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ANL-GenIV-111

Supercritical Carbon Dioxide Cycle Control Analysis

Nuclear Engineering Division

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Abstract

This report documents work carried out during FY 2008 on further investigation of control strategies for supercritical carbon dioxide (S-CO_2) Brayton cycle energy converters. The main focus of the present work has been on investigation of the S-CO_2 cycle control and behavior under conditions not covered by previous work. An important scenario which has not been previously calculated involves cycle operation for a Sodium-Cooled Fast Reactor (SFR) following a reactor scram event and the transition to the primary coolant natural circulation and decay heat removal. The Argonne National Laboratory (ANL) Plant Dynamics Code has been applied to investigate the dynamic behavior of the 96 MWe (250 MWt) Advanced Burner Test Reactor (ABTR) S-CO_2 Brayton cycle following scram. The timescale for the primary sodium flowrate to coast down and the transition to natural circulation to occur was calculated with the SAS4A/SASSYS-1 computer code and found to be about 400 seconds. It is assumed that after this time, decay heat is removed by the normal ABTR shutdown heat removal system incorporating a dedicated shutdown heat removal S-CO_2 pump and cooler. The ANL Plant Dynamics Code configured for the Small Secure Transportable Autonomous Reactor (SSTAR) Lead-Cooled Fast Reactor (LFR) was utilized to model the S-CO_2 Brayton cycle with a decaying liquid metal coolant flow to the Pb-to-CO_2 heat exchangers and temperatures reflecting the decaying core power and heat removal by the cycle. The results obtained in this manner are approximate but indicative of the cycle transient performance. The ANL Plant Dynamics Code calculations show that the S-CO_2 cycle can operate for about 400 seconds following the reactor scram driven by the thermal energy stored in the reactor structures and coolant such that heat removal from the reactor exceeds the decay heat generation. Based on the results, requirements for the shutdown heat removal system may be defined. In particular, the peak heat removal capacity of the shutdown heat removal loop may be specified to be 1.1 % of the nominal reactor power.

An investigation of the oscillating cycle behavior calculated by the ANL Plant Dynamics Code under specific conditions has been carried out. It has been found that the calculation of unstable operation of the cycle during power reduction to 0 % may be attributed to the modeling of main compressor operation. The most probable reason for such instabilities is the limit of applicability of the currently used one-dimensional compressor performance subroutines which are based on empirical loss coefficients. A development of more detailed compressor design and performance models is required and is recommended for future work in order to better investigate and possibly eliminate the calculated instabilities. Also, as part of such model development, more reliable surge criteria should be developed for compressor operation close to the critical point. It is expected that more detailed compressor models will be developed as a part of validation of the Plant Dynamics Code through model comparison with the experiment data generated in the small S-CO_2 loops being constructed at Barber-Nichols Inc. and Sandia National Laboratories (SNL). Although such a comparison activity had been planned to be initiated in FY 2008, data from the SNL compression loop currently in operation at Barber Nichols Inc. has not yet become available by the due date of this report.

To enable the transient S-CO_2 cycle investigations to be carried out, the ANL Plant Dynamics Code for the S-CO_2 Brayton cycle was further developed and improved. The improvements include further optimization and tuning of the control mechanisms as well as an adaptation of the code for reactor systems other than the Lead-Cooled Fast Reactor (LFR). Since the focus of the ANL work on S-CO_2 cycle development for the majority of the current year has been on the applicability of the cycle to SFRs, work has started on modification of the ANL Plant Dynamics Code to allow the dynamic simulation of the ABTR. The code modifications have reached the point where a transient simulation can be run in steady state mode; i.e., to determine the steady state initial conditions at full power without an initiating event. The results show that the steady state solution is maintained with minimal variations during at least 4,000 seconds of the transient. More SFR design specific modifications to the ANL Plant Dynamics Code are required to run the code in a full transient mode, including models for the sodium pumps and their control as well as models for reactivity feedback and control of the reactor power.

1. Introduction

Work on developing the ANL Plant Dynamics Computer Code for the S-CO_2 cycle and further development of the control strategy for the cycle control has been continued at Argonne National Laboratory.

The following tasks were planned for FY 2008:

- Modification of the ANL Plant Dynamics code to include surge control, shutdown cooling loops, or other key features to facilitate analysis of transient S-CO_2 cycle dynamics and extend analysis of cycle transients;

- Perform validation of Plant Dynamics code models using available data for small scale S-CO_2 cycle demonstration components.

The work that was carried out under those tasks along with the results obtained is described herein.

The focus of the S-CO_2 cycle development work has been on the cycle applicability to the Sodium-Cooled Fast Reactor (SFR). Consequently, the majority of the calculations described in this report are aimed at S-CO_2 cycle power conversion for the SFR.

2. Plant Dynamics Code Development

2.1. Compressor Surge Control

One of the goals for current year for S-CO_2 cycle control strategy development was an introduction of compressors surge protection systems for the two compressors with corresponding equipment and control logic. Usually [6], the surge control system consists of the compressor bypass (recirculation) line with an integrated cooler. When an approach to surge is detected by the compressor control system, the bypass line valve is opened such that part of the flow is recirculated from the high-pressure compressor outlet to the low-pressure compressor inlet. This partial flow recirculation causes the compressor outlet pressure to decrease and the compressor inlet pressure to increase resulting in lower pressure ratio across the compressor. Low pressure ratio will result in increased flow rate through the compressor such that the compressor operating point moves away from low-flow high-pressure-ratio surge conditions. Since the flow recirculation brings hotter flow from the compressor outlet to the colder compressor inlet, an additional cooler is installed in the recirculation line to avoid otherwise uncontrolled temperature increase in the compressor.

It is noted that the initiation of the compressor surge protection system starts with a detection of the approach to surge. Thus, a reliable surge prediction criterion is required. Several criteria have been proposed [7] for centrifugal compressors, such as conditions where the pressure ratio-versus-flow rate curve reaches its maximum point or some empirical blade stall criteria. However, there are no commonly accepted surge criteria mostly due to the lack of experiment data, since experiment verification of surge requires operation of a compressor under surge conditions which would damage a compressor. For these reasons, a combination of several surge conditions is used in the Plant Dynamics Code. The surge flow is defined as a maximum of flow rates at which either pressure curve reaches its maximum or a blade stall criterion is satisfied. It is unknown how applicable such empirical correlations are to the supercritical conditions.

The results obtained so far (reported previously in [1] and further in this report) show that unstable compressor operation, similar to that expected under surge conditions, is sometimes calculated even at flow rates above the surge limit based on the above mentioned criteria. An additional effort has therefore been made to investigate the cause of the instability before a reliable surge control system can be developed for S-CO_2 cycle compressors.

2.1.1. Stability Issues

During the simulation of different transients with the ANL Plant Dynamics Code, unexpected cycle behavior was sometimes calculated. An example of such unstable behavior is demonstrated in Figure 1 during a load reduction at 3 %/min rate from 100 % to 0 % load with subsequent load increase back to 100 %. At about 3500 seconds, some parameters start to oscillate leading to a very small time step defined by the code dynamic time step control. Eventually, the time step becomes too small such that the Dynamic Code calculations are halted on a time step lower limit criterion ($<10^{-10}$ s).

Figure 2 analyzes in details the conditions during the onset of the oscillations. Even though it is difficult, due to the interdependency of the equations, to pinpoint the parameter which starts to oscillate first, it is clear that oscillations first start for the parameters calculated for the main compressor (Compressor No. 1) which is the cycle component operating closest to the critical point. Note that when the oscillations start, significant surge and choke margins are calculated for the compressor (in fact, Figure 1 demonstrates that the compressor can stably operate at lower margins during the transient). Also, Figure 2 shows that the control (valve) action is smooth during the oscillations meaning that the oscillations are not caused by the control system.

One of the most probable reasons for the oscillation is mathematical interpolation between the compressor performance lines obtained from the precalculated performance maps. To check this hypothesis, an option has been added to the Plant Dynamics Code to use the performance subroutines directly in the dynamics calculations. Under this option, the compressor characteristics, such as flow rate and outlet temperature, are calculated by the same performance subroutines which were used to generate the performance maps. Since those subroutines incorporate several layers of iterations on flow rate and CO_2 conditions, using those subroutines significantly slows down the dynamic calculations (compared to the maps option). It was found, however, that using the performance subroutines instead of the precalculated maps did not improve the results; the oscillations were still calculated.

Based on the analysis, it is suggested that the oscillations are based on limits of the applicability of the compressor performance calculation approach to the S-CO_2 cycle conditions. The current approach is based on calculating the CO_2 conditions only at few key locations inside the compressor, such as the impeller inlet, impeller outlet, diffuser inlet, and diffuser outlet. Then, the empirical loss coefficients are applied to each component (impeller or diffuser) based on the average between inlet and outlet conditions. It is noted from Figure 2 that the CO_2 enters the main compressor impeller at subcritical pressure and leaves the compressor at supercritical pressure while the inlet temperature is still close to but above the critical value. Therefore, a transition through a pseudocritical point must occur somewhere inside the compressor. Even though the property change at pseudocritical conditions is not as sharp as at the critical point, this change could still be significant. Therefore, there might be a condition where, depending on flow parameters, the location of the pseudocritical conditions might shift from impeller to diffuser and back. If this happens, it is expected that the parameters calculated on some average values, such as loss coefficients for example, might change significantly for both affected impeller and diffuser resulting in significant variation of the outlet conditions and, therefore, the flow rate through the compressor. It is difficult however to verify those conditions with the current performance models under the dynamic calculations.

Based on the results of the analysis, it is recommended that a more detailed performance (and design) model to be implemented in the dynamics code. This model should better account for the properties variation inside each compressor component (rather than relying on inlet and outlet conditions only) with correspondingly more detailed loss calculations for each component. Also, the applicability of the currently used empirical loss coefficients to S-CO_2 conditions should be investigated. Until such an improved compressor performance model is developed, it is impossible to further investigate the cause of the unstable compressor operation.

It is also difficult to implement and test the surge control system under the conditions where unstable compressor operation, similar to that expected under surge conditions, is calculated where surge is not expected. It is also required to verify, and if necessary, develop more reliable surge criteria for S-CO_2 conditions.

Both those tasks are expected to be carried as a part of the future experiment verification of the S-CO_2 compressor performance (see Section 2.2 below).

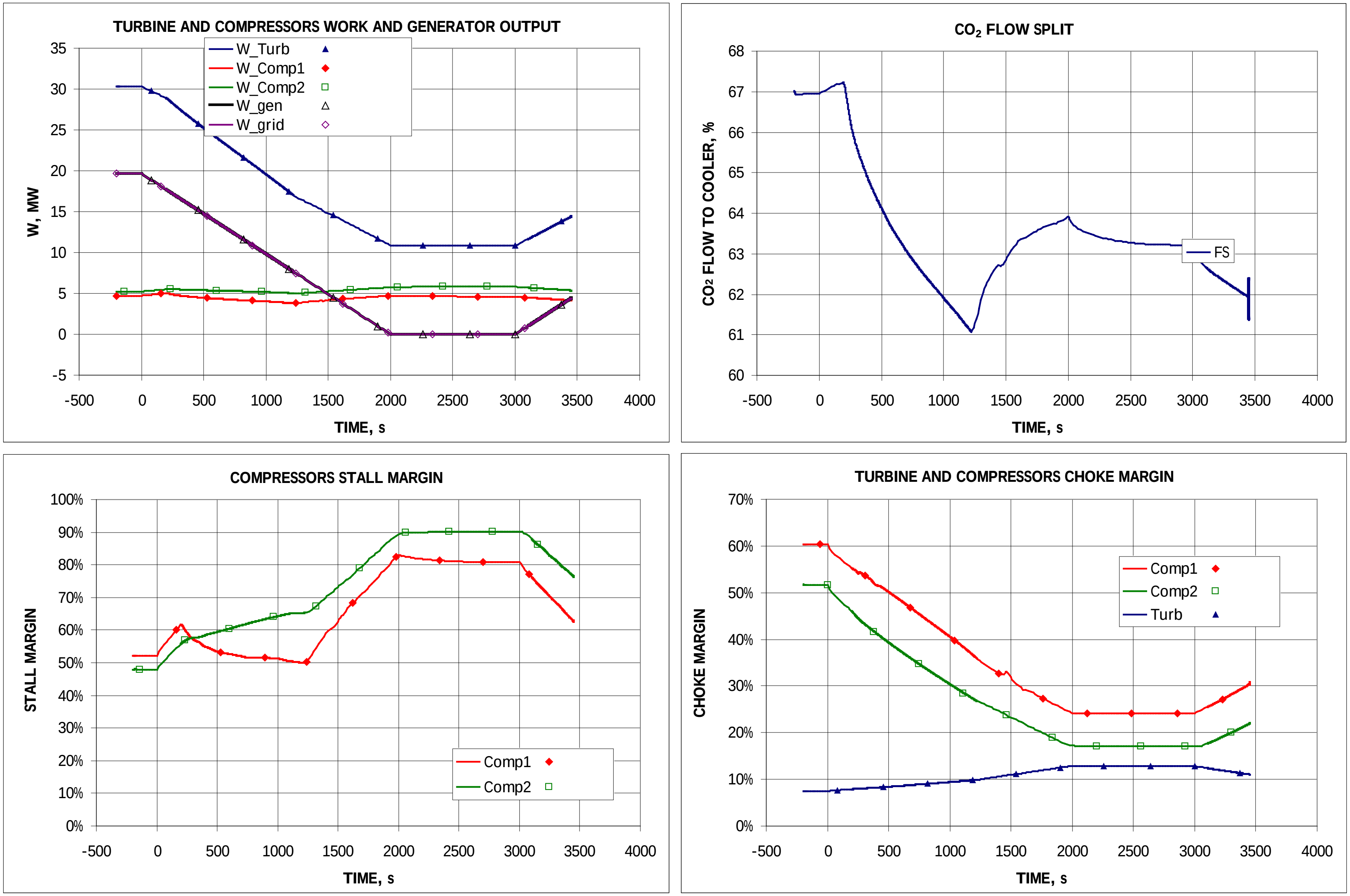

Figure 1. S-CO$_2$ Cycle Operation under Load Reduction to 0 %.

