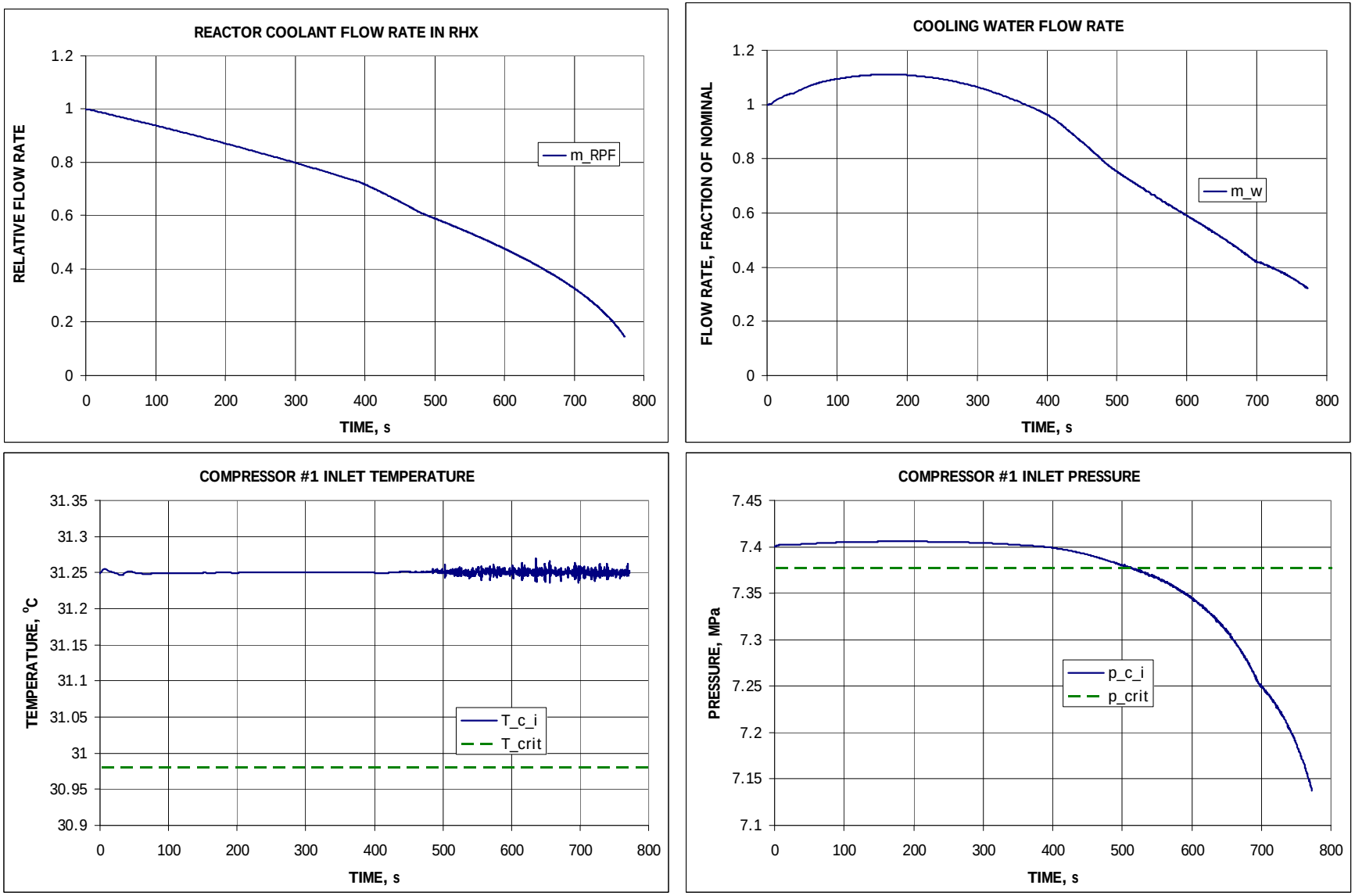


Figure 7. Transient Results for Option 3. (Continued)

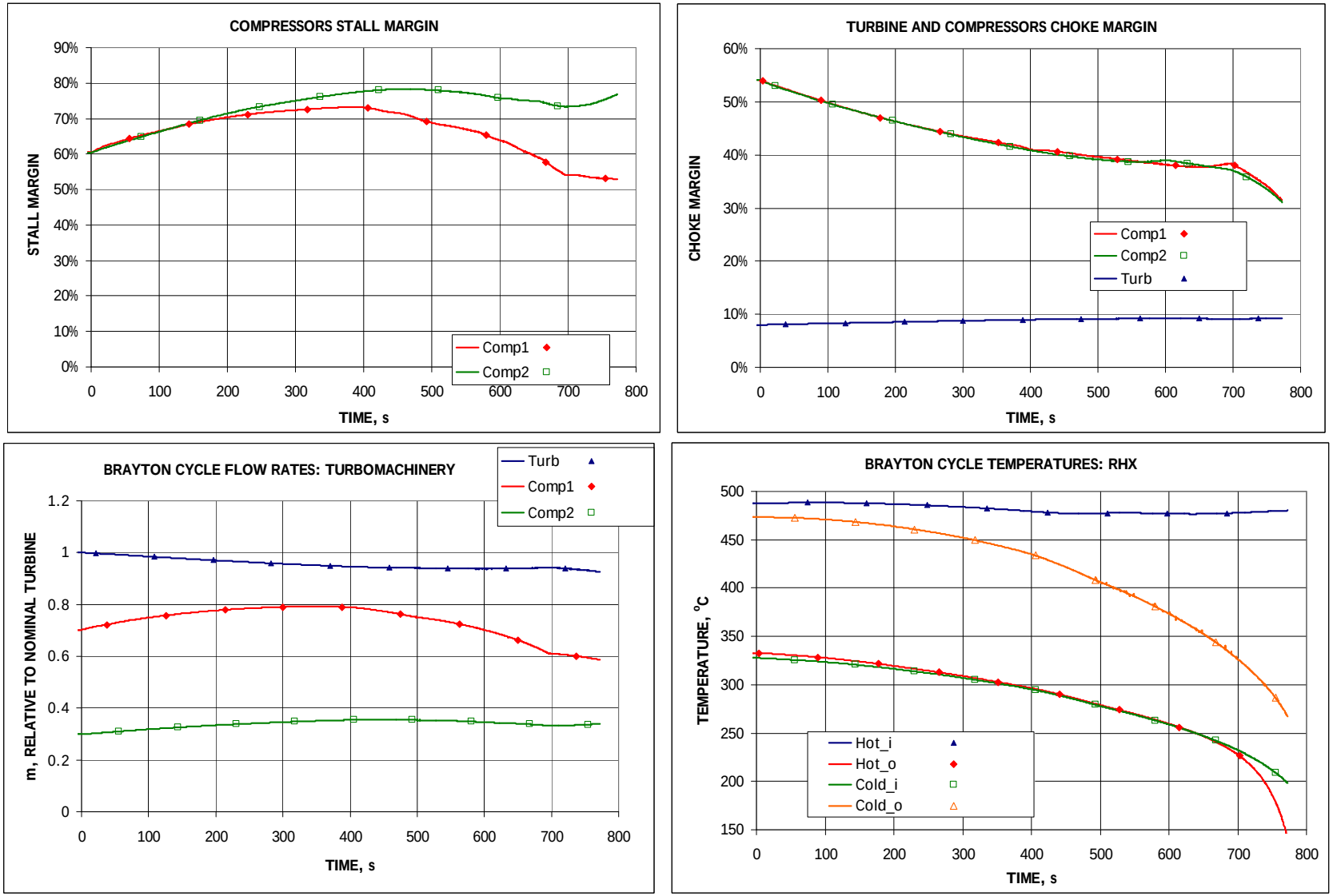
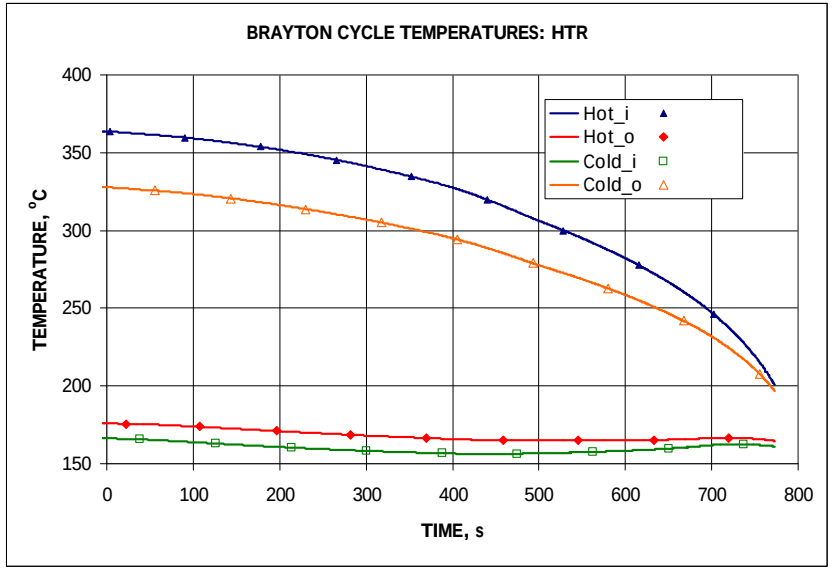