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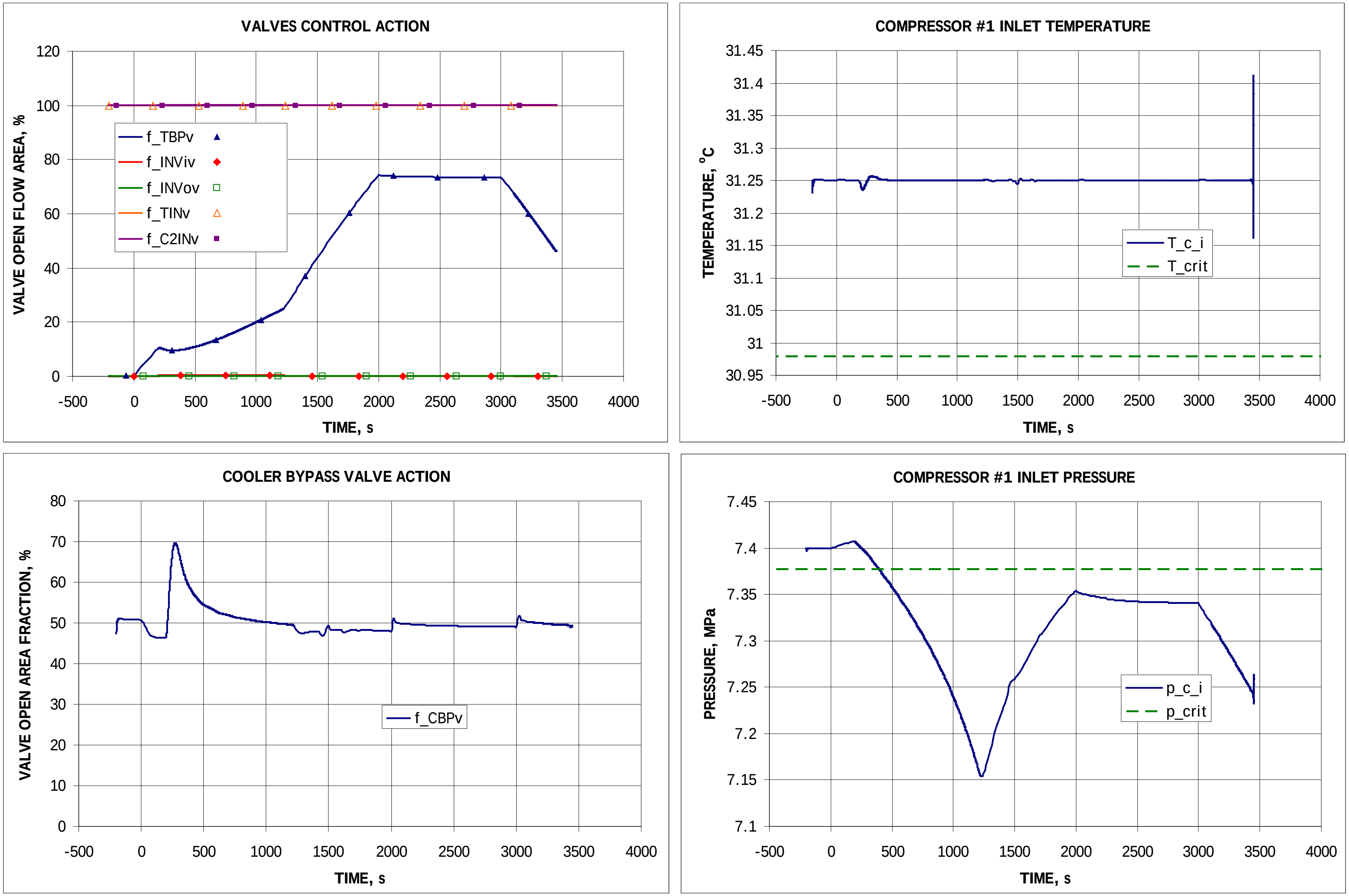

Figure 1. S-CO$_2$ Cycle Operation under Load Reduction to 0 %. (Continued)

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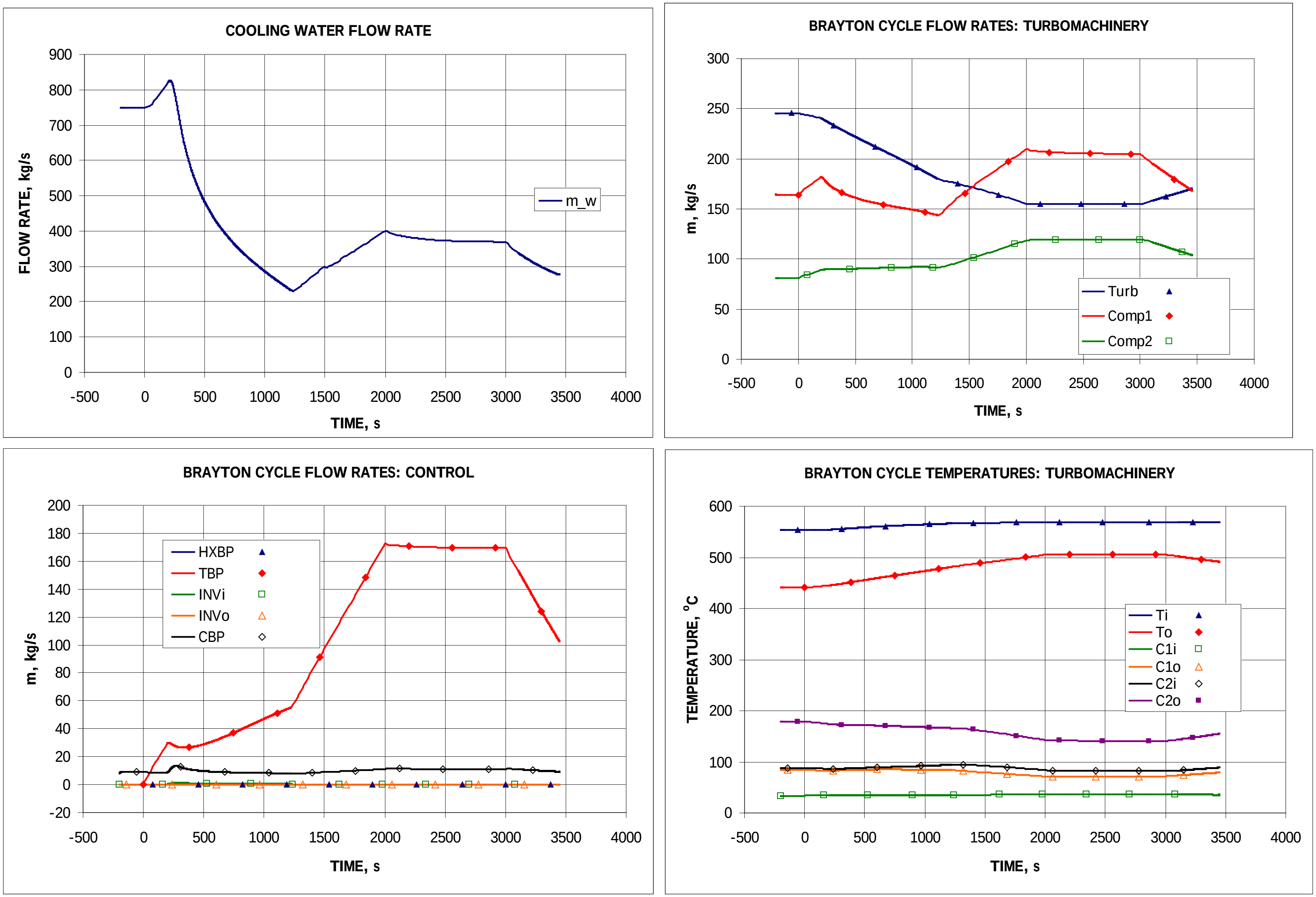

Figure 1. S-CO$_2$ Cycle Operation under Load Reduction to 0 %. (Continued)

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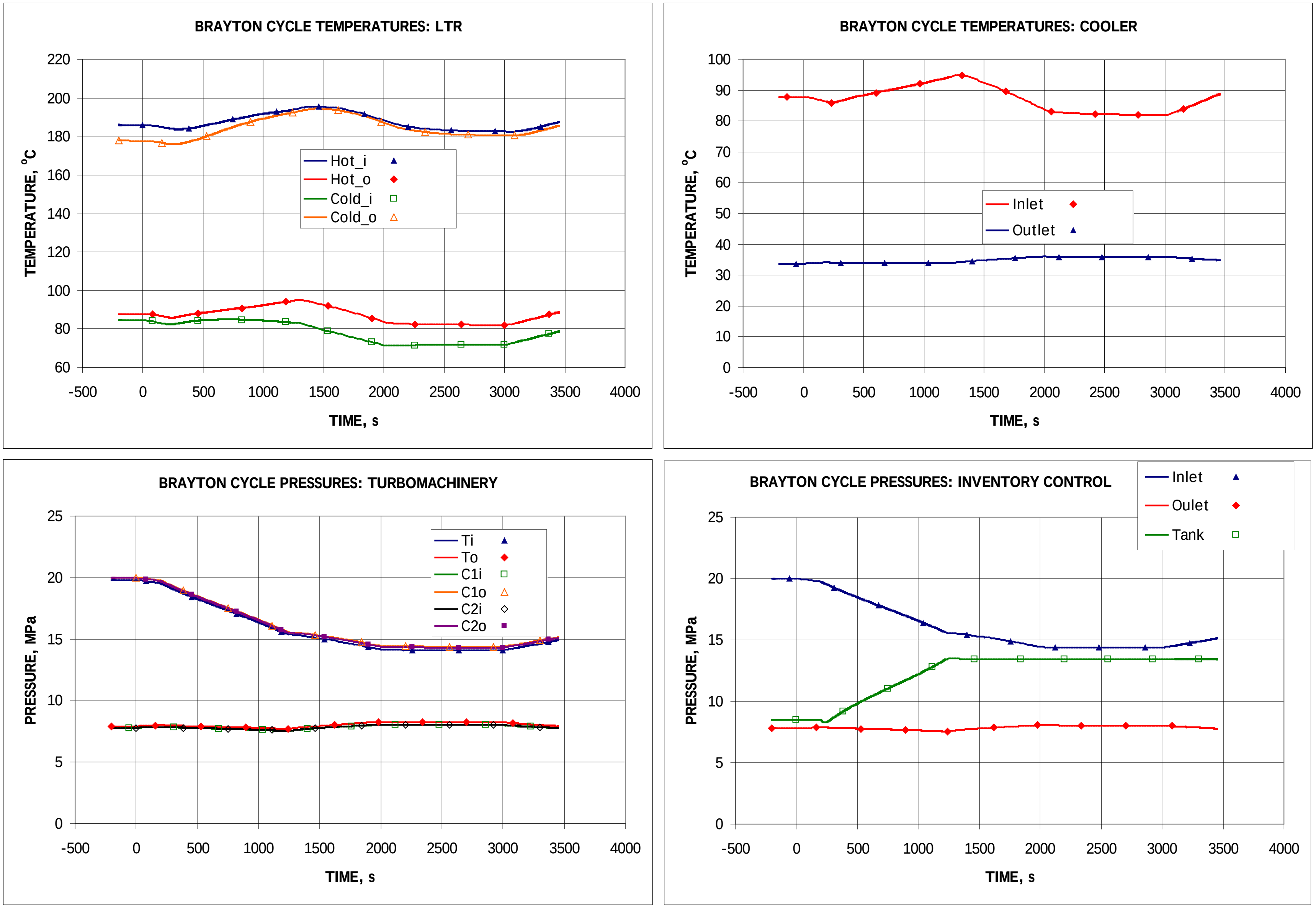

Figure 1. S-CO$_2$ Cycle Operation under Load Reduction to 0 %. (Continued)

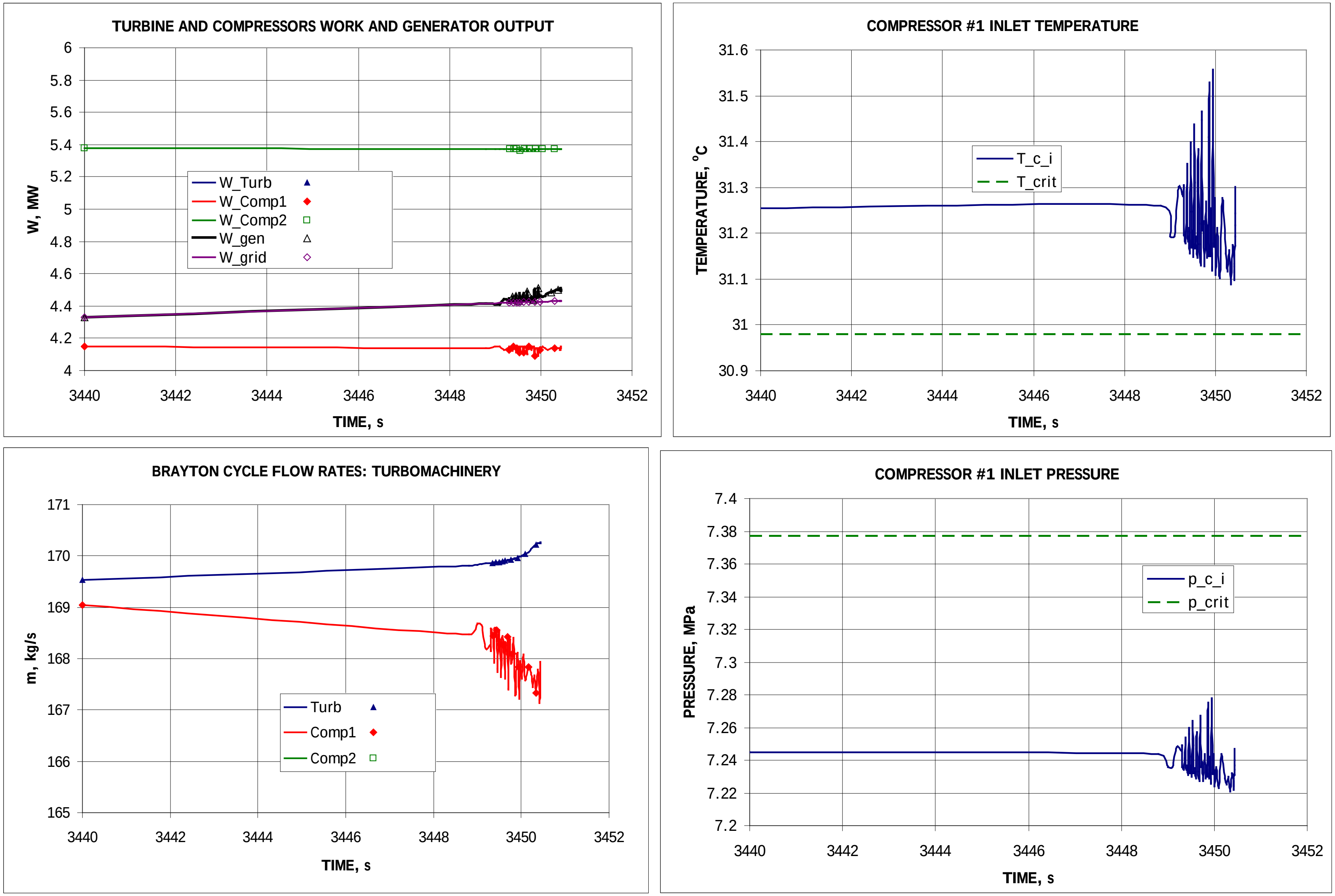

Figure 2. Detailed Results for the Instability Region.