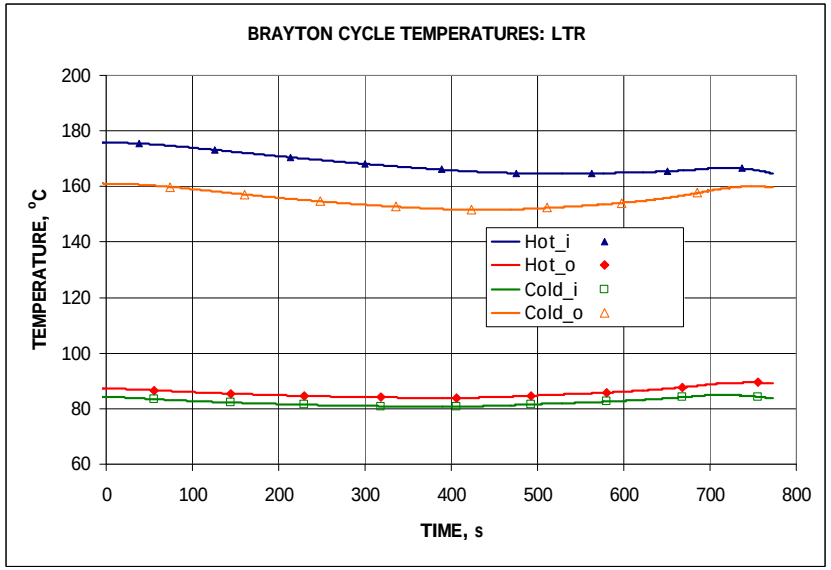
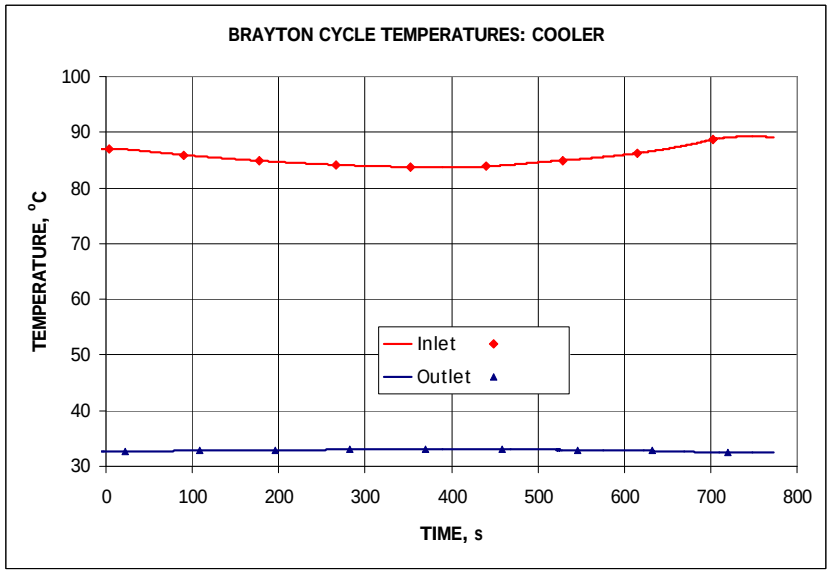


Figure 7. Transient Results for Option 3. (Continued)







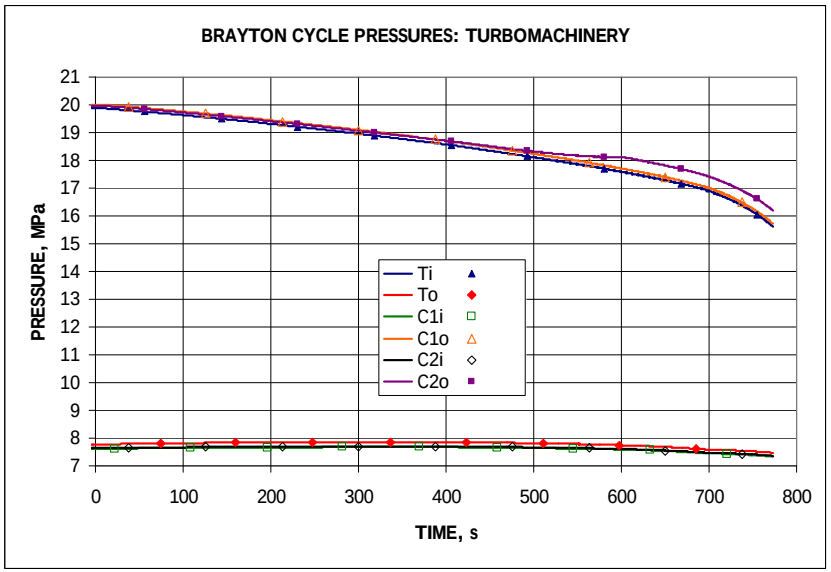


Figure 7. Transient Results for Option 3. (Continued)

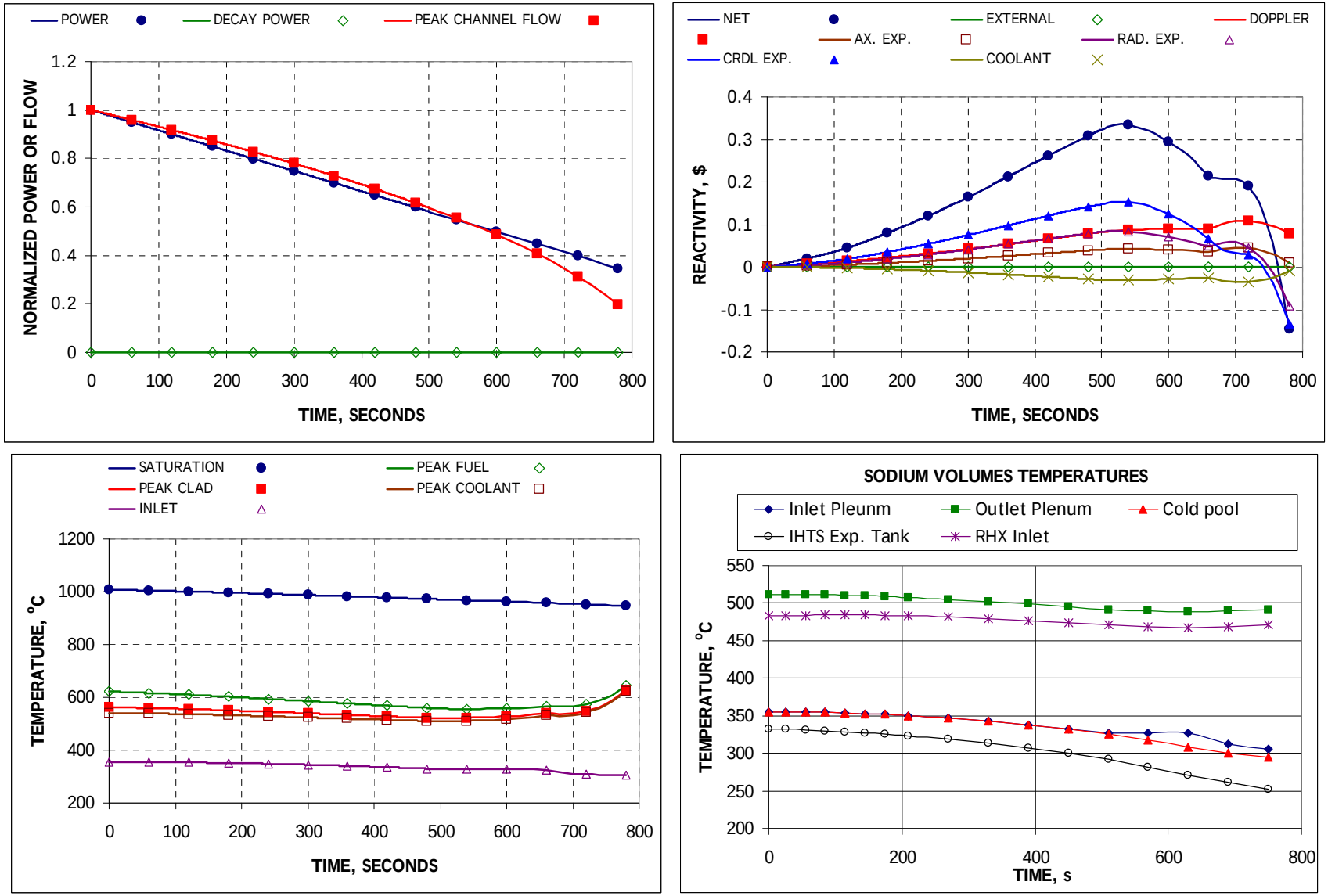


Figure 7. Transient Results for Option 3. (Continued)