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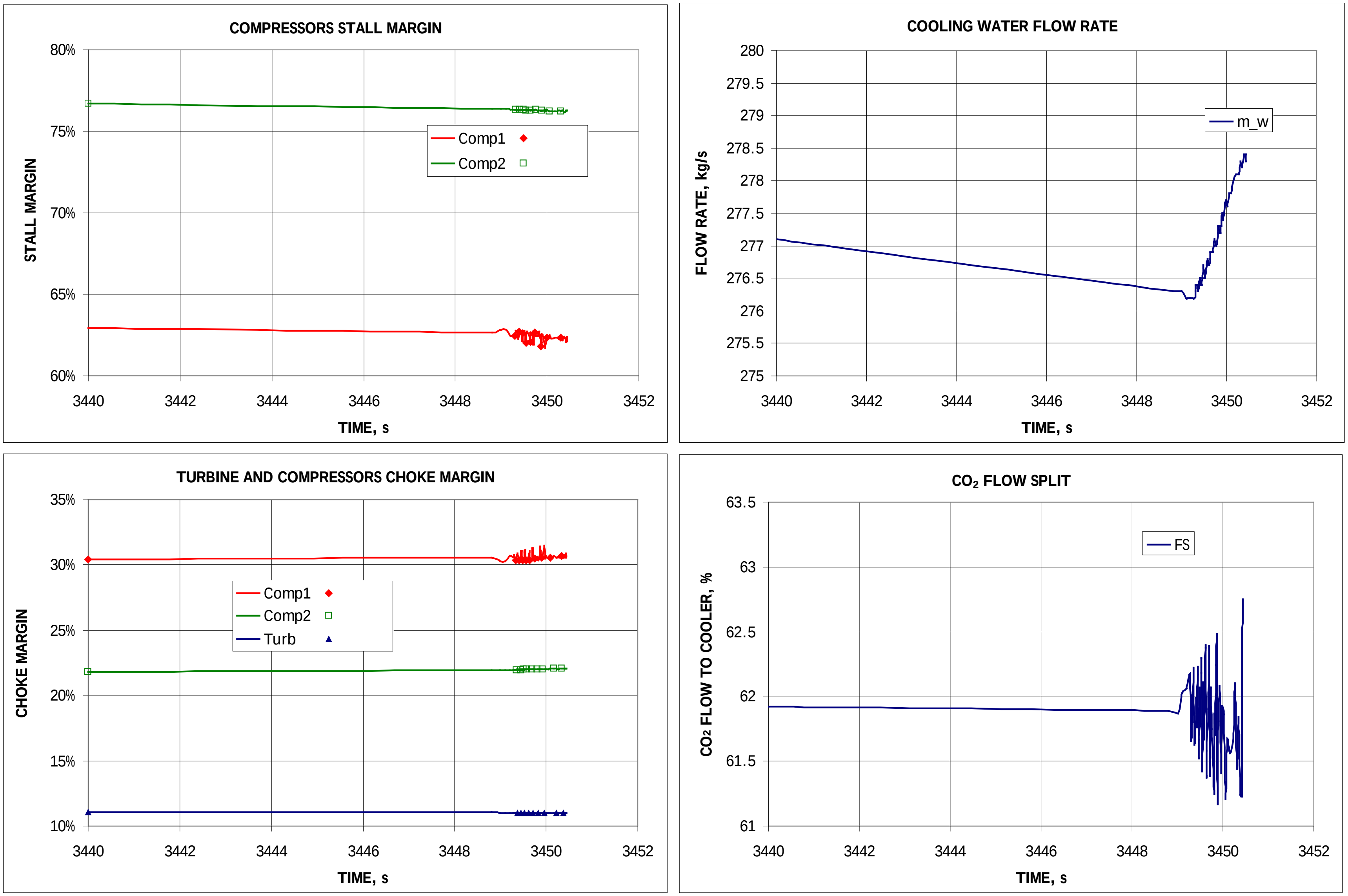

Figure 2. Detailed Results for the Instability Region. (Continued)

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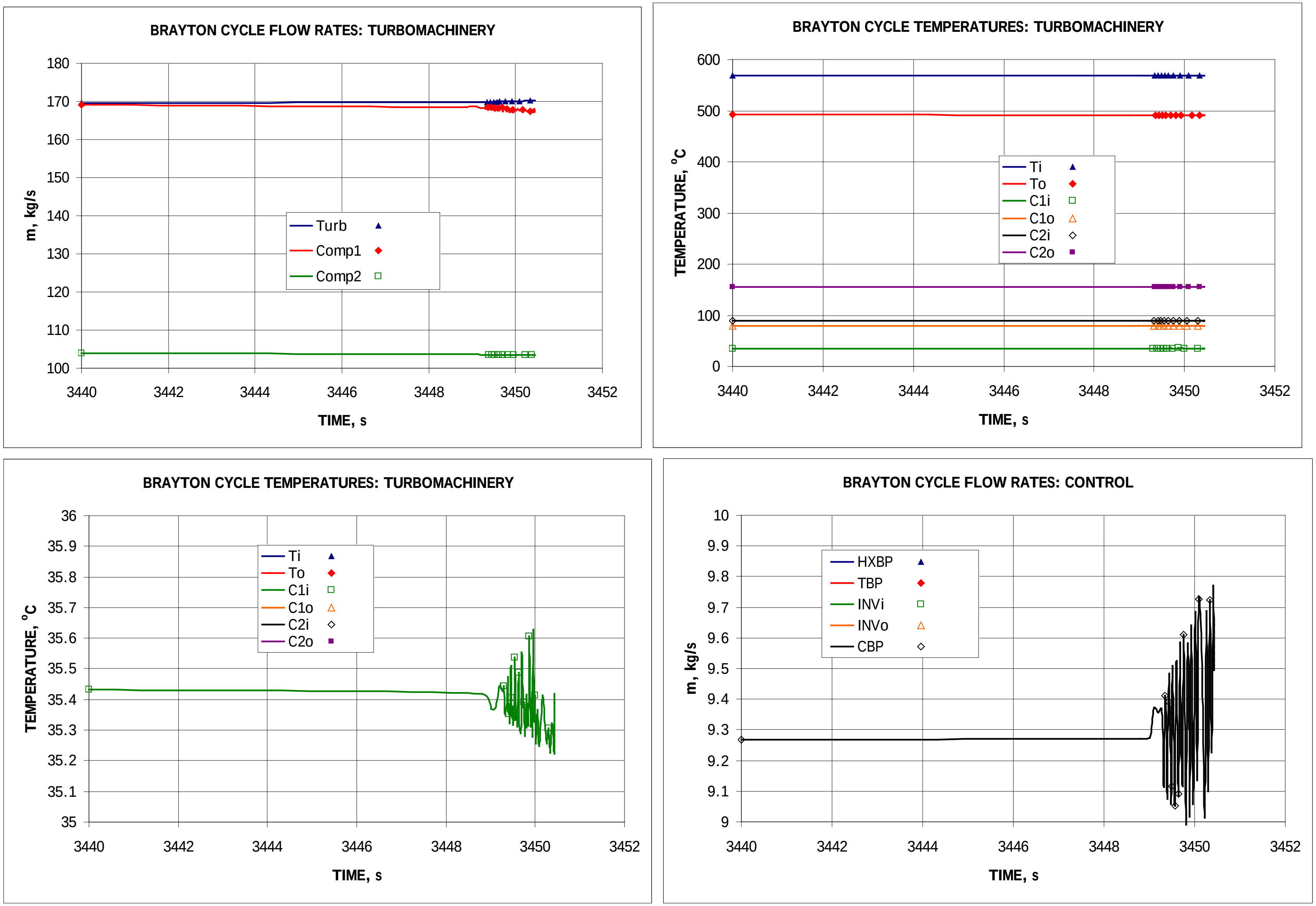

Figure 2. Detailed Results for the Instability Region. (Continued)

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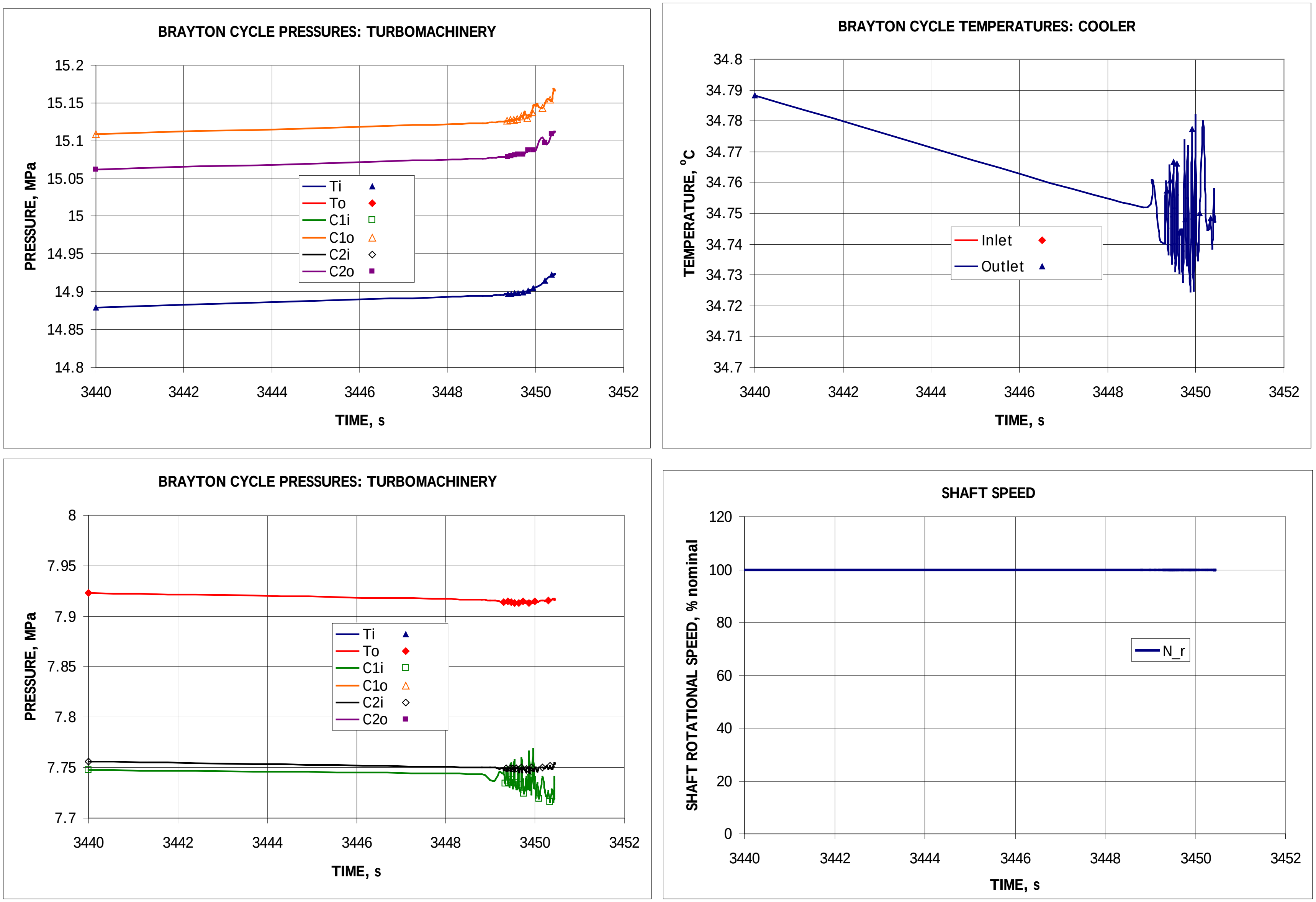

Figure 2. Detailed Results for the Instability Region. (Continued)

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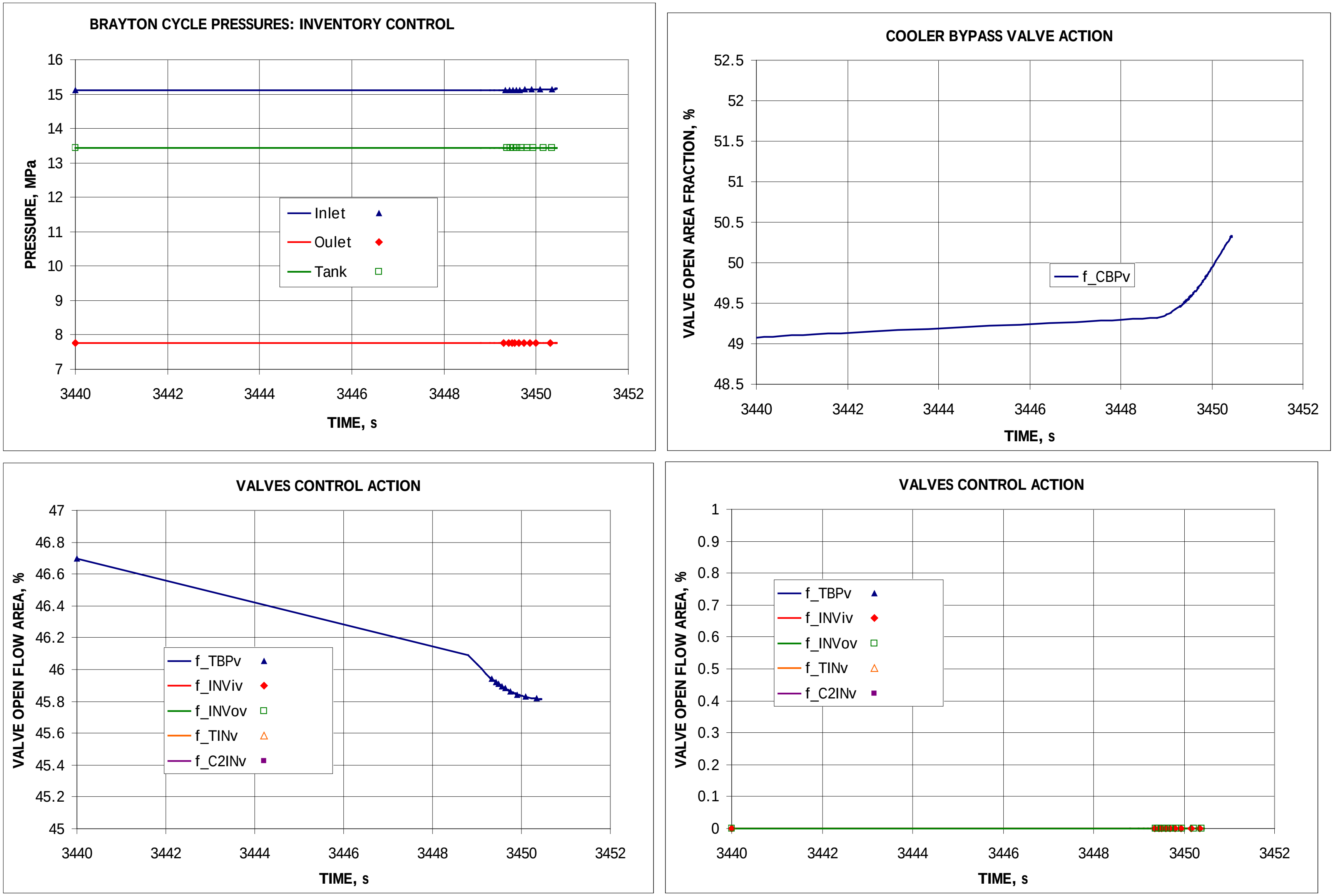

Figure 2. Detailed Results for the Instability Region. (Continued)

2.2. Comparison with Compressor Test Data

One of the objectives of the ANL work for FY 2008 was a comparison of the compressor performance subroutine predictions with experiment data obtained at the Sandia National Laboratories (SNL) S-CO_2 compression which is currently in operation at Barber-Nichols Inc.