3.4. *Comparison of the Control Options*

A comparison of some of the calculated parameters for the three alternate control options considered is shown in Figure 8. The results for Options 1 and 2 (fixed sodium inlet conditions and autonomous reactor operation, respectively) are very similar. The main difference is in the intermediate sodium temperature at the RHX inlet. All other parameters, including the RHX-outlet temperature, are almost identical for these two options. The results for Option 3 (linear reactor power and flow rate control) are completely different from those for Options 1 and 2, as discussed above. The cycle efficiency results for Option 3 are shown for the first 480 s before the oscillations start.

The cycle efficiency in Option 3 is somewhat higher than that for Options 1 and 2 for the first 200 s. Higher efficiency, however, is achieved at the expense of an ultimately catastrophic system cool down. The efficiency for Option 3 drops faster after 200 s, where the inventory control is applied in Options 1 and 2.

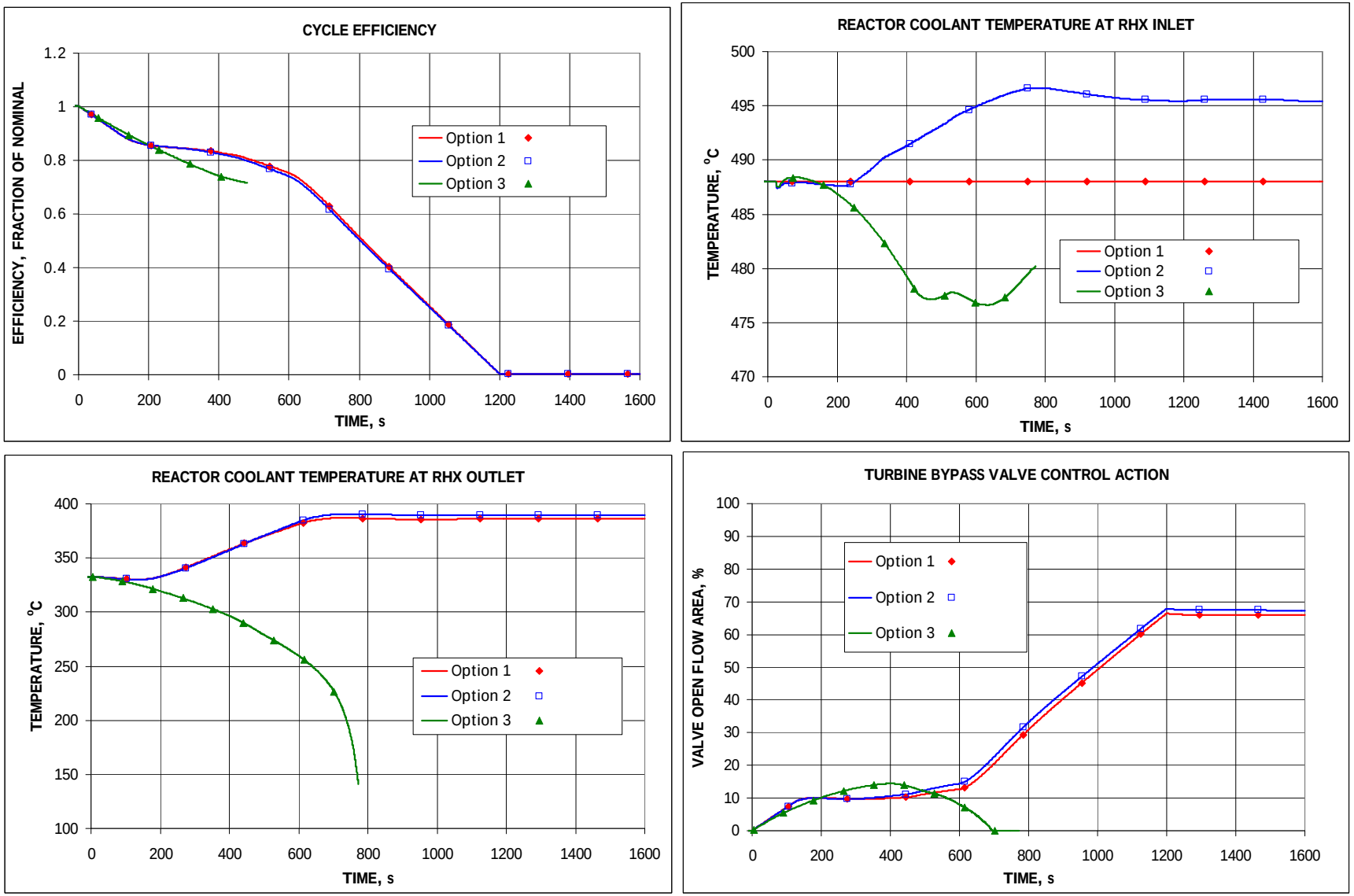


Figure 8. Comparison of the Control Options.

4. Summary and Conclusions

Development of control strategies for S-CO_2 Brayton cycles has been expanded to include the analysis of overall plant control strategies for a Sodium-Cooled Fast Reactor. Sodium-Cooled Fast Reactors usually incorporate two sodium loops (primary and intermediate) with forced circulation in both loops (compared to natural circulation in the SSTAR LFR considered in previous S-CO_2 cycle control analysis). Unlike SSTAR, the ABR-1000 SFR considered in this work is not designed for autonomous reactor operation; it was envisioned that the reactor power would be actively controlled by the control rods when necessary. However, the ABR-1000 like other metallic-fueled SFRs embodies large reactivity feedback coefficients similar to a metallic-fueled or nitride-fueled LFR raising the possibility of autonomous SFR operation. Thus, the ABR-1000 as well as other SFRs provides additional options for system control not previously considered for S-CO_2 cycle and plant-wise transient analysis.

Before the transient analysis was carried out, it was discovered that the S-CO_2 cycle design for the ABR-1000 is somewhat different than analyzed previously for the LFR. The most significant differences are the CO_2 conditions at the cooler outlet/compressor inlet and the size of the system. For the ABR-1000, the cooler outlet temperature is about 1 °C closer to the critical point than in SSTAR. That closer proximity to the critical point results in the need to re-optimize the S-CO_2 