However, due to various delays in fabrication of the compression loop, no experiment data has been provided to ANL in FY 2008. It is expected that the data will be available next fiscal year such that the model validation task can be started in FY 2009.

2.3. Adaptation of Plant Dynamics Code for Sodium-Cooled Fast Reactors

Since the focus of the S-CO_2 cycle work for FY 2008 has been on developing the cycle for SFRs, work on adapting the ANL Plant Dynamics Code to SFRs has been initiated. The code was initially developed for LFRs; last year, the S-CO_2 cycle part of the code was decoupled from the reactor part [1]. The reference SFR design for this work is the Advanced Burner Test Reactor (ABTR) [3, 4, and 5]. The Advanced Burner Test Reactor (ABTR) is a 96 MWe (equivalent to 250 MWt) metallic-fueled pool-type Sodium-Cooled Fast Reactor (SFR) operating with core outlet and inlet temperatures of 510 and 355°C, respectively. The ABTR was developed at Argonne National Laboratory (ANL) as a first step in demonstrating technologies for the transmutation of transuranics recovered from Light Water Reactor (LWR) spent fuel, and hence, the benefits of fuel cycle closure to nuclear waste management. Additional ABTR objectives are to 1) incorporate and demonstrate innovative design concepts and features that may lead to significant improvements in cost, safety, efficiency, reliability, or other favorable characteristics that could promote public acceptance and future private sector investment in Advanced Recycling Reactors (ARRs); 2) to demonstrate improved technologies for safeguards and security; and 3) to support development of the U.S. infrastructure for design, fabrication, and construction, testing, and deployment of systems, structures, and components for the ARRs. The reactor and S-CO_2 cycle ABTR flow diagram is shown in Figure 3.

In order to adapt the Plant Dynamics Code to SFRs, some modifications had to be made to the steady state part of the code. Most of the code modifications are due to presence of the intermediate sodium loop with intermediate heat exchangers (IHXs). Another major difference of the reference ABTR design compared to the reference STAR LFR designs is forced circulation of primary and intermediate coolants instead of natural circulation of the primary liquid metal coolant. The steady state code modifications include:

- Geometric parameters of the primary system and the intermediate loop, such as core dimensions, thermal difference between the core and IHX, and so on;

- IHX design, performance calculations, and pressure drops;

- Power requirements for sodium pumps;

- Possibility to use Printed Circuit Heat Exchanger^{TM} (PCHE^{TM}) technology for intermediate sodium-to-CO_2 heat exchangers (only straight tube HXs have previously been supported for In-Reactor Heat Exchangers (IRHXs) in the Plant Dynamics Code so far).

In addition to the steady state code, the corresponding modifications were made to the dynamic calculation initialization subroutine. The subroutine calculates the volumes and masses required for the dynamic calculations. The subroutine can now calculate the volumes and masses for SFR primary and intermediate circuits. Also, the performance maps are calculated as part of the dynamic initialization. So far, only synchronous maps have been recalculated for the ABTR S-CO_2 cycle turbine and compressors.

The modifications of the dynamic subroutines for SFRs have been started but have not yet been completed. The modification of the dynamic subroutines is completed up to the point where the equations can be solved for steady state operation of the entire plant. To carry out the actual transient calculations, development of a sodium pump model along with the corresponding control system still needs to be carried out for the Plant Dynamics Code. In addition, the reactivity feedback and reactor power control models have to be modified for SFRs.

The SFR Plant Dynamics Code has been tested for steady state operation; i.e., when the time dependent equations are solved, but no transient initiating event is introduced. No significant deviation from steady state values is observed during a 4,000 second run at full power nominal operating conditions.

2.4. PCHE Model

As a part of the PCHE experiment work at ANL, the PCHE thermal hydraulic model is being developed at ANL. The model is currently being updated to improve the heat transfer and pressure drop predictions based on the recent data obtained at ANL during the PCHE S-CO_2-to-S-CO_2 heat exchanger experiment work. Once the model update is complete, the PCHE model will be presented in the coming Generation IV reports and/or conference or journal papers.

3. S-CO_2 Cycle Control Update

3.1. Control Adjustment

During the work on the S-CO_2 dynamic model, improvement and adjustment of the cycle control system strategy has been continued. The adjustments to the control system during this year's work have been limited to improving each control mechanism's response by fine tuning the control input parameters, such as PID coefficients and valve opening and closing rates. No major updates to the control system, such as introduction of new controls or change of the general control strategy, have been implemented this year.

3.2. Normal Shutdown Heat Removal System

Previous analysis [2] demonstrated that the S-CO_2 cycle may not be suitable for removing heat from the reactor following reactor scram (i.e., removing the decay heat). It was previously found that a significant reduction of the heat removal causes the rapid decrease in the CO_2 temperature at the turbine inlet with subsequent reduction in the turbine outlet temperature. Due to the recuperative nature of the S-CO_2 cycle, this reduction in turbine temperatures causes a decrease in the CO_2 temperatures at the main heat exchanger inlet, which in turn further reduces the turbine inlet temperature. It has been calculated [2] that if the S-CO_2 turbomachinery rotational speed is not controlled by the grid frequency (asynchronous mode), then the reduction in CO_2 temperature leads to reduction in turbine work below the required compressor work input in about 60 seconds such that CO_2 circulation cannot be maintained. If the turbomachinery continues to operate in a synchronous mode such that the compressors are run from the generator, than in about 400 seconds, the drop in CO_2 temperatures in the main heat exchanger lead to the freezing on the primary side coolant (molten Pb in Reference [2]). An attempt was made to adjust the cycle operating parameters, such as the turbomachinery rotational speed, for operation under the decay heat removal mode, but no acceptable solution (control scheme) was found which would enable long-term operation of the S-CO_2 cycle in this mode.

It has therefore been identified that a dedicated shutodwn heat removal loop needs to be added to the S-CO_2 cycle. An example of such loop could be a CO_2 bypass circuit from the main heat exchanger to the existing cooler or some other decay heat removal heat exchanger. This bypass loop would require a separate CO_2 pump/circulator. Figure 3, repeated here from Reference [3 and 5, shows the proposed decay heat removal system for ABTR.

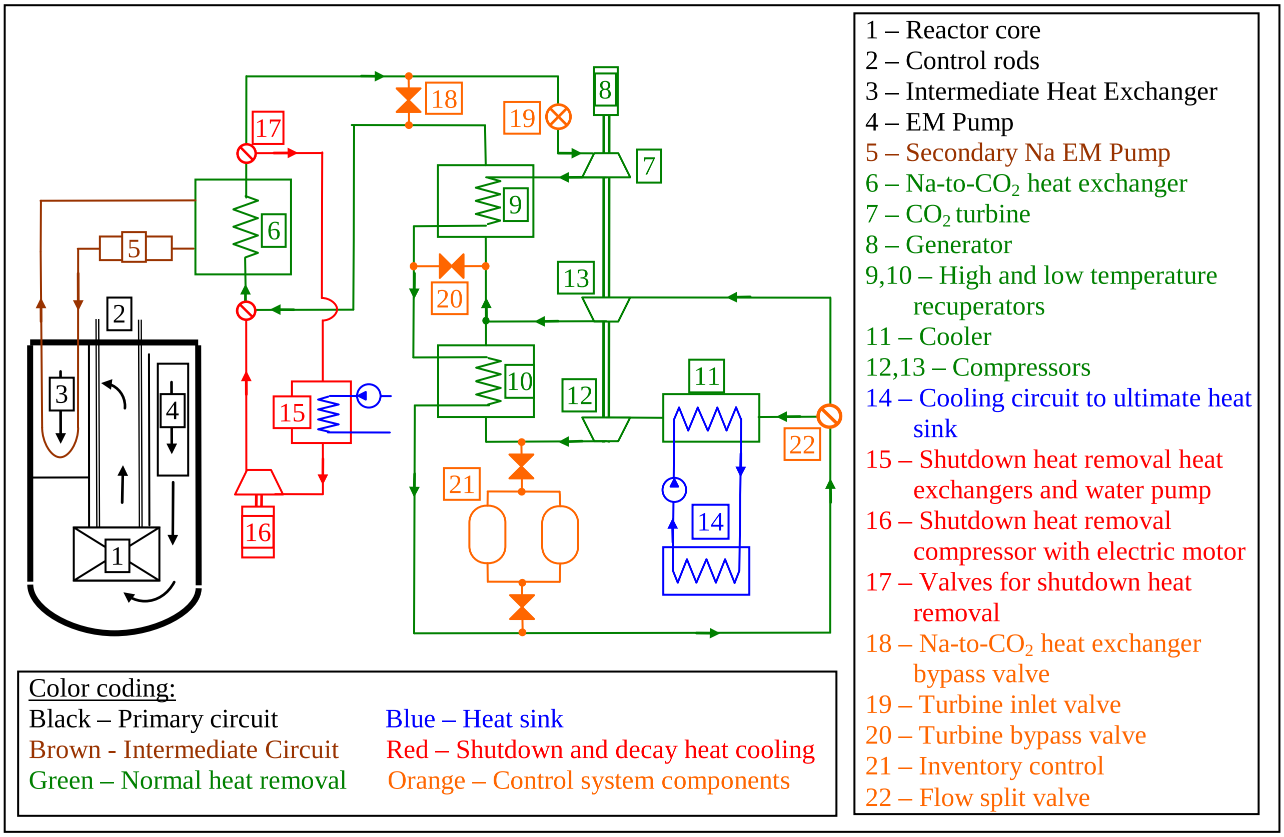

Figure 3. ABTR S-CO_2 Cycle and Shutdown Heat Removal Loop.

One of the goals of the current work was to introduce a shutdown cooling loop to the dynamic model of the S-CO_2 cycle. However, before such a shutdown system can be activated, the cycle control system should be able to accommodate a transition from normal operation into the shutdown decay heat removal mode. Thus, an analysis of the control system response to a reactor scram event has been carried out in order to:

- Assure that the control system can handle the transition to the decay heat removal mode; i.e., S-CO_2 cycle can operate for some reasonable time after the reactor scram; and
- Define the requirements for the shutdown heat removal system, such as starting time, power level, and CO_2 temperatures and pressures at the main heat exchanger inlet and outlet at the time of shutdown heat removal system startup (i.e., at the end of the transition).

3.2.1. Cycle Operation under Reactor Scram

The event is initiated by an ABTR reactor scram where the reactor fission power is shut down by the movement of reactor control rods (large negative reactivity is inserted in few seconds). The reactor operates in the decay heat mode. The event is considered to be a single-fault design basis event (DBE); that is, the only fault is the initiating event causing the reactor scram. All other systems, including primary and S-CO_2 Brayton cycle control systems are assumed to be operational and function as intended. To avoid thermal shock to the reactor structures resulting by the fast power reduction which reduces the core outlet temperature, the primary and intermediate electromagnetic sodium pumps are tripped such that the pumps coast down due to their inertia followed by a transition to natural circulation sodium flow. The primary coolant flow rate versus time is calculated using SAS4A/SASSYS-1 ABTR model and is shown in Figure 4.

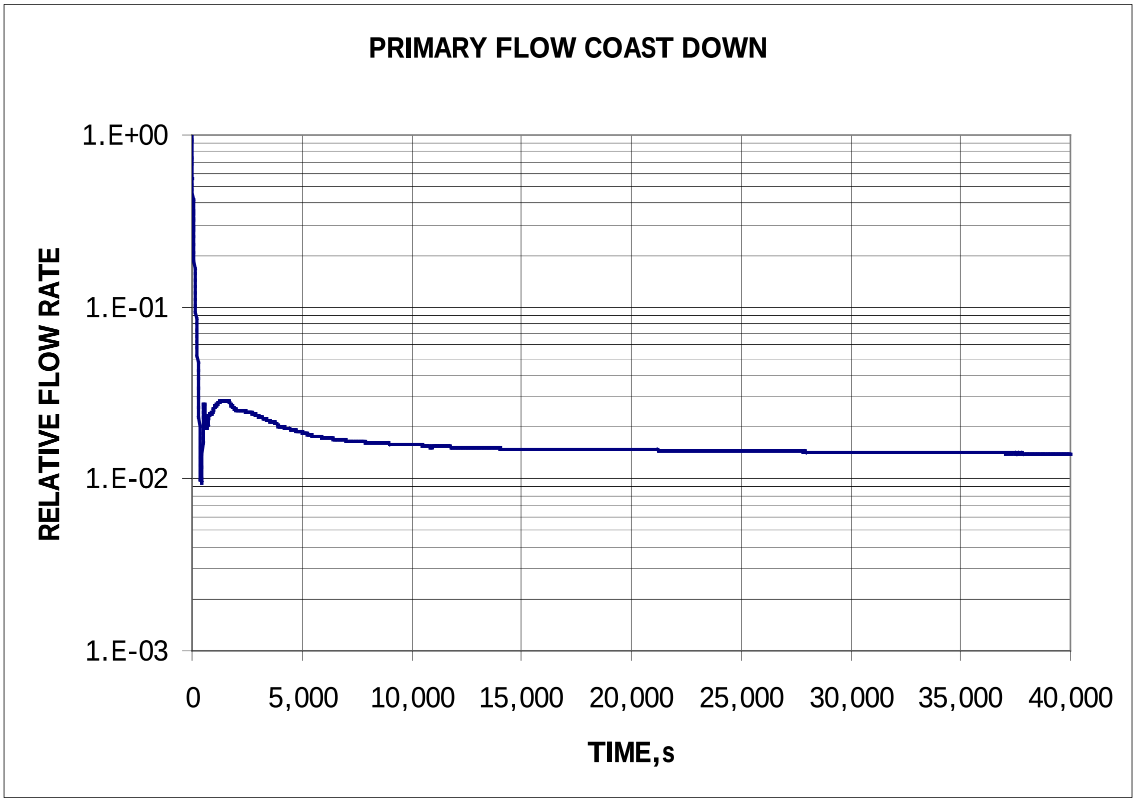

Figure 4. Primary Coolant Flowrate as Calculated by SAS4A/SASSYS-1.

Analytical Tool and Assumptions

The current version of the SAS4A/SASSYS-1 code does not model the S-CO_2 Brayton cycle. Therefore, a Plant Dynamics Code [2] developed for SSTAR LFR is used in the analysis. This code, however, does not currently have a capability to simulate the SFRs with intermediate sodium loops. Therefore, the following assumptions have been made in order to approximately simulate the ABTR S-CO_2 cycle response. It is assumed that the heat addition to the S-CO_2 cycle in ABTR intermediate Na-to-CO_2 heat exchangers is simulated by the SSTAR primary Pb-to-CO_2 heat exchangers. The Pb flow rate is artificially corrected to represent the flow rate shown in Figure 4 as described below.

The 250 MWt ABTR S-CO_2 Brayton cycle is assumed to be represented by the 45 MWt SSTAR S-CO_2 Brayton cycle. This includes the dimensions of the cycle components (turbomachinery and heat exchangers), CO_2 flow rates and temperatures, as well as the turbomachinery response (performance maps). The flow rates, HX heat ratings and turbomachinery power ratings are scaled to the steady state nominal design values to account for the difference between the ABTR and SSTAR power inputs. The differences in S-CO_2 temperatures and turbomachinery response are neglected in this analysis.

It is envisioned that it would take few minutes to accomplish a smooth transition from the normal S-CO_2 cycle operation to the operation under the shutdown heat removal mode. Therefore, it is sufficient to show that the S-CO_2 cycle could effectively remove the decay heat from the reactor during first few minutes of the transient. Figure 5 shows the history of the primary flow coast down presented in Figure 4 during first few 2000 seconds (~33 minutes) of the transient. It can be seen in Figure 5 that the transition from the forced flow cost down caused by the primary pumps inertia to the natural circulation flow occurs between 400 and 800 seconds into the transient. Therefore, 400 seconds (~7 minutes) is considered to be a sufficient time for the shutdown heat removal loop to start. Therefore, the initial portion of the transient, 400 seconds characterized by the primary pump coastdown time, is selected for the S-CO_2 cycle transient analysis using the ANL Plant Dynamics Code.

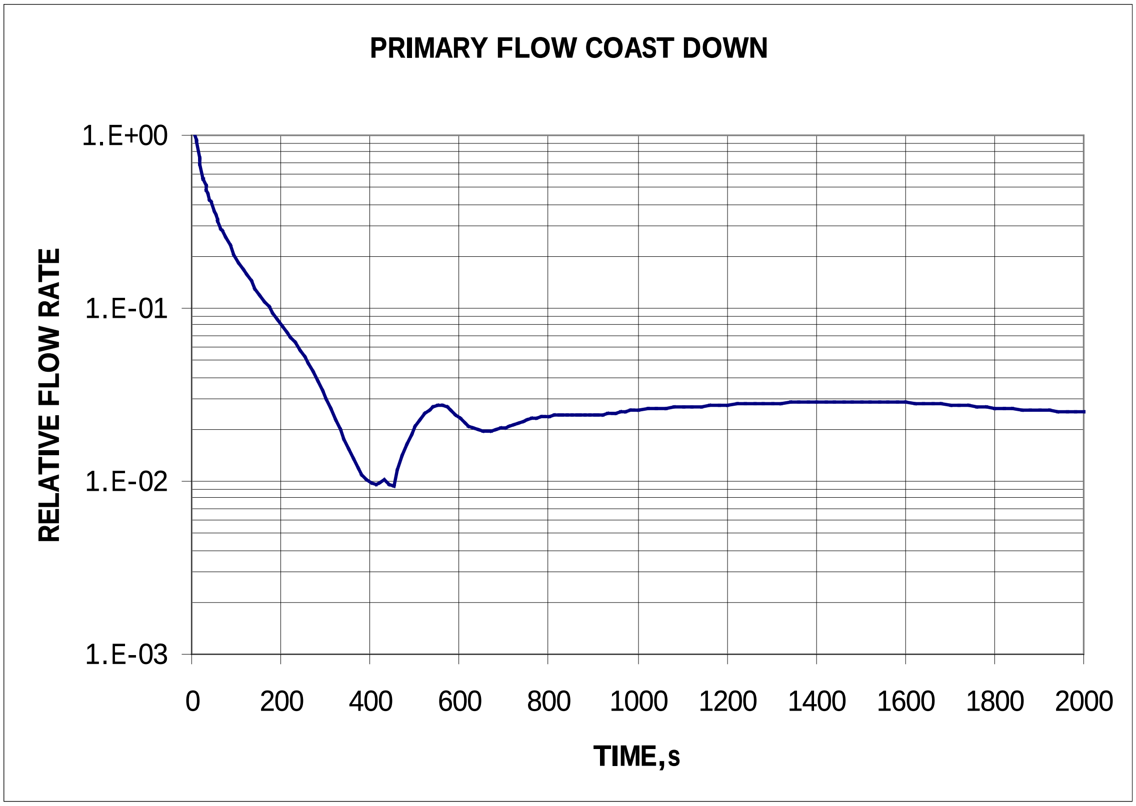

Figure 5. ABTR Primary Flowrate during First 2000 seconds.

Figure 6 demonstrates that during the first 400 seconds the primary flowrate can be approximately described by a simple exponential law. (Any inaccuracy of the fit seems to be small compared to the other assumptions made for the analysis, such as representing the Na-to-CO_2 heat exchanger with a Pb-to-CO_2 HX.) Therefore, the exponential law presented in Figure 6 has been adopted to describe the primary coolant flow rate during the transient analysis of the S-CO_2 cycle. The primary coolant temperatures are calculated directly in the Plant Dynamics Code from the reactor decay heat and the heat removal rate by the CO_2.

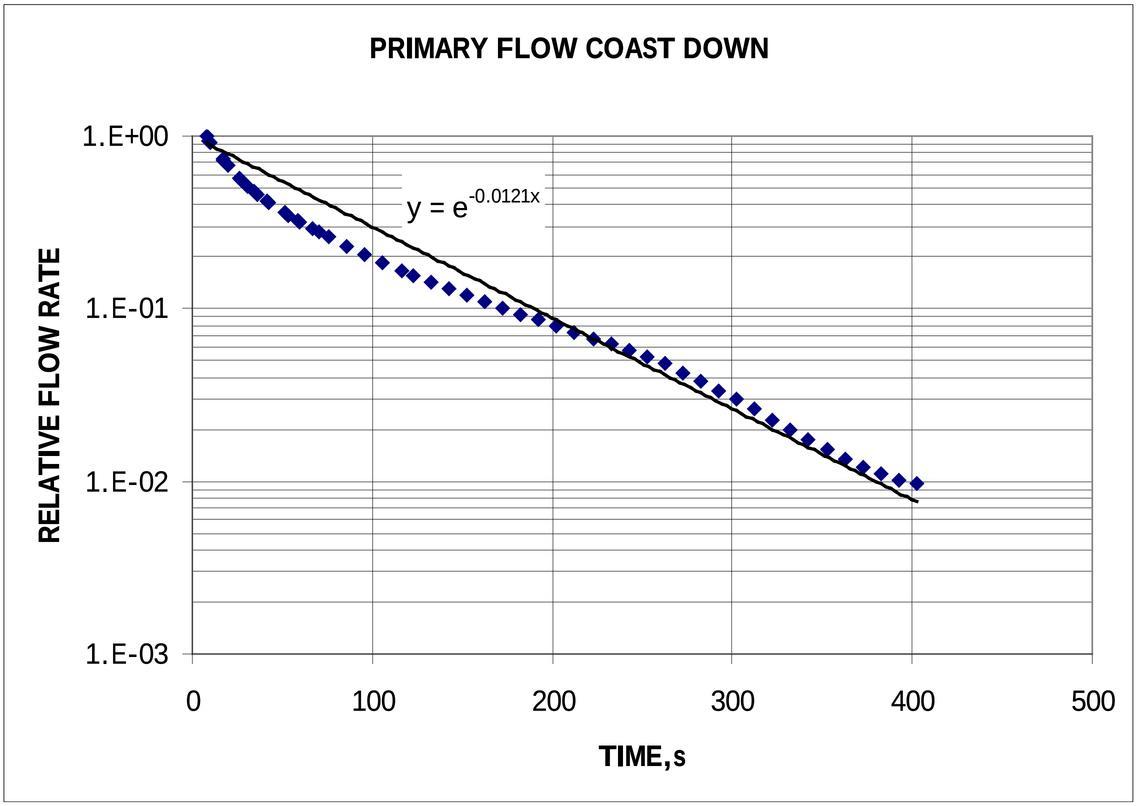

Figure 6. Primary Flow Coastdown Fit.

S-CO_2 Cycle Operation during Reactor Scram Transient

For the single-fault DBE, the S-CO_2 cycle balance of plant (BOP) and its controls are assumed to be fully operational. However, the decision has not yet been made how the cycle control system would handle such transients or any other events related to the transition to the decay heat removal mode. Therefore, two possible control strategies have been analyzed here, as described below.

a) Operation in Synchronous Mode with Large Electrical Grid

Under this mode, it was assumed that the generator is connected to the grid and stays connected during the whole transient. The grid is considered to be large enough compared to the generator (plant) output that the variation in the generator power output does not affect the grid frequency and, therefore, the turbogenerator rotational speed. Practically, this means that the grid would accept any output from the generator and, if during the transient, the net generator output drops below zero, the generator will operate in the motor mode effectively spinning the compressors at a constant speed.

Although the S-CO_2 cycle control was developed in a way to control the generator output, it could not increase the generator output; i.e., no "reserve power" is implemented in the cycle design. As the results show, the drop in the heat addition rate leads to a decrease in the generator output. Since the control system cannot increase the generator output, the generator control stays inactive during the accident (there is still an active control of the compressor inlet conditions).

The results of the simulation of the synchronous mode are presented in Figure 7. The results show that the cycle operates during the 400 seconds transient: compressor stall and choke conditions are not observed such that the CO_2 is still being circulated through the main heat exchanger. The CO_2 conditions at the main compressor inlet, however, drop into the two-phase region. This raises the potential for damage of the compressor blades due to droplet impacts. The net generator output is reduced to zero at the end of the transient (this is just a coincidence; no control was applied to the generator output).

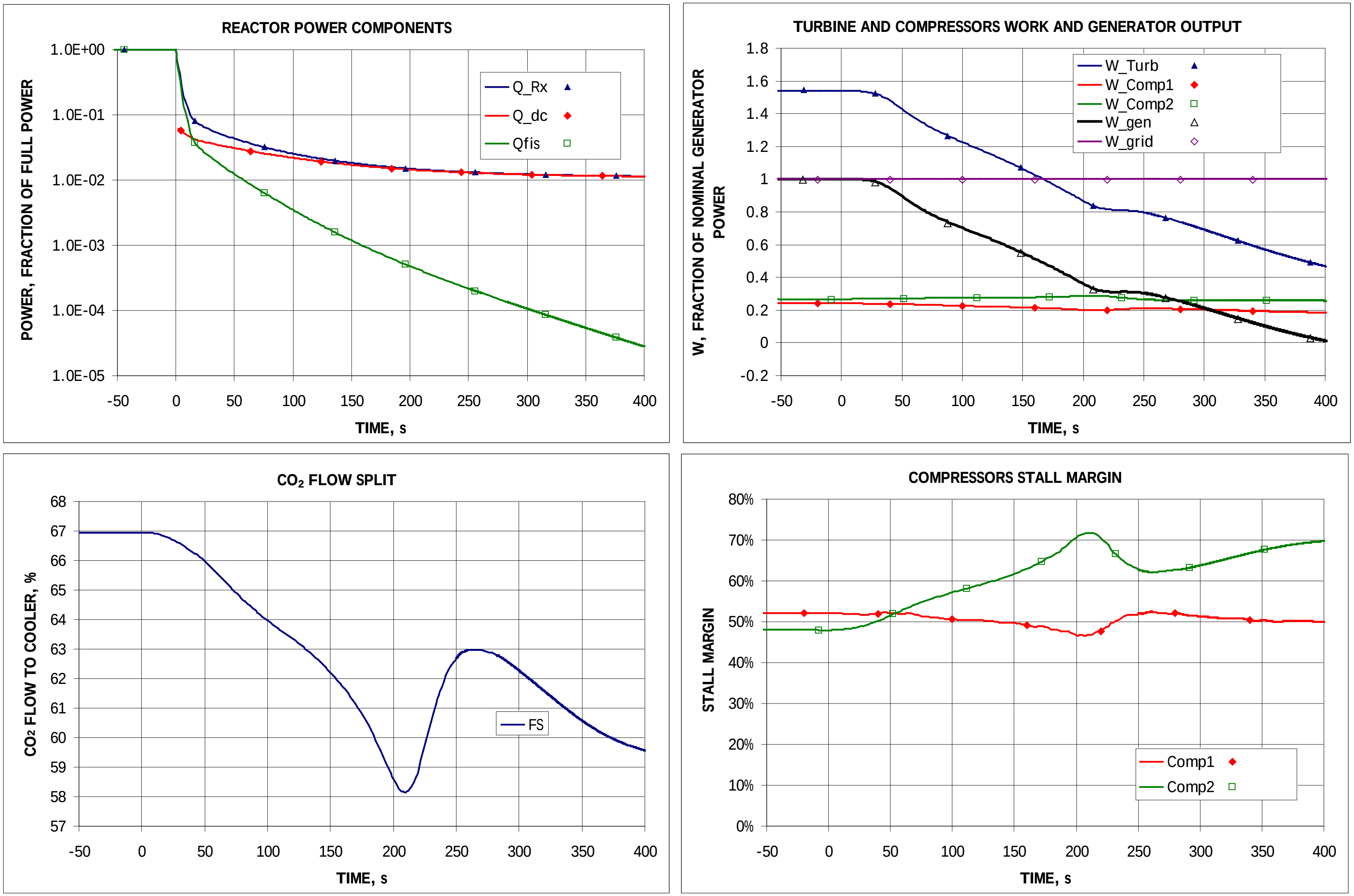

Figure 7. S-CO_2 Cycle Operation Following Reactor Scram with Synchronous Grid Connection.

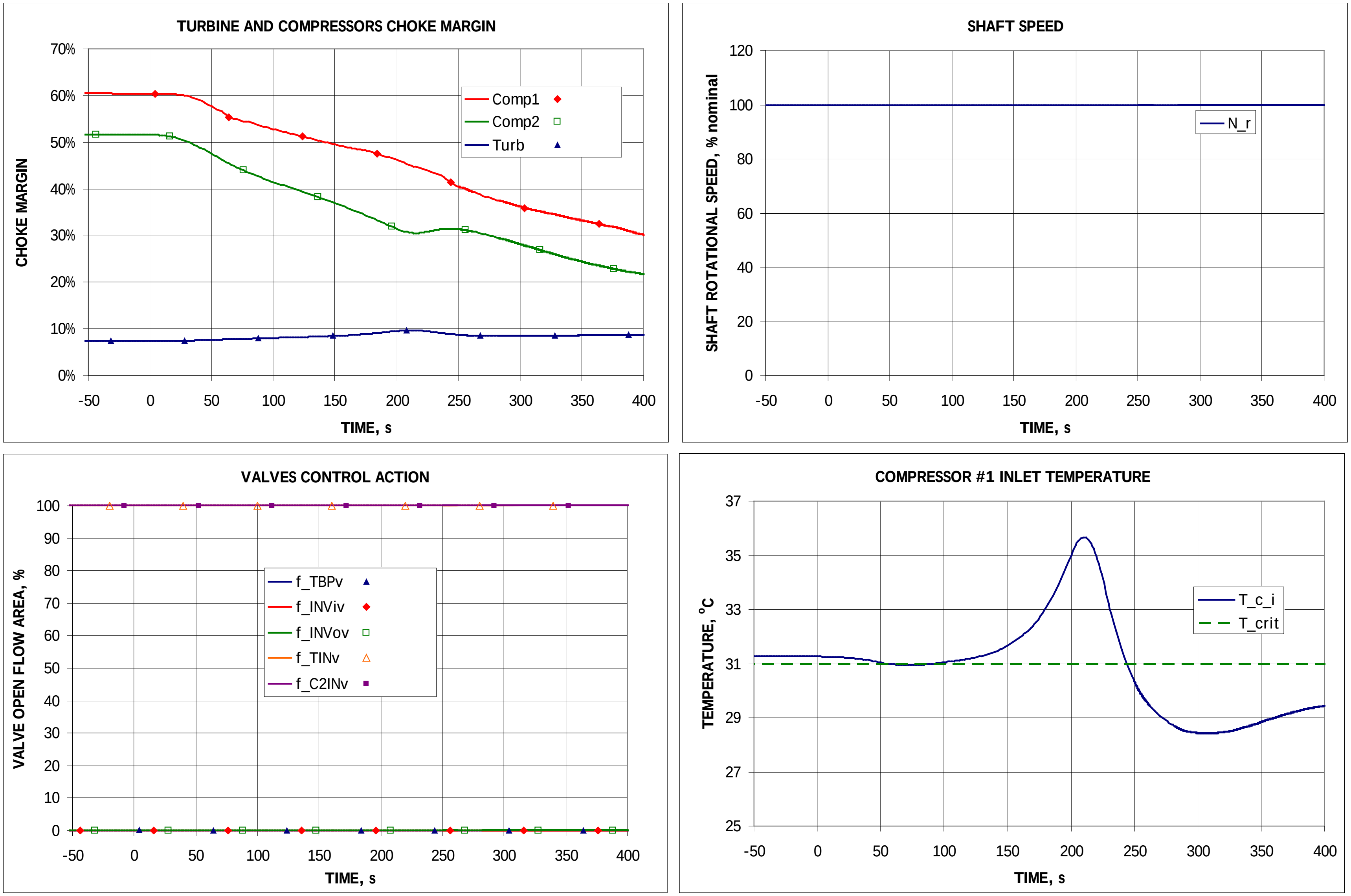

Figure 7. S-CO$_2$ Cycle Operation Following Reactor Scram with Synchronous Grid Connection. (Continued)

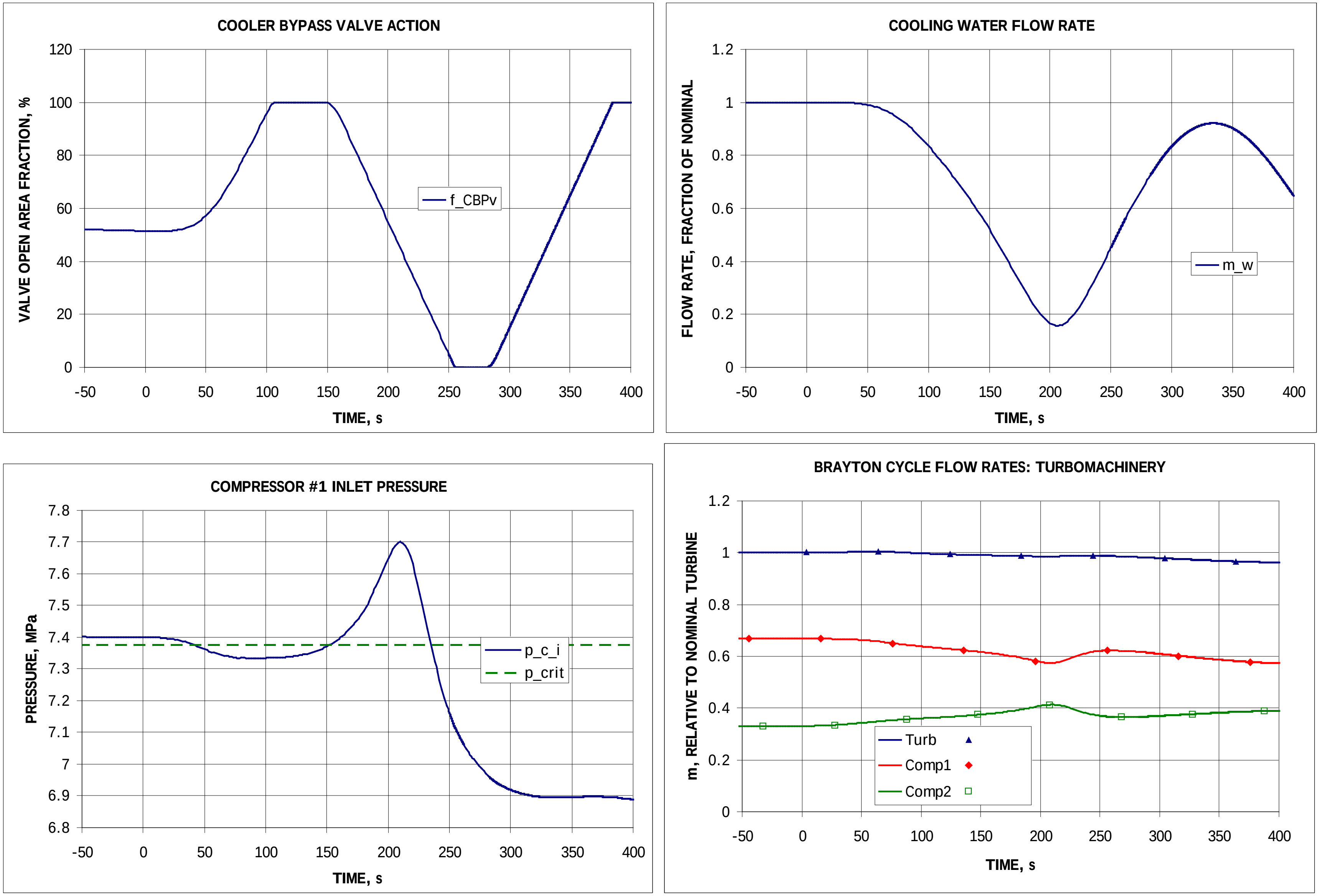

Figure 7. S-CO$_2$ Cycle Operation Following Reactor Scram with Synchronous Grid Connection. (Continued)

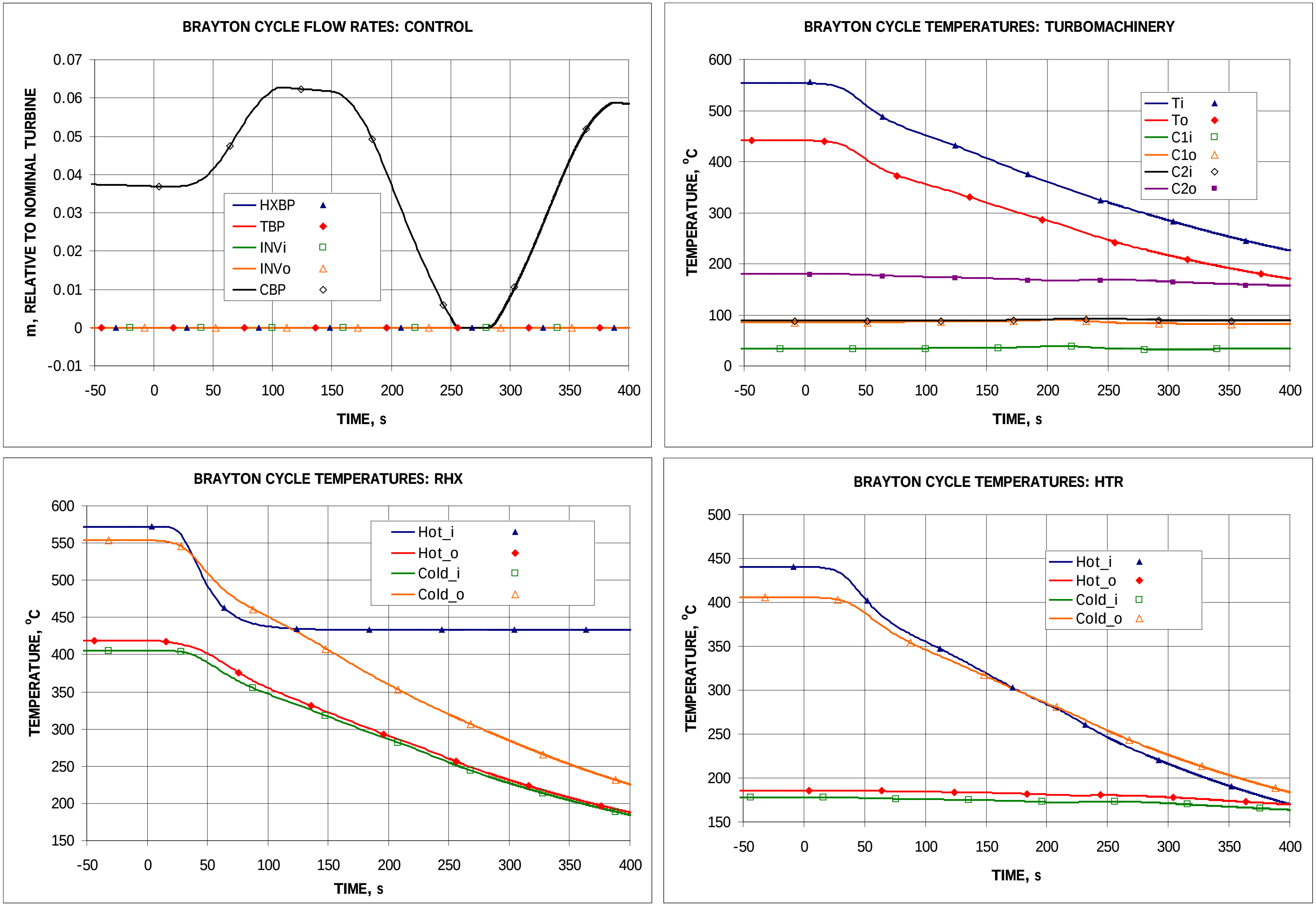

Figure 7. S-CO$_2$ Cycle Operation Following Reactor Scram with Synchronous Grid Connection. (Continued)

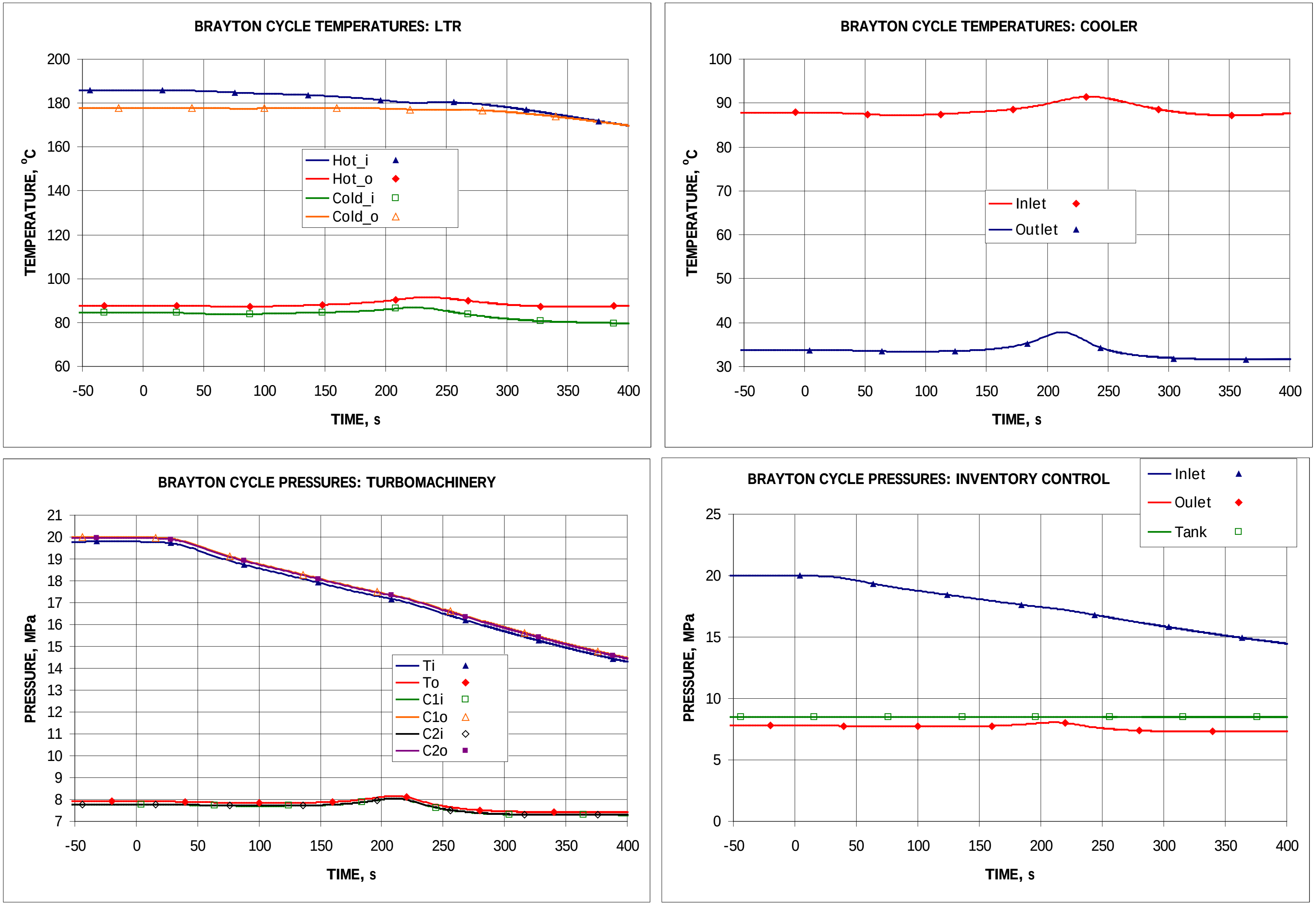

Figure 7. S-CO$_2$ Cycle Operation Following Reactor Scram with Synchronous Grid Connection. (Continued)

b) *Operation with Disconnection from the Electrical Grid*

Although the previously described operating mode assumes synchronous grid connection, the more realistic mode would be a disconnection from the grid following the reactor scram. However, sudden disconnection from the grid is not recommended, since initially almost full power (250 MWt in the ABTR case) is still delivered to the S-CO_2 cycle. Therefore, full generator power (100 MWe) would be applied to the turbomachinery quickly accelerating its rotation and probably causing rotor damage. Thus, in this simulation, the net generator power is first reduced to zero by the means of the Brayton cycle control system and then the generator is disconnected from the grid. This way, there is almost no power imbalance in the turbogenerator shaft at the time of disconnection such that its rotational speed could be safely maintained. It is assumed that the generator power is reduced to zero during first 10 seconds of the transient.

The results of the simulation of operation in this mode are presented in Figure 8. The results show that CO_2 flow through the main HX and the heat removal are present during the transient. The compressors maintain CO_2 circulation during the transient. The maximum variation in the shaft rotational speed does not exceed 2.5 %. The assumed generator power reduction rate – 100 % in 10 seconds or 10 %/s is far larger than any normal operational transients the control system was optimized for; thus some oscillations are observed in the shaft rotational speed and CO_2 flow rates at the beginning of the transient. Similar to the previous case, the S-CO_2 cycle control system could not maintain supercritical conditions at the main compressor inlet.

The turbine bypass control action initially almost fully opens the bypass valve to compensate for the difference between the turbine output and cumulative compressor power consumption to control the shaft rotational speed. This action, however, reduces over time as the turbine output is reduced by the diminishing heat addition to the cycle. The action reaches almost zero bypass flow at the end of the simulation (400 s) meaning that almost no excess power is produced by the turbine at this point. Once the turbine excess power reaches zero, which is estimated to occur around 410 to 420 seconds into the transient, the turbine would not be able to maintain compressor rotation and the CO_2 circulation will stop shortly after that. Thus, the transition to the shutdown heat removal loop operation should occur during the first 400 s after the reactor trip event. These results are similar to those obtained in the synchronous generator operation mode, where the net generator power reaches zero at about the same time – around 400 s. The difference is that in the synchronous case, the CO_2 circulation could be maintained beyond 400 s as generator starts to operate as a motor.

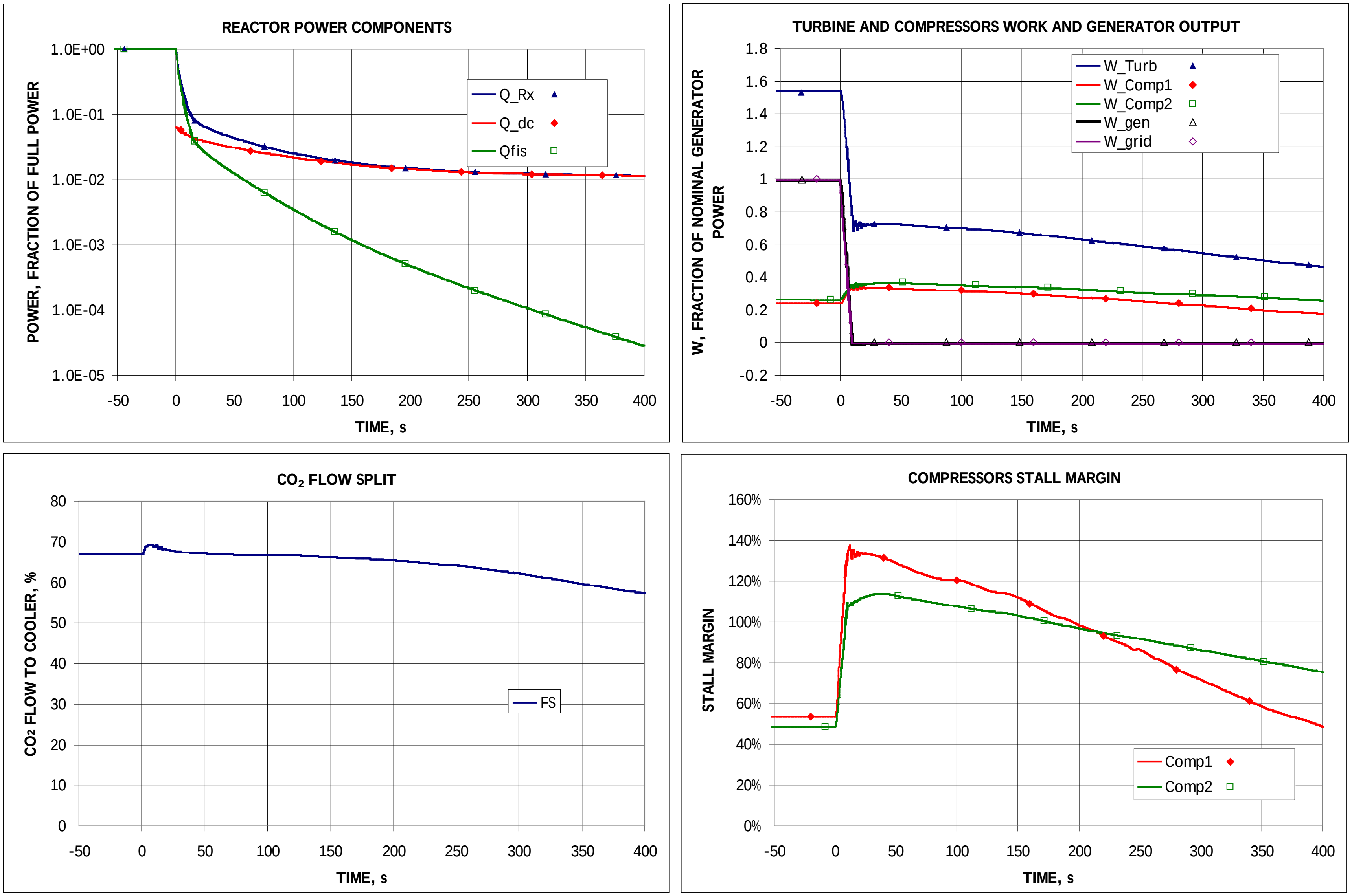

Figure 8. S-CO_2 Cycle Operation Following Reactor Scram with Disconnection from the Grid in 10 Seconds.

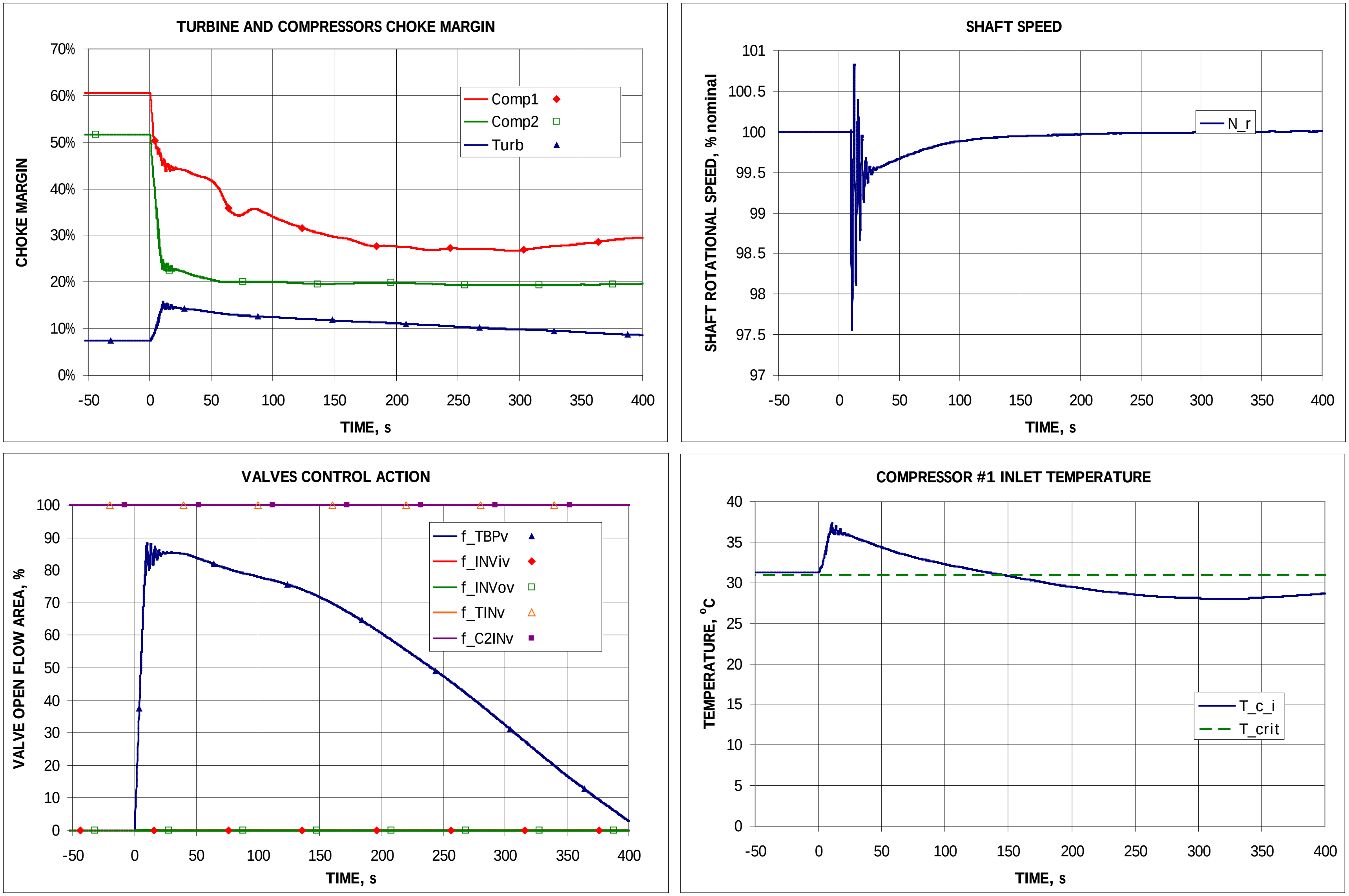

Figure 8. S-CO$_2$ Cycle Operation Following Reactor Scram with Disconnection from the Grid in 10 Seconds. (Continued)

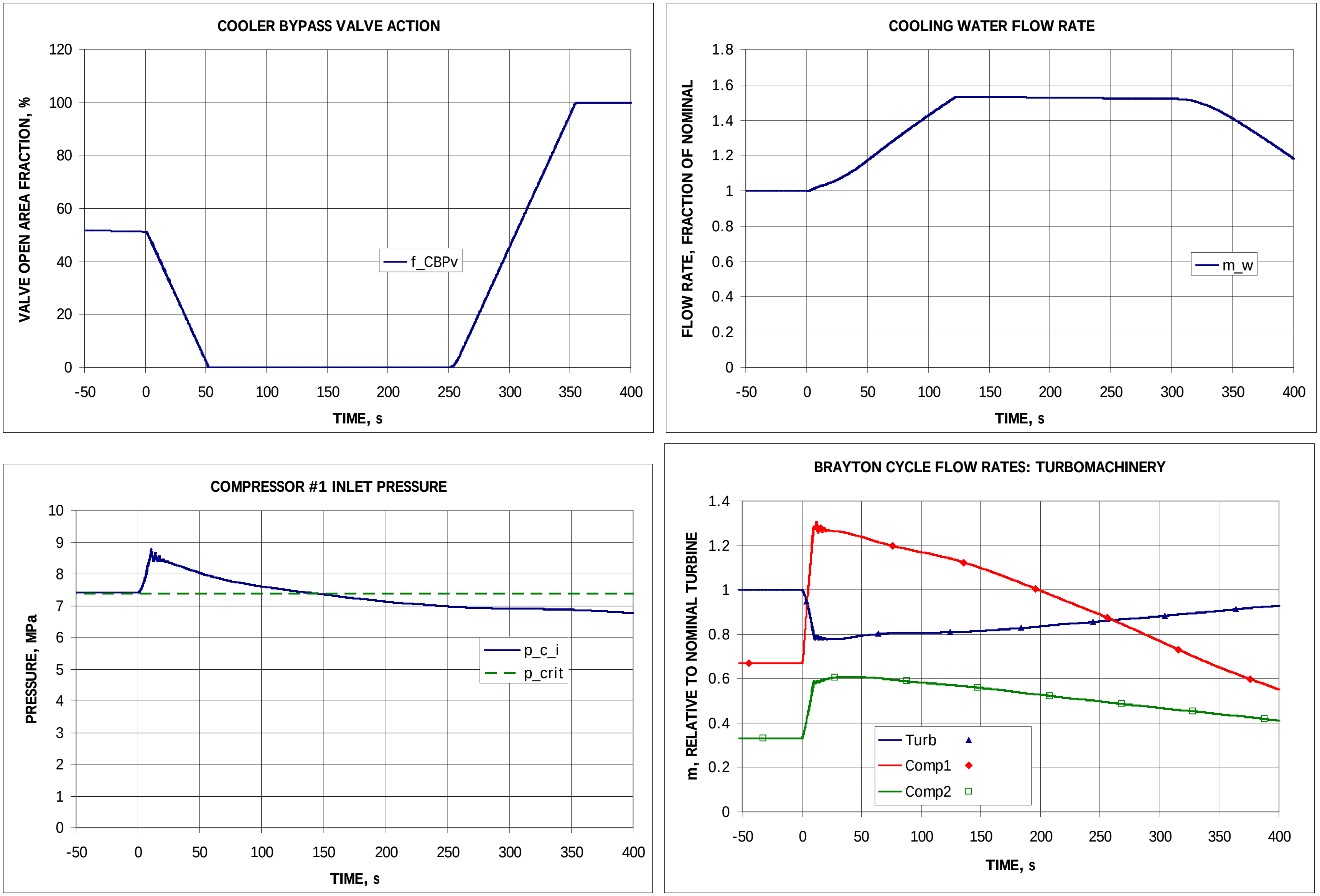

Figure 8. S-CO$_2$ Cycle Operation Following Reactor Scram with Disconnection from the Grid in 10 Seconds. (Continued)

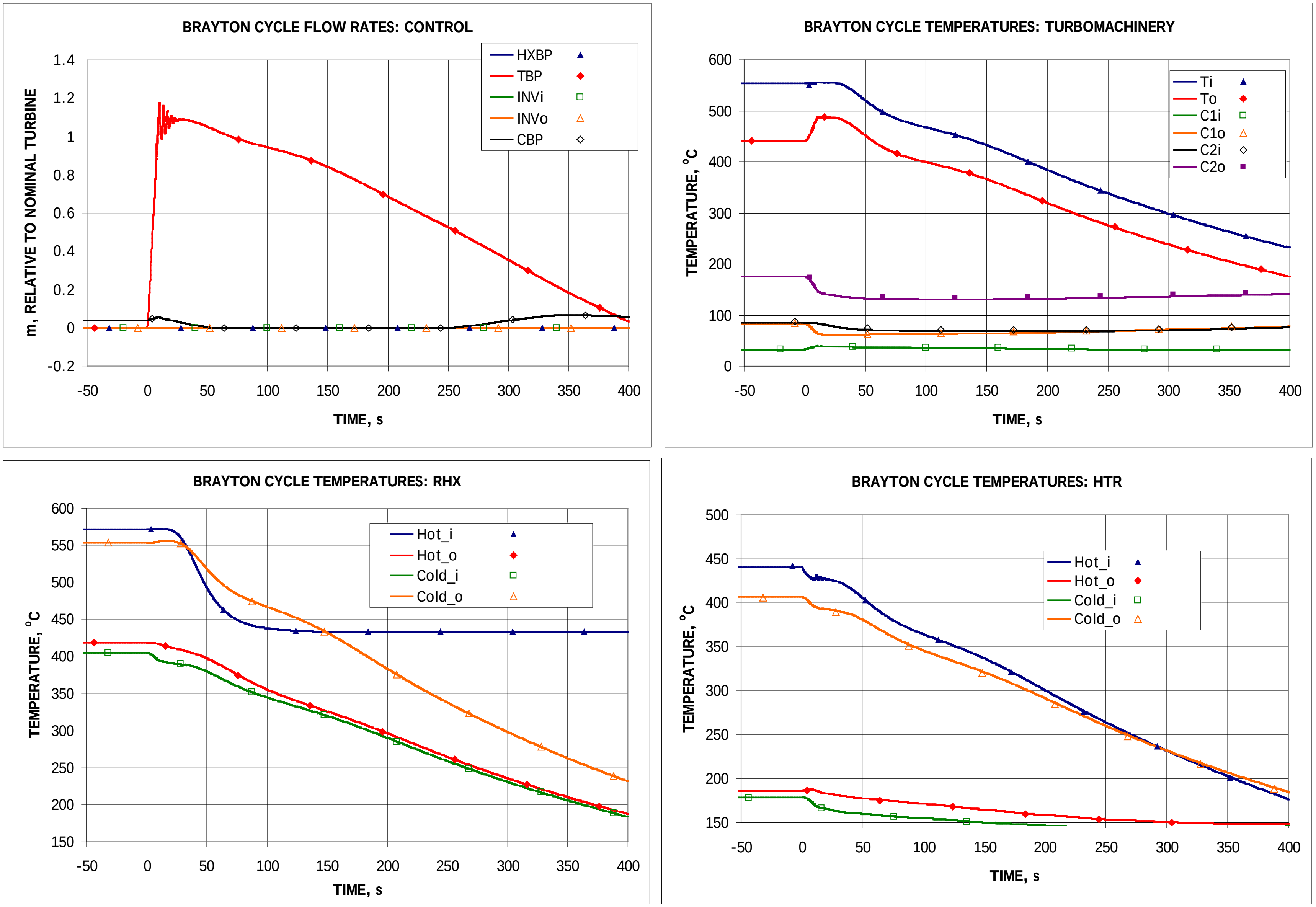

Figure 8. S-CO$_2$ Cycle Operation Following Reactor Scram with Disconnection from the Grid in 10 Seconds. (Continued)

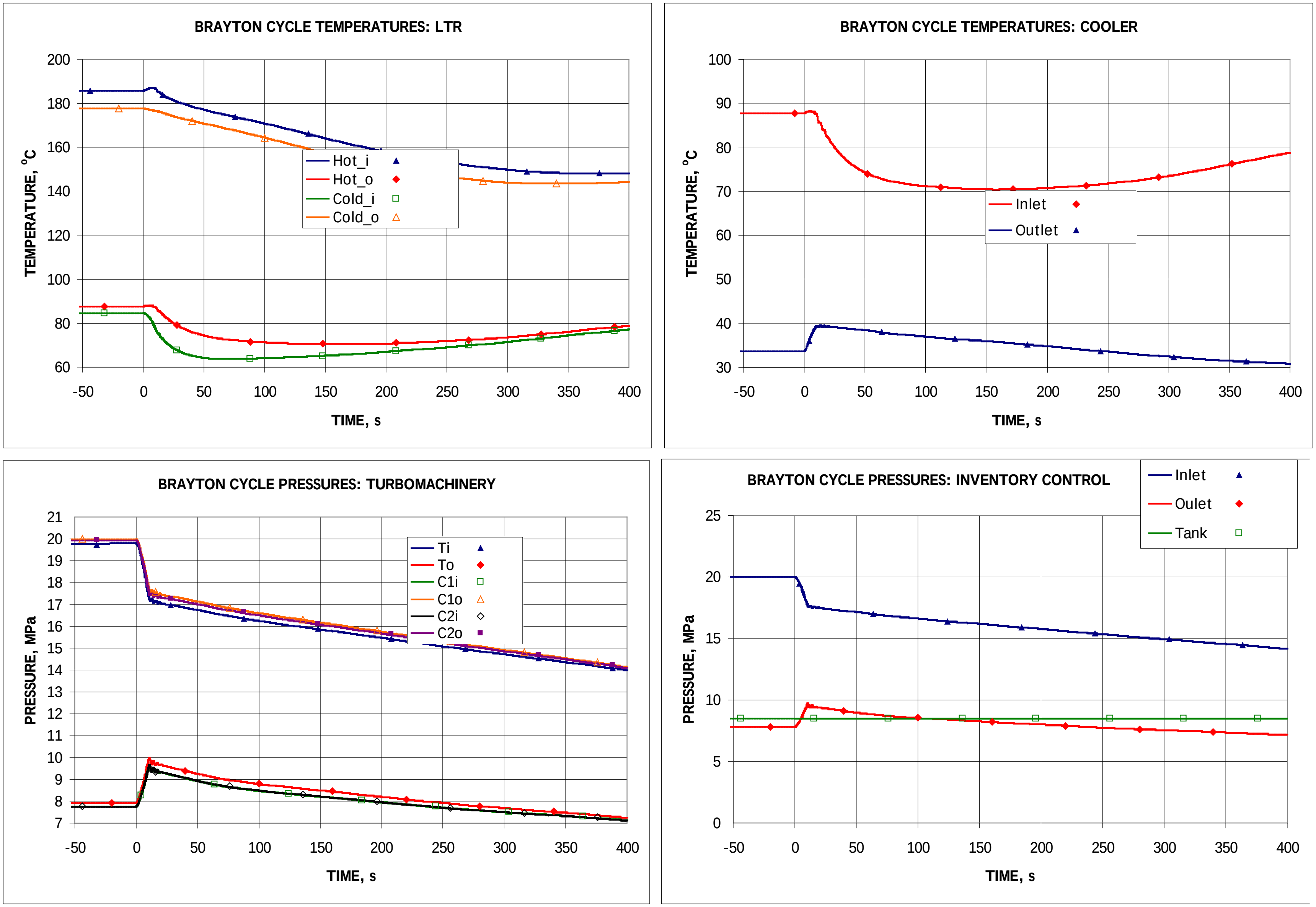

Figure 8. S-CO$_2$ Cycle Operation Following Reactor Scram with Disconnection from the Grid in 10 Seconds. (Continued)

3.2.2. Shutdown Heat Removal System Design Requirements

Based on the results of the reactor scram simulation, the following requirements can be formulated for the shutdown heat removal system. The requirements are based on the S-CO_2 cycle conditions at the end of the reactor scram simulation (Figure 8):

- The shutdown cooling system should be able to remove at least 1.1 % of the full nominal power;

- The shutdown cooling system should be able to start and reach its full capacity in less than 400 seconds;

- If a thermal shock on the main heat exchanger during the switch from S-CO_2 cycle circulation to the shutdown loop is to be avoided, the system should be able to cool CO_2 from about 230 ^{o}C to about 180 ^{o}C. The corresponding CO_2 flow rate under these conditions is about 93 % of the nominal CO_2 flow rate through the turbine; the corresponding CO_2 pressure is about 14 MPa.

4. Publications

A paper entitled “Controllability of the Supercritical Carbon Dioxide Brayton Cycle Near the Critical Point” by A. Moisseytsev and J. J. Sienicki was presented at the 2008 International Congress on Advances in Nuclear Power Plants (ICAPP ‘08) in Anaheim, CA, June 8-12, 2008. The paper summarizes the work on S-CO_2 cycle development performed at ANL during the last fiscal year. A. Moisseytsev and J. Sienicki attended the ICAPP ‘08 conference to present the paper and participate in the Innovative/Advanced Energy Conversion System session of the conference as well as in other discussions related to S-CO_2 cycle at the conference.

A paper entitled “Transient Accident Analysis of a Supercritical Carbon Dioxide Brayton Cycle Energy Converter Coupled to an Autonomous Lead-Cooled Fast Reactor” by A. Moisseytsev and J. J. Sienicki has been published in the journal, Nuclear Engineering and Design, No.238 (2008), pp. 2094-2105.

5. Summary and Conclusions

The ANL Plant Dynamics Code has been applied to investigate the dynamic behavior of the 96 MWe (250 MWt) Advanced Burner Test Reactor (ABTR) S-CO_2 Brayton cycle power converter preconceptual design following a design basis event reactor scram. The timescale for the primary sodium flowrate to coast down and for the transition to natural circulation of the primary sodium coolant to occur was calculated with the SAS4A/SASSYS-1 computer code and found to be about 400 seconds. The ANL Plant Dynamics Code configured for the Small Secure Transportable Autonomous Reactor (SSTAR) Lead-Cooled Fast Reactor (LFR) was utilized to approximately model the ABTR S-CO_2 Brayton cycle power converter with a decaying liquid metal coolant flow to the Pb-to-CO_2 heat exchangers and temperatures reflecting the decaying core power and heat removal by the cycle. The Plant Dynamics Code calculations show that the S-CO_2 cycle continues to operate for about 400 seconds following reactor scram driven by the thermal energy stored in the reactor structures and coolant such that heat removal from the reactor exceeds the decay heat generation in the core. Following this time, decay heat will be removed by the normal ABTR shutdown heat removal system incorporating a dedicated shutdown heat removal S-CO_2 pump and cooler. Thus, the S-CO_2 Brayton cycle power converter is calculated to remove greater heat from the reactor system than is generated by the decay heat in the core until the normal shutdown heat removal system is placed into operation which is assumed to happen by 400 seconds following scram. Based on the calculations, requirements for the shutdown heat removal system have been defined including the capability to remove 1.1 % of the nominal reactor power. If the normal shutdown heat removal system were postulated to be unavailable after 400 seconds, then the Direct Reactor Auxiliary Cooling System (DRACS) heat exchangers immersed in the primary sodium pool for emergency decay heat removal would subsequently remove the core heat generation.

An investigation of the oscillating and unstable cycle behavior calculated by the ANL Plant Dynamics Code under specific conditions has been carried out. The results of the investigation indicate that the calculated oscillations during transients involving reduction in power to 0 % nominal may be numerical artifacts attributed to the modeling of the main compressor. In particular, the most probable reason for such instabilities is the limit of applicability of the currently used one-dimensional compressor performance subroutines which are based on empirical loss coefficients. Development of more detailed compressor design and performance models is required and is recommended for future work in order to better investigate and potentially eliminate the calculated instabilities. Also, as part of the development of improved compressor modeling, more reliable surge criteria should be developed for S-CO2 compressor operation close to the critical point. The development of more detailed compressor models is expected to be carried out as part of validation of the Plant Dynamics Code through model comparison with the experiment data generated in the small S-CO_2 loops being constructed at Barber-Nichols Inc. and Sandia National Laboratories (SNL). Although such a comparison activity had been planned to be initiated in FY 2008, data from the SNL compression loop currently in operation at Barber Nichols Inc. will not become available until FY 2009.

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