cycle controls for the minimum temperature. In addition, a limited flow split control by means of compressor throttling is shown to be effective in avoiding unfavorable conditions of compressor operation reducing the numerical oscillations otherwise calculated as part of the transient results. The size of the system (400 MWe for ABR-1000 versus 20 MWe for SSTAR) requires re-optimization of the inventory control table.

Once the control system design was finalized, the transient analysis was carried out for three alternate options for reactor control:

1) Constant intermediate sodium flow rate and its inlet temperature at the Na-CO_2 reactor heat exchanger (RHX),

2) Autonomous reactor operation, and

3) Direct linear reactor power and flow rate control matching the linear decrease in load demand.

The transient results were obtained when necessary by finding an iterative solution for the simultaneous run of the Plant Dynamics Code for the S-CO_2 cycle and the SAS4A/SASSSYS-1 code for the reactor side. Based on the results of the transient analysis, the flowing conclusions are drawn.

The behavior of the S-CO_2 cycle under turbine bypass and the inventory controls is very similar to that observed in the previous analyses for other systems. With turbine

bypass, the cycle efficiency reduces almost linearly with the grid demand meaning that the heat added to the reactor is transferred to the cooler directly instead of the turbine. It is therefore the most inefficient way of cycle and whole plant operation. The benefits of this control is that there are no limits on its range and the speed of the control is virtually limited to the valve opening and closing rates – the system response to pressure and flow changes is almost instantaneous. The inventory control provides the most efficient operation at the reduced loads. However, the range of this control is limited by the total inventory tank volume. In addition, the speed of inventory control is limited to how fast a distortion of the flow at the compressor outlet and inlet (where inventory control is connected to the cycle) can be applied without having a significant negative effect on compressor operation. The minimum temperature control, consisting of cooler bypass and water flow controls, is once again shown to be effective and necessary for the S-CO_2 Brayton cycle. Overall, the control strategy selected in previous work for S-CO_2 cycle – inventory control with turbine bypass control outside of the range of the former assisted by cooler bypass and water flow rate controls – has proven to be effective and optimal for the S-CO_2 cycle coupled to a SFR.

The results of the investigation of the alternate reactor control options shows that the heat removal rate by the cycle is defined by the control mechanisms on the S-CO_2 cycle side. When turbine bypass control is the main control mechanism, the heat removal rate by the cycle does not change significantly. With inventory control, the heat removal rate changes closely proportional to the specified grid demand. The results of the transient analysis demonstrate that for the most efficient operation of the system, the power production on the reactor side should match the heat removal rate on the S-CO_2 side. However, an attempt to deliberately reduce the reactor power and primary and intermediate sodium flow rates to exactly match the decrease in the grid demand results in a heat imbalance in the RHX leading to gradual cooldown of the system, eventually resulting in loss of the ability to maintain the generator power on the S-CO_2 side and possible coolant freezing on the reactor side.

The autonomous operation of the reactor, where no active control is applied to the reactor power and flows, is demonstrated to be a feasible option for the ABR-1000 preconceptual design with a S-CO_2 Brayton cycle BOP. It is demonstrated that the plant can effectively follow the load over the entire range (0 % to 100 %) by means of the automatic S-CO_2 cycle control. The only negative feature of autonomous reactor operation discovered during the analysis is a slight increase of the hot side sodium temperatures – the intermediate sodium hot leg temperature is calculated to increase by a maximum of about 10 °C during the load reduction transient.

Overall, the most satisfactory system behavior is achieved with Option 1 where the intermediate sodium temperature and flow rate at the RHX inlet are assumed to be fixed. Practically, this assumption means that the reactor power and flow rate controls are applied to provide the constant temperatures and flow rates. However, the results for the case where no reactor control is applied (autonomous operation in Option 2) are very similar to those in Option 1. This means that very small adjustments to the reactor power and flow beyond those resulting from the autonomous changes due to reactivity feedback

effects would be needed to achieve the conditions assumed for Option 1. Since for autonomous reactor operation the sodium inlet temperature at RHX inlet increases by less than 10 °C compared to the steady-state value, a relatively small reactivity insertion would be needed to preclude that temperature increase during the transient.

Acknowledgements

The authors are grateful to Paul Pickard (SNL), the former Generation IV National Technical Director for Energy Conversion, as well as John Kelly (SNL), the current National Technical Director, for their continuing support of this work. The authors are also indebted to Tom Fanning (ANL/NE) for his support with SAS4A/SASSYS-1 code. Finally, the authors would like to thank Jim Cahalan, the former ANL Work Package Manager, for his support.

References

1. Moisseytsev, A. and Sienicki, J. J., "Development of a Plant Dynamics Computer Code for Analysis of a Supercritical Carbon Dioxide Brayton Cycle Energy Converter Coupled to a Natural Circulation Lead-Cooled Fast Reactor," ANL-06/27, Argonne National Laboratory, July 2006.

2. Moisseytsev, A. and Sienicki, J. J., "Controllability of the Supercritical Carbon Dioxide Brayton Cycle Near the Critical Point," 2008 International Congress on Advances in Nuclear Power Plants (ICAPP 2008), Anaheim, CA, June 8-13, 2008, Paper 8203.

3. Moisseytsev, A. and Sienicki, J. J., "Transient Accident Analysis of a Supercritical Carbon Dioxide Brayton Cycle Energy Converter Coupled to an Autonomous Lead-Cooled Fast Reactor," *Nuclear Engineering and Design*, 238 (2008), pp. 2094-2105.

4. Moisseytsev, A. and Sienicki, J. J., "Automatic Control Strategy Development for the Supercritical CO_2 Brayton Cycle for LFR Autonomous Load Following," paper 6074, Proceedings of 2006 International Congress on Advances in Nuclear Power Plants, ICAPP' 06, Reno, NV, June 4-8, 2006.

5. Moisseytsev, A. and Sienicki, J. J., "Analysis of Supercritical CO_2 Cycle Control Strategies and Dynamic Response for Generation IV Reactors," ANL-GenIV-124, Argonne National Laboratory, September 15, 2009.

6. Kim, T. K., Yang, W. S., Grandy, C., and Hill, R. N., "Core Design Studies for a 1000 MWth Advanced Burner Reactor," Annals of Nuclear Energy, 36 (2009) pp. 331–336.

7. Moisseytsev, A. and Sienicki, J. J., "Supercritical Carbon Dioxide Cycle Control Analysis," ANL-GenIV-111, Argonne National Laboratory, September 15, 2008.

Appendix A.
Input Files for Dynamic Calculations with the Plant Dynamics Code

```
************* Input data for dynamic calculations *******************
Simulation time, s
1600
Time to obtain SS (not included into simulation time), s
100
Time step (initial), s
0.001
Report every N calculations
200 2000
Print out (=1) the detailed results for components?
1
Required convergence
1.D-5
Order for RX and BC parts (max=9)
1 5
Reactor power calculation method (1 - PRKE, 2 - Quasi-Static)
1
SAS RHX hot side element number
17
Number of SAS loops in the plant
4
Compressibility value to switch to incompressible flow
0.8
Compressibility value to switch to compressible flow
0.85      (recommended to be higher than above)
Volumes at turbine and compressors (1 and 2) exhausts, m3
10.0 10.0 10.0
Generator's moment of inertia, kg-m2
31000
Number of points in grid load table (1 - no action)
2
Grid load table (Time,s; % nominal) (For LOL put -1)
0   1200 2000
100 0    0
Grid connection mode (1-synchronous, 2-asynchronous)
1
Equivalent pipe break diameter, cm
0
Location of the break (dynamic-code node)
5
Run mode: 0 - calculation, 1 - test (allow files access)
1
```

```
****************** Input parameters for the Brayton cycle control ***************
########################## Rotational speed control ####################
Number of points in the rotational speed control table
1
Rotational speed control table (Time; Nr, % nominal)
0
100
############################ Turbine Bypass ##############################
Valve name (from SS Cycle_dat.txt file)
TBPv
Flow splitter name (from SS Cycle_dat.txt file; for fraction printout only)
TBPsp
Coefficients for turbine bypass control (P D I)
5 1 0.1
Opening and closing rate limits, %/s
10 10
----------- Manual control -----------------
Number of points in the manual control table (1 - no action)
1
Turbine bypass valve control table (Time; f_open,%)
0
0
############################### Inventory ################################
Inlet valve name (from SS Cycle_dat.txt file)
INVIv
Outlet valve name (from SS Cycle_dat.txt file)
INVOv
Number of points in the inventory control table
6
Inventory control table (Load,%; dM_tank,kg)
50    60     70     80      90  100
1.0E4 0.75E4 0.5E4  0.25E4  0   0
Coefficients for inventory control (P D I)
0.01 1 0
Inlet valve opening and closing rate limits, %/s
0.1 0.1
Outlet valve opening and closing rate limits, %/s
1 1
------- Manual control - Inlet valve ------
Number of points in the manual table - inlet (1 - no action)
1
Inventory inlet valve control table (Time,s; f_open,%)
0
0
------- Manual control - Outlet valve ------
Number of points in the manual control table - outlet (1 - no action)
1
Inventory outlet valve control table (Time; f_open,%)
0
0
############################ Turbine Inlet ###############################
Valve name (from SS Cycle_dat.txt file)
TINv
Number of points in the valve control table
1
Valve control table (Load,%; dp_valve,MPa)
100
0
Coefficients for valve control (P D I)
5 5 0.1
Valve opening and closing rate limits, %/s
10
----------- Manual control -----------------
Number of points in the manual control table (1 - no action)
1
Turbine inlet valve control table (Time; f_open,%)
0
100
########################## Compressor2 outlet ##########################
Valve name (from SS Cycle_dat.txt file)
C2Ov
```

```
Valve opening and closing rate limits, %/s
0.5 0.5
----------- Manual control -----------------
Number of points in the manual control table (1 - no action)
2
Compressor outlet valve control table (Time; f_open,%)
0   600
100 20
############################# Cooler Bypass ##############################
Valve name (from SS Cycle_dat.txt file)
CBPv
Flow splitter name (from SS Cycle_dat.txt file; for fraction printout only)
CBPsp
Coefficients for valve control (P D I)
25 0.25 0.1
Valve opening and closing rate limits, %/s
10 10
----------- Manual control -----------------
Number of points in the manual control table (1 - no action)
1
Cooler bypass valve control table (Time; f_open,%)
0
0
------- Water flow rate -------------------
Coefficients for water flow rate control (P D I)
1 10 0
Water flow rate change limit, %nom/s
10
Water flow rate limit, %nom
200
################################ HX Bypass ################################
Valve name (from SS Cycle_dat.txt file)
RBPv
Flow splitter name (from SS Cycle_dat.txt file; for fraction printout only)
RBPsp
----------- Manual control -----------------
Number of points in the manual control table (1 - no action)
1
HX Bypass valve control table (Time; f_open,%)
50
0
```

Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

www.anl.gov

A U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC