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Status Report on Thermal Extraction Modeling within HYBRID

February 2023

Changing the World's Energy Future

Daniel Mark Mikkelson, Junyung Kim, Aaron S Epiney

Idaho National Laboratory

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ABSTRACT

Idaho National Laboratory continues to be at the forefront of research into advanced reactor systems and integrated energy systems (IES). HYBRID is the computational modeling repository for evaluating potential IES configurations. To support IES analysis, it is necessary to develop models that can evaluate a range of thermal integration points within various energy conversion systems. This work encompasses as many technologies as possible, under the expectation that many technologies will be deployed to broadly reduce the climate impacts of energy-intensive processes. To enable this analysis, a new BOP model was created. This report discusses the progress made in regard to this new main model, and explores the nominal conditions pertaining to the primary reactor types contained within HYBRID.

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LIST OF ACRONYMS

A-LWR	advanced light-water reactor
BOP	balance of plant
FY	fiscal year
HTGR	high-temperature gas-cooled reactor
IES	integrated energy systems
LPV	low-pressure valve
LWR	light-water reactor
SFR	sodium-cooled fast reactor
TES	thermal energy storage

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1. INTRODUCTION

Integrated energy systems (IES) have been proposed for thermally and electrically integrating nuclear power generators with energy users. Many IES deployment strategies are dynamic in nature; multiple selectable operation modes, dynamic loads, and systems with memory all require time-dependent modeling to conduct complete system analyses. The HYBRID repository houses IES dynamic models—programmed in the Modelica language—that can be used to simulate various systems for analysis [1]. Applying HYBRID models to analyses of physical integration is of particular interest, and many models built over the past few years were created with this goal in mind.

Models are built around certain key questions. How is heat removed from the nuclear plant? Where are the integration points? Where should returned mass flow streams be reintroduced? How are plants impacted when their operation modes are changed? How should the control scheme of the combined system be operated? What unintended feedback may appear on the nuclear side of the plant as a result of this new operating paradigm? What system dictates where energy streams go? How many subsystem connections should exist (and should all energy producers and storers be able to distribute energy to all other energy storers and users)? The IES team has focused on producing models capable of answering such questions such. Within the nuclear subsystem of an IES, three main model subsets must be robustly built to support these analyses.

The first subsystem model is that of the primary nuclear heat system, and it includes the nuclear core, associated internal piping, fuel modeling, coolant characterization, neutronic capability, control systems, and primary loop side of the main heat exchanger. In anticipation of a variety of vendor-provided nuclear plant options in the upcoming era of advanced nuclear reactor deployments, various types of reactors have already been built, with still others being slated for development. The full suite of reactor types should include the existing light-water reactor (LWR) fleet, advanced LWRs (A-LWRs) such as the NuScale and Holtec designs, molten-salt reactors, high-temperature gas-cooled reactors (HTGRs) such as pebble-bed and prismatic reactors, and liquid-metal-cooled fast reactors (usually some type of sodium-cooled fast reactor [SFR]).

The other two subsystems are on the balance-of-plant (BOP) side. The second subsystem is the steam manifold system, which enables heat removal (nominally steam, though no restrictions within the Modelica framework preclude another type of heat transfer fluid) at the hottest point in the system (i.e., just downstream of the primary heat exchanger). The third subsystem, typically called the BOP, includes the thermal-to-electric conversion system (turbines), and modeling has progressed to the point that additional details (e.g., physical feedwater heating systems, multi-stage turbines, and multiple pumps) can be included to better reflect realistic system operations.

The present document primarily summarizes HYBRID’s current status with regard to thermal extraction analysis and modeling. This includes the existing BOP template setups for current reactors, along with the development of BOP models to enhance HYBRID’s modeling capabilities in regard to analyses of thermal extraction points in reactor systems. HYBRID modeling utilizes the Dymola integrated development environment and is dependent on the Transient Simulation Framework of Reconfigurable Models [2] [3].

2. BOP MODELING

The BOP system is considered to be the connected set of models that converts thermal energy transferred from the nuclear reactor into electrical energy usable by the electricity grid. The primary BOP components are the turbines, condensers, feedwater pumps, feedwater heaters, and various valves. This section discusses both current and potential methods of modeling BOP systems.

2.1 Existing Modeling

Three BOP models (discussed in this section) have been covered in prior HYBRID development reports.

The primary turbine model used in HYBRID utilizes the Stodola cone law to effectively model an infinite number of turbine stages. The specific turbine performance is set via nominal values which calculate performance coefficients.

2.1.1 Single-Stage Turbine

In the single-stage turbine model, only a single turbine model is implemented. Downstream of the turbine, the fluid enters a condenser. A pump returns feedwater at the demanded mass flow rate and pressure. In this model, feedwater is reheated by using a heating boundary condition (see Figure 1). This model was developed when the primary modeling concerns were (1) to capture the nuclear primary side behavior and (2) to create a BOP model capable of aptly capturing changes in the heat exchanger. Thus, specifics within the BOP were not of primary interest in this modeling. Furthermore, this model was constructed prior to non-LWR types being included within HYBRID. In LWR systems, the impact of feedwater heating via steam bypass is less severe than in other advanced reactor types.

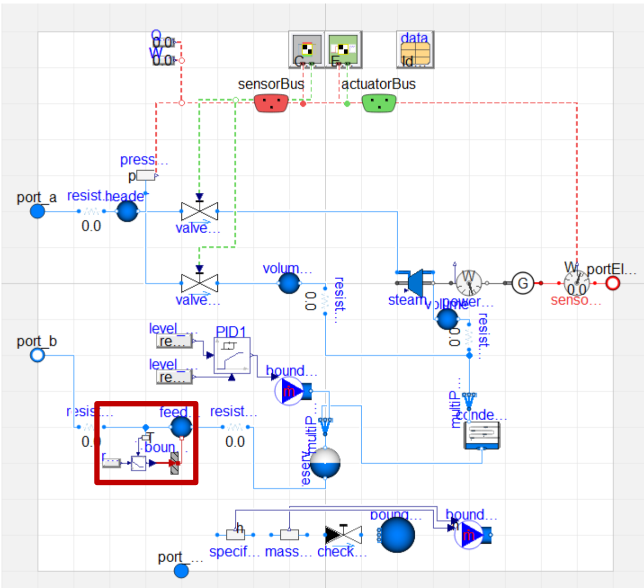

Figure 1. Single-stage turbine model containing non-physically integrated feedwater heating (red box). Model: NHES.Systems.BalanceOfPlant.Turbine.SteamTurbine_L1_boundaries.mo.

Older examples within HYBRID, including fiscal year (FY) 2018 IES examples, integrate this model to obtain results.

2.1.2 Two-Stage Turbine

To better capture the impacts of a feedwater heating system that uses primary steam bypass, a two-stage turbine was developed so that intermediate-pressure steam could be bypassed to provide feedwater heating. Three steam streams are available for use in feedwater heating: the maximum-temperature steam taken upstream of the first turbine, the intermediate-pressure steam tapped between two turbine models, and the steam upstream of the condenser as seen in Figure 2. Capturing a physical source of feedwater heating should foster a much more complete understanding of the impacts of heat removal from these systems, as feedwater condition demands remain constant so long as the reactor power is unchanged.

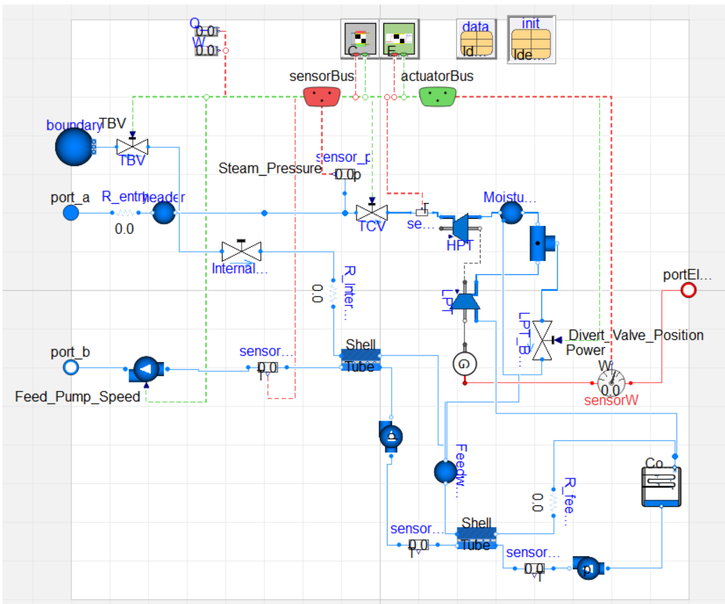

Figure 2. Two-stage turbine model with two-stage feedwater heating using steam bypass. Model: NHES.Systems.BalanceOfPlant.Turbine.SteamTurbine_L2_ClosedFeedHeat.mo.

The new thermal energy storage (TES) use case models already—or will in the near future—integrate either this BOP model or a very similar one.

2.1.3 Stage-by-Stage Turbine

The stage-by-stage turbine model seen in Figure 3 was specifically designed to more thoroughly capture efficiency losses that occur in turbomachinery during reduced load. To achieve this, a new design paradigm was employed, centering around turbine design parameters such as flow area and stage deflection angles. These values are used in a cylindrical coordinate system to model the translation, rotational, and angular velocities of the steam passing through the turbine. The amount of detail required by this model far exceeds what is expected for a typical analysis. A single current example using this system is maintained: a BOP model based on the NuScale design documents submitted to the Nuclear Regulatory Commission for design certification.

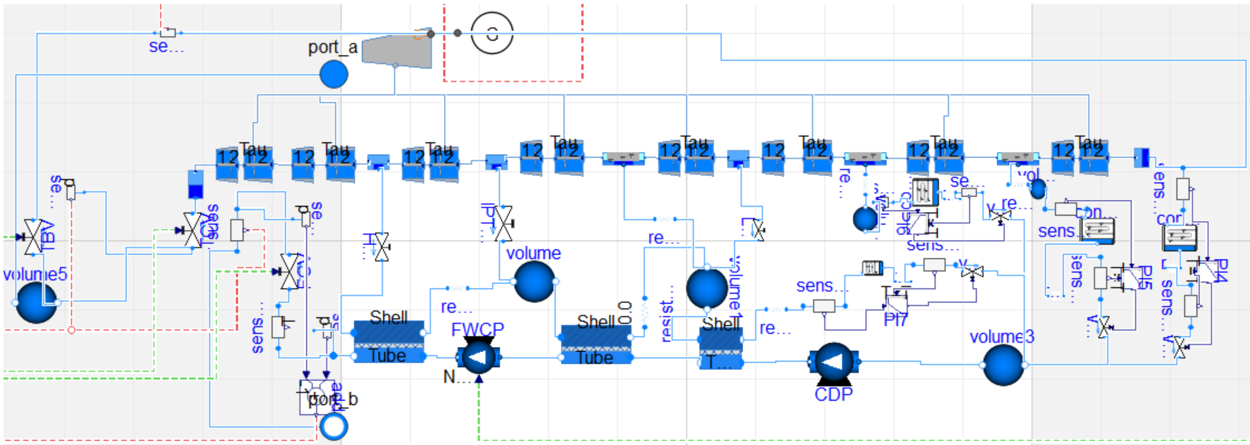

Figure 3. Stage-by-stage turbine model with multiple turbine taps and moisture separators. Model: NHES.Systems.BalanceOfPlant.Turbine.StagebyStageTurbineSecondary.NuScale_Secondary.

Multiple example implementations exist that use this model, including one that integrates steam produced from a solid media TES unit introduced between the fourth and fifth turbine stages.

2.2 New Modeling

Prior modeling has focused on steadily capturing more dynamic behavior of nuclear system BOPs. By introducing the two-stage turbine model, a straightforward BOP system exists that contains physical feedwater heating. However, because the final turbine stage is used in feedwater heating, the system cannot readily be changed to allow for steam extraction analysis. To analyze a larger number of steam extraction points, a three-stage turbine was developed, with its first and second stages becoming design-restricted to maintain system setpoints.

2.2.1 Three-Stage Turbine

This model was developed by extending the two-stage turbine model (see Section 2.1.2), when the primary modeling concern was to create a BOP model capable of capturing changes in turbine power demand. This meant that specifics within the BOP were not of primary interest. The HYBRID model design is shown in Figure 4. After the first stage of the turbine, a T-junction pipe directs steam to either the first bypass valve (LPV-1) or the first low-pressure turbine stage. After the second stage, a moisture separator directs any liquid content to mix with and heat the feed flow sourced from the condenser. A valve (LPV-2) downstream of the moisture separator but upstream of the third turbine stage is controlled to bypass additional flow in order to preheat the feed flow to the desired temperature.

To meet external electricity demands, the control for the HTGR- BOP must be able to function during cyclical operation ramping up/down of turbine power. The BOP control methods are summarized in Table 1, which matches operating conditions found in literature for an older iteration of X-energy’s Xe-100 design [4]. The turbine control valve operates to maintain the steam pressure at the steam generator outlet. To maintain the steam temperature, the feedwater control pump increases or decreases its speed in order to increase or decrease the pumping power. Note that the turbine power is governed by LPV-1 and that the feedwater temperature is what triggers LPV-2 to open and close.

Table 1. Control methods summary [4].

Label	Name	Controlling	Setpoint
1	Turbine control valve	Steam pressure	140 bar
2	Feedwater control pump	Steam temperature	540°C
3	Low-pressure turbine bypass valve-1 (LPV-1)	Turbine power	–
4	Low-pressure turbine bypass valve-2 (LPV-2)	Feedwater temperature	208°C

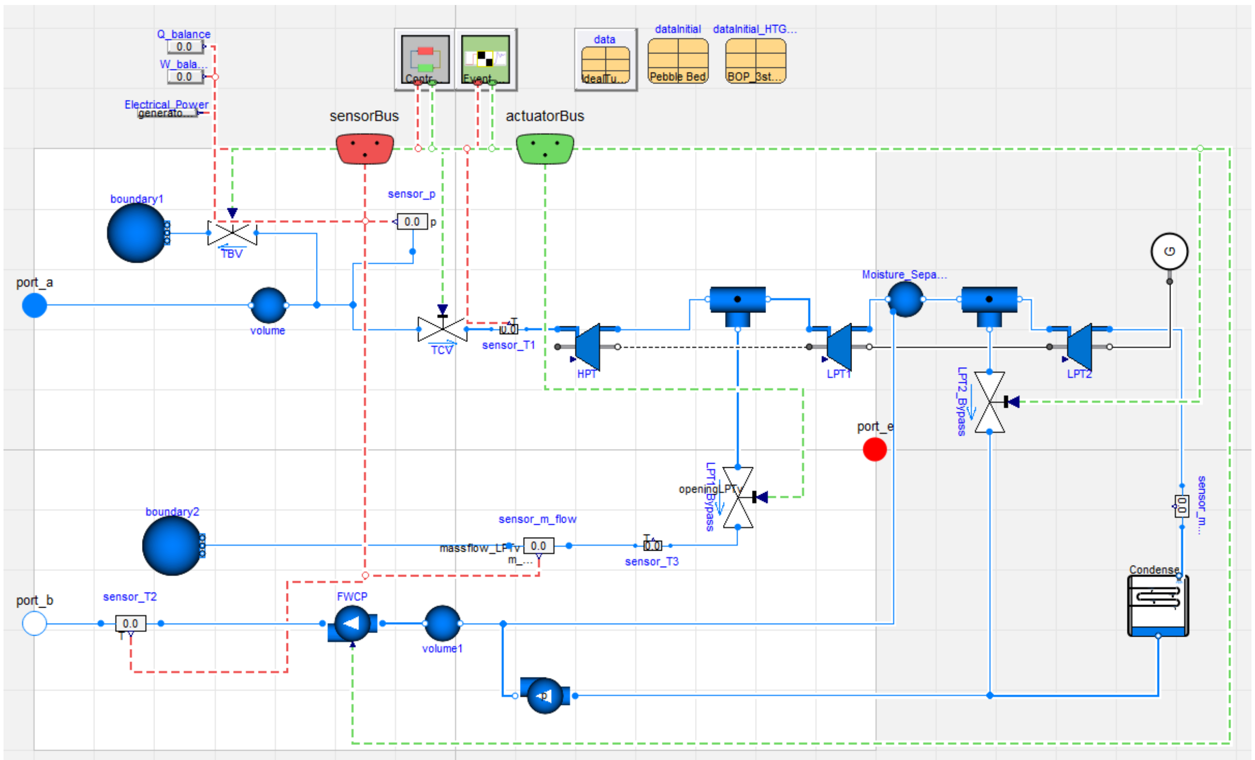

Figure 4. Three-stage turbine model with one-stage feedwater heating using steam bypass. Model: NHES.Systems.BalanceOfPlant.Turbine.HTGR_RankineCycles.HTGR_Rankine_Cycle_3stagedBOP.

This model is not yet considered finalized. Three changes are needed before it is regarded as complete. First, the open feedwater heater must be moved downstream of the first pump in the system. Second, ports need to replace the boundary conditions currently used that accept the steam bypass to other processes. Third, a pressure relief turbine bypass valve must be put in place.

2.2.2 Transient Modeling of a Rankine-Cycle HTGR, Using BOP Models

Transient modeling capabilities were developed as the first step in implementing the several HTGR system use cases. Figure 5 and Figure 6 show transient models for a Rankine-cycle HTGR, as coupled with different BOP models. The purpose of developing and implementing Modelica models is to evaluate the system's controls and to understand the dynamic behavior of IES—something that will be done in future work. This section describes the specific implementation of transient modeling within Modelica, focusing on BOP modeling and the control methods used. For further background on the development of the template for the BOP models, see Section 3.

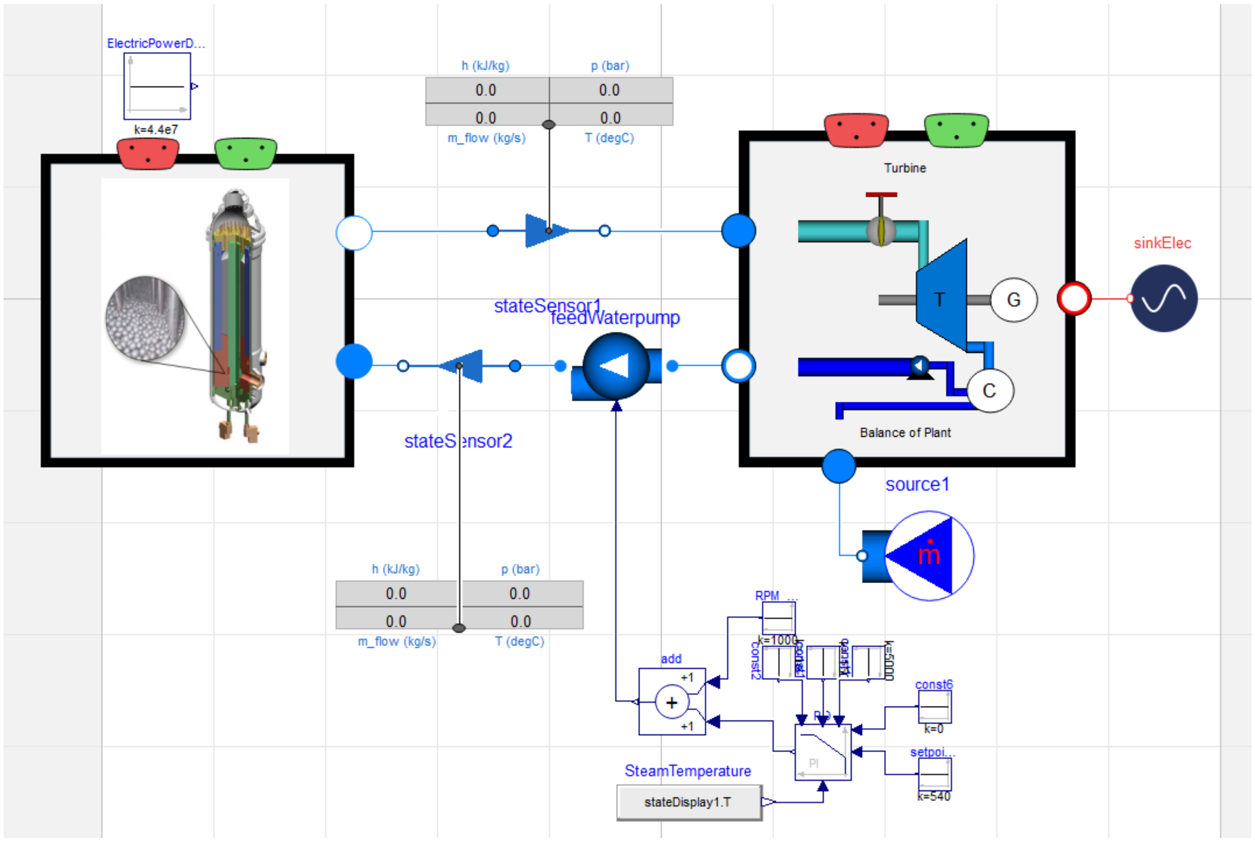

Figure 5. Modelica process flow diagram of the HTGR-One_Stage_Turbine BOP model. Model Paths: (Plant Models) NHES.Systems.PrimaryHeatSystem.HTGR.HTGR_Rankine.Examples and Rankine_HTGR_OneStageTurbine_Transient; (Reactor Models) NHES.Systems.PrimaryHeatSystem, HTGR.HTGR_Rankine.Components, and HTGR_PebbleBed_Primary_Loop_STHX; (BOP Model) NHES.Systems.BalanceOfPlant.Turbine.SteamTurbine_L1_boundaries.

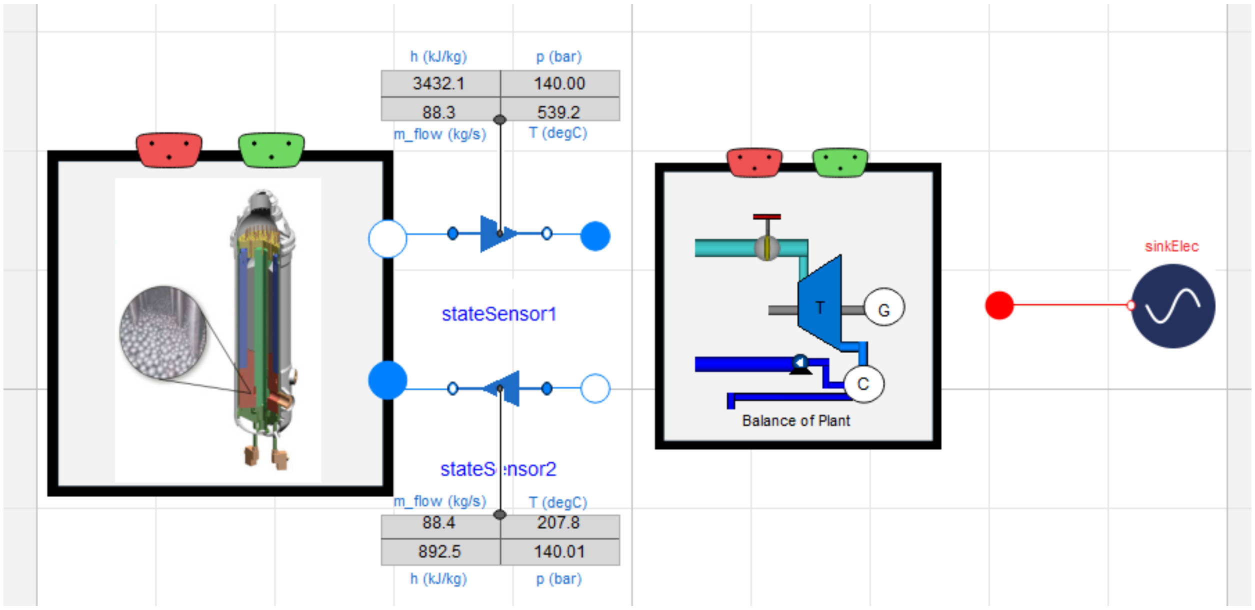

Figure 6. Modelica process flow diagram of the HTGR-Three_Stage_Turbine BOP model. Model Paths: (Plant Models) NHES.Systems.PrimaryHeatSystem.HTGR.HTGR_Rankine.Examples and Rankine_HTGR_ThreeStageTurbine_Transient; (Reactor Models) NHES.Systems.PrimaryHeatSystem and HTGR.HTGR_Rankine.Components.HTGR_PebbleBed_Primary_Loop_STHX; (BOP Model) NHES.Systems.BalanceOfPlant.Turbine.SteamTurbine_L3_HTGR.

Figure 7 shows key process variables for two different transient models. Note that, following the initialization process, these variables are identical—or at least very close to each other. Also note that in the one-stage turbine BOP model, extra heat energy was provided for heating up the feedwater. This was the motivation behind developing the three-stage turbine BOP model, which can reheat the feedwater by using extracted thermal energy following a high-pressure turbine stage.

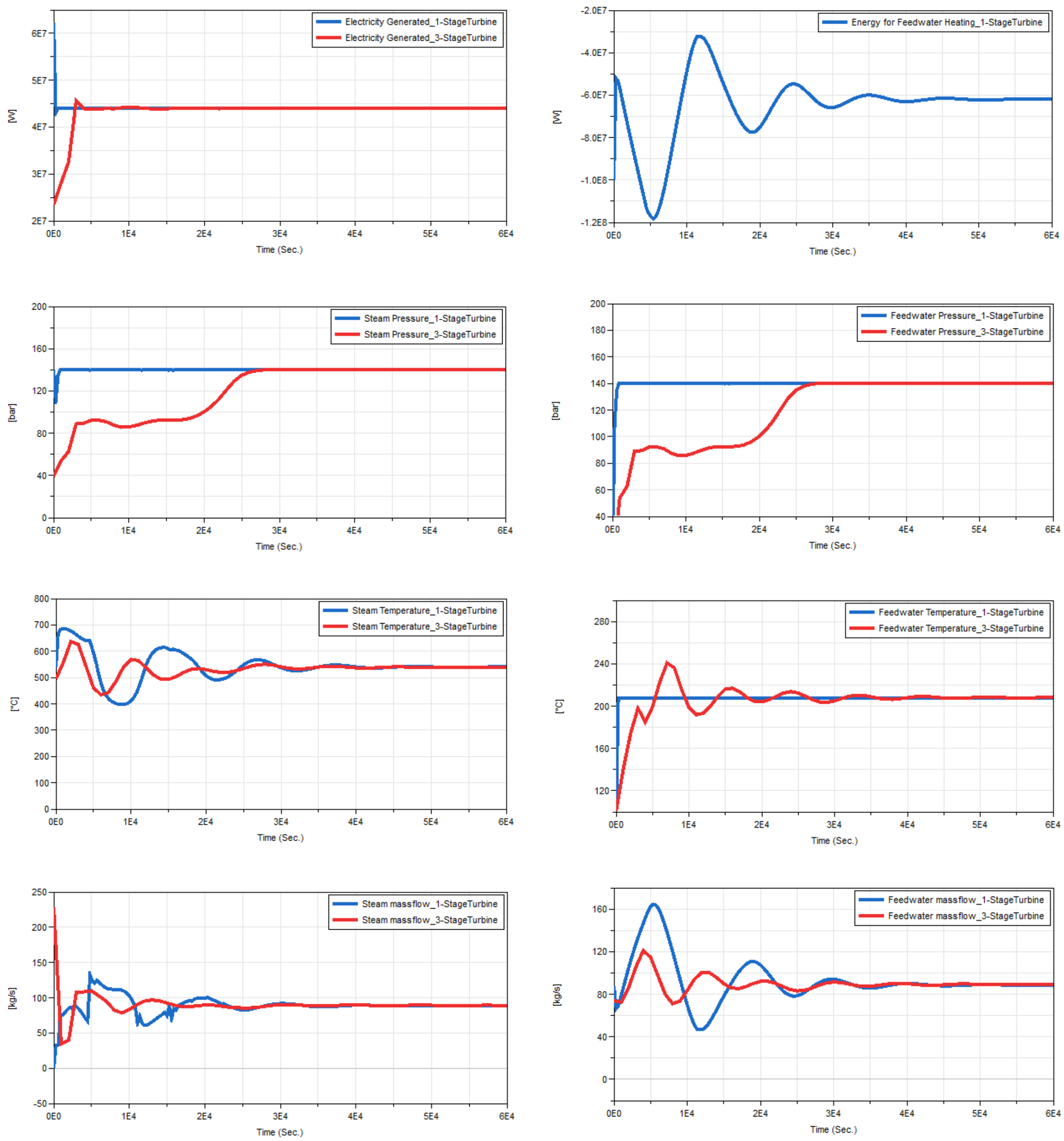

Figure 7. Benchmarking key process parameters of the HTGR three-stage turbine BOP model with the HTGR one-stage turbine BOP model.

The HTGR-Three_Stage_Turbine BOP transient model was run through cyclical ramping to establish expectations on how the system would respond to dynamic dispatching while maintaining predetermined process variable set points. The shakedown test, simulated from after steady state initialization to 1e+5 seconds forced the system to periodically (one cycle = 86400 seconds = 24 hours) ramp down/up the turbine power. By using this type of demand profile, the model can be pushed to its extreme operating points, and it becomes possible to obtain initial evaluations of how a system may respond. Figure 8 through Figure 11 show the key results generated by the shakedown simulation. Figure 8 shows the imposed demand on the system and the corresponding electricity generation. Aside from small demand misses immediately before and after the demand ramps, the system was able to meet the electricity demand. Note that the thermal power remains within a 3% band of nominal and does not decrease with electricity demand, as the electricity deficit is caused by thermal bypass and so the net thermal load remains nearly constant. Figure 9 shows the feedwater and steam temperatures throughout the simulation. Feedwater temperature is a parameter of interest because it sets the main steam generator conditions and can dramatically impact primary coolant conditions. Brief changes in feedwater temperature occur during system changes caused by changes in system flow. These alterations are brief, and by and large the control system is able to respond accordingly and reestablish the setpoint temperature value.

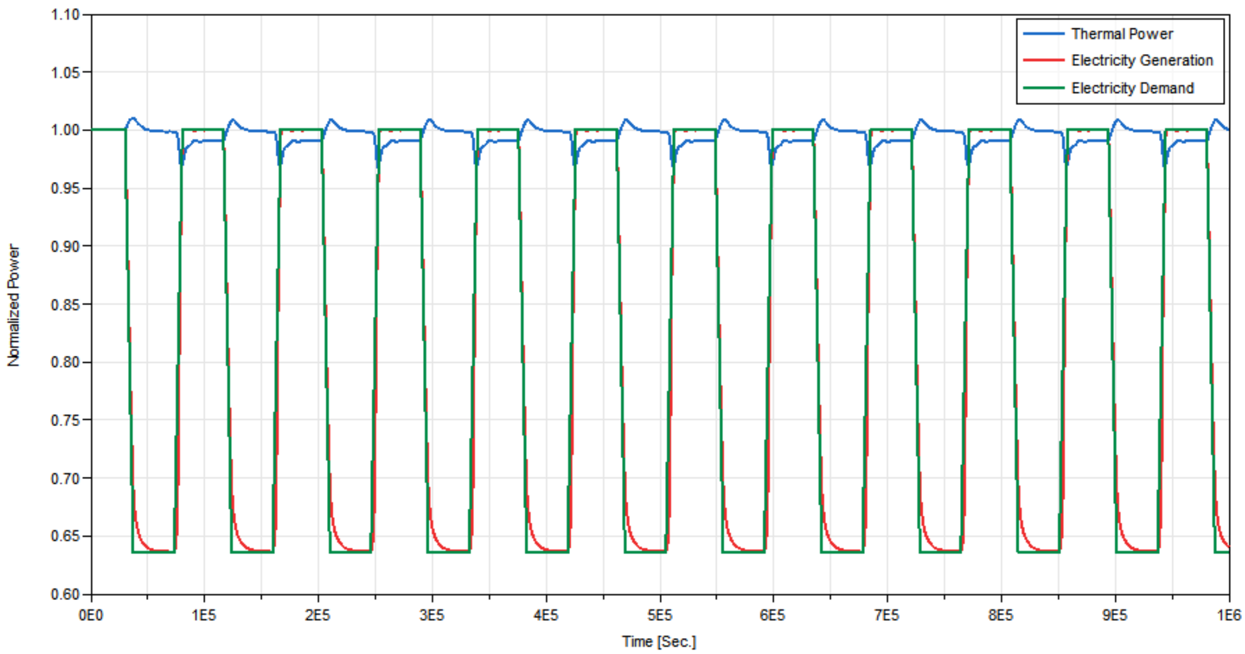

Figure 8. Electric demand and electricity generation curves (normalized) for the HTGR-BOP model.

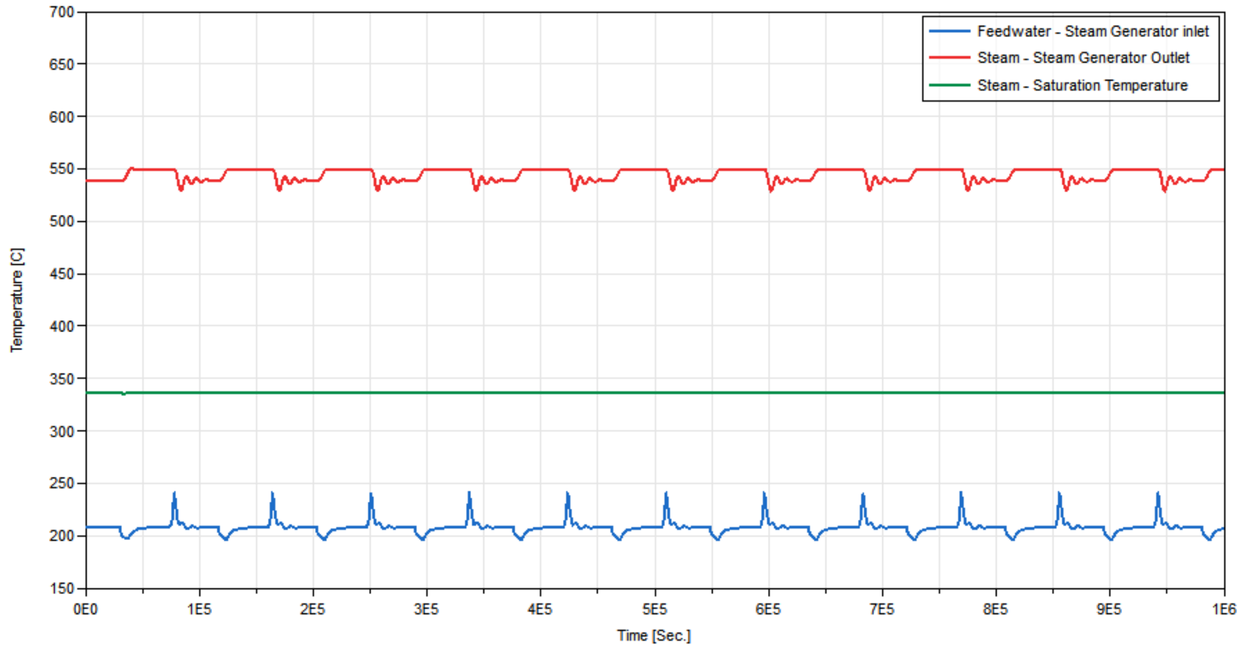

Figure 9. Feedwater and steam temperature data for the HTGR-BOP model.

Figure 10 shows the steam generator mass flow rate, which is also related to feedwater temperature. As the total steam mass flow rate suddenly increases or decreases, the feedwater temperature will decrease or increase in corresponding fashion. Figure 11 shows how much the valves (LPV-1 and LPV-2) had to cycle throughout this shakedown test in order to meet the electricity demand while maintaining the feedwater temperature. Note that the electricity demand controls the valve opening area of LPV-1, which in turn governs the electricity generation. The feedwater temperature shifts in response to electricity generation changes, and the LPV-2 valve area oscillates to maintain the feedwater at its temperature setpoint.

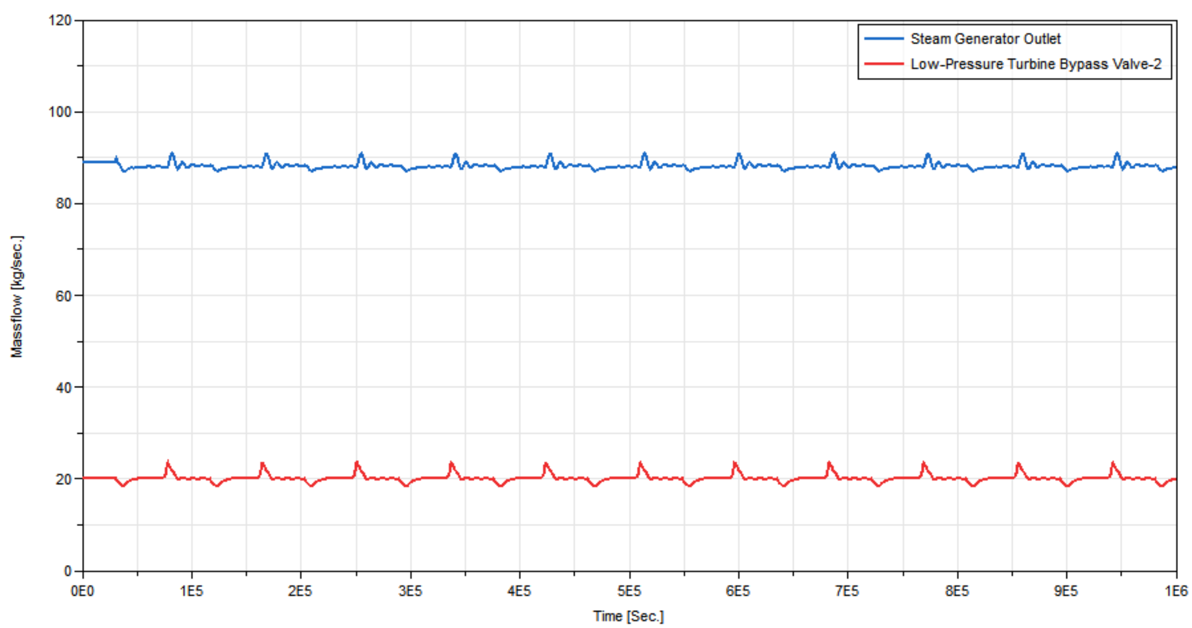

Figure 10. Mass flow of both LPV-2 and the steam generator outlet, for the HTGR-BOP model.

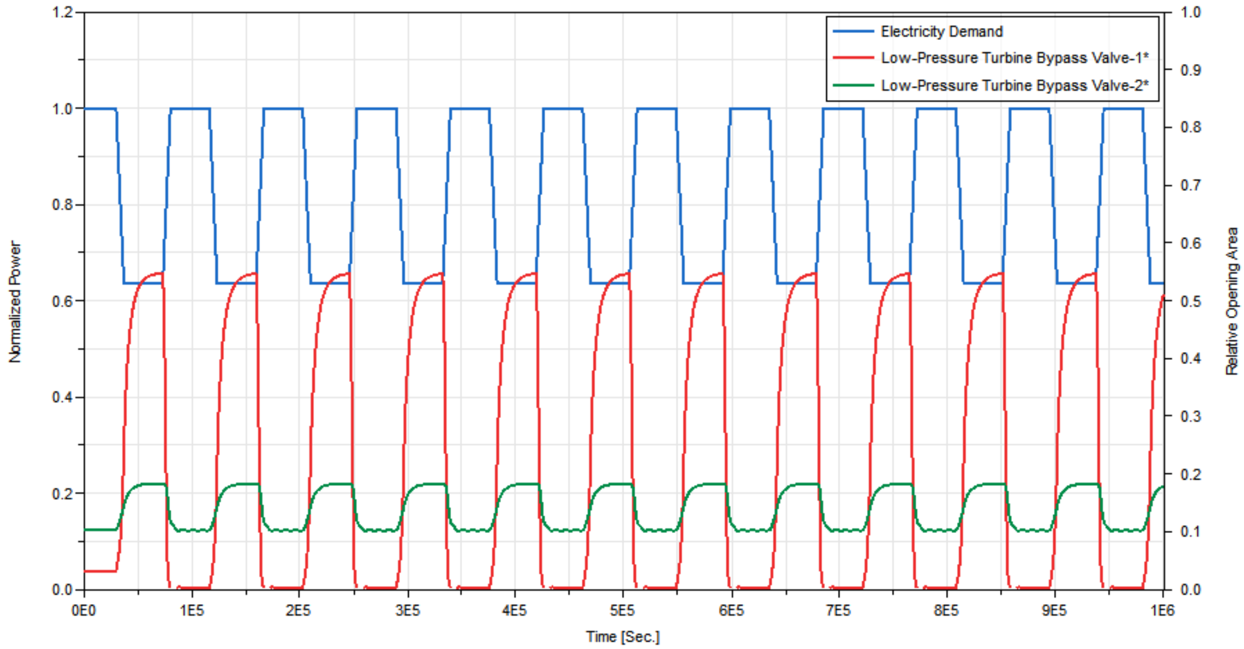

Figure 11. Valve opening profiles responding to changing electricity demand for the HTGR- BOP model (0 = closed and 1 = opened).

Overall, the new three-stage turbine has been demonstrated to allow for simulated operational flexibility while also minimizing the use of unaccounted boundary conditions. By leveraging this new model once it is completed, HYBRID analysts can characterize thermal extraction within the standard operation bands for a variety of reactor types, including those discussed in Section 3.

3. TEMPLATE BOP MODELS

This section examines the currently used template BOP model, along with some system setpoints and results. Since the three-stage turbine is so new, it has not yet been implemented with each reactor type within HYBRID. External references pertaining to the BOP design are also included to indicate where further information on the design can be found.

3.1 A-LWR

The A-LWR model within HYBRID is based on publicly available information on the NuScale design. See Figure 12 for the BOP referenced in the license application submitted to the Nuclear Regulatory Commission [5]. This model has been connected with three different BOP models: single-stage turbine, two-stage turbine within an IES featuring TES, and stage-by-stage turbine. The results have been presented in prior reports and are thus not reiterated here [6] [7] [8]. Continuing work is required to set up the new three-stage BOP with the A-LWR model. In the HYBRID repository, these models are found within the following system examples:

- NHES.Systems.Examples.TES_Use_Case.SMR_SHS_Test_Config_Peaking_TempControl
- NHES.Systems.Examples.SMR_Coupling_Test
- NHES.Systems.Examples.SMR_IES_CTES.

Nominal conditions for the A-LWR model within HYBRID are given in Table 2.

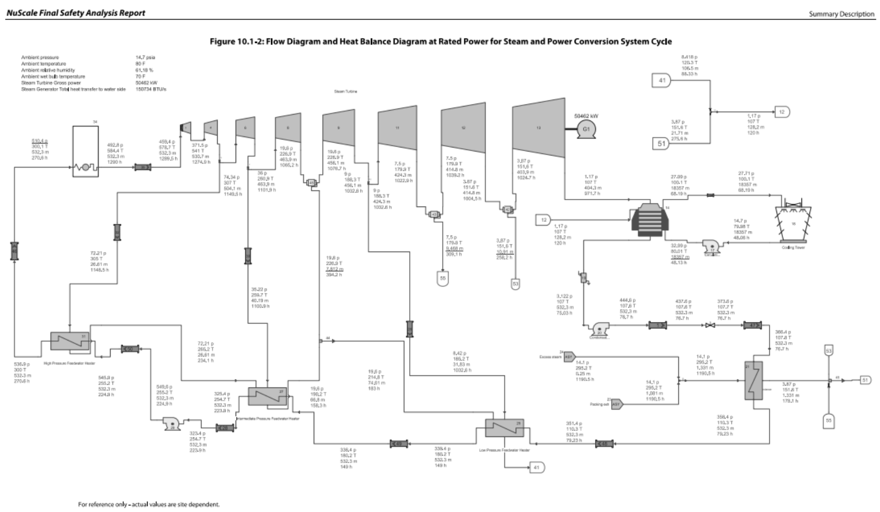

Figure 12. NuScale BOP design document for licensing with the Nuclear Regulatory Commission. A full-page size document is given in Appendix A [5].

Table 2. Nominal full-power conditions for the ALWR model within HYBRID.

Physical Parameter	Value (unit)
Core power	160 (MWth)
Primary coolant flow rate	561 (kg/s)
Average coolant temperature	283 (℃)
Generator power	50 (Mwe)
Steam pressure	34.6 (bar)
Steam generator exit temperature	308 (℃)
Feed and steam mass flow rate	67.5 (kg/s)

3.2 HTGR

The BOP modeling results for the HTGR have been well documented in Section 2. The primary reference used by the HYBRID modeling team was an analysis conducted by a research team that included members from the advanced reactor vendor X-energy. Prior results from the HTGR model can be found in previous reports by INL's IES team [9]. Nominal conditions for the HTGR within HYBRID are given in Table 3.

Table 3. Nominal full-power conditions for the HTGR model within HYBRID.

Physical Parameter	Value (unit)
Core power	125 (MWth)
Primary coolant flow rate	47.5 (kg/s)
Coolant temperature at core exit	750 (°C)
Generator power	43.75 (MWe)
Steam pressure	140 (bar)
Steam generator exit temperature	540 (°C)
Feed and steam mass flow rate	50 (kg/s)

3.3 Sodium Fast Reactor

SFR model development is relatively new within the team [9]. New reference values have been discovered based on prior Power Reactor Innovative Small Module (PRISM) reactor development conducted by General Electric (GE) [10]. Key design data have been reported, and will be used in conjunction with the HYBRID models in order to construct the SFR template BOP. The primary and intermediate loops within the HYBRID model both employ sodium coolant. Nominal conditions for the SFR within HYBRID are given in Table 4.

Table 4. Nominal full-power conditions for the SFR model within HYBRID.

Physical Parameter	Value (unit)
Core power	840 (MWth)
Primary coolant flow rate	4762 (kg/s)
Coolant temperature at core exit	499 (°C)
Intermediate loop flow rate	4409 (kg/s)
Intermediate loop maximum temperature	477 (°C)
Generator power	303 (MWe)
Steam pressure	152 (bar)
Steam generator exit temperature	429 (°C)
Feed and steam mass flow rate	390 (kg/s)

4. FUTURE WORK

This report seeks to provide context for future efforts within this work package. The future work can be divided into three main categories: capability development, generalized knowledge-base expansion where capabilities are leveraged, and specific analysis, which evaluates the knowledge base for specific technologies and deployment.

4.1 Finalizing the BOP Modeling

A few tasks still remain before the BOP modeling within this work package is complete. The first task is to finalize the features in the general three-stage BOP model. The feedwater system should be robustly constructed to ensure appropriate control and physical responses within the system. Specifically in regard to Figure 4, this means either adding a pump between the intersection of the LPT_2Bypass valve outlet and the condenser, or altering the model so that the LPT_2Bypass valve outlet comes after the current pump in the model. In either case, the bypass flow should flow into a location with higher pressure than the condenser or steam will be produced when water flashes within the feedwater system—something that would not work in a physical system. A second task for usability is to alter the existing BOP models such that the same systemwide conditions can be met when changing between BOP models that feature different numbers of turbine stages. The main criteria for this are (1) having similar pumping capabilities in each of the feed systems, (2) ensuring that the extraction capabilities are as similar as possible, and (3) introducing changes primarily through parameter blocks in data structures. Finally, when the three-stage model is complete, determining a default BOP for each reactor type will be key for allowing future users access to different reactor types without needing to reinvent component parameter sets.

4.2 Sweeping and Setpoint Searching

When the default, or reference, BOP models are available for various reactor technologies, parameters can be swept to generate a thermal extraction capability knowledge base. To investigate the conditions under which mid-cycle thermal extraction would occur, a variety of parameters can be altered to investigate the impact on plant operations. Dymola, the Modelica compiler program, is inherently able to sweep across different values for a single parameter within an individual "run" by the user. To analyze across multiple variables, information must be altered; this can be done manually by using a set of different input files, or automatically by using either a script or with the established Risk Analysis Virtual Environment (RAVEN) interface. Example types of desired data include curves for system efficiency relative to extraction conditions, available mass flow rates at different conditions, and other system conditions deemed relevant at the time of analysis.

4.3 IES BOP Optimization

Once the possible set of conditions is established, BOP optimization is the next logical step. It is likely that only general rules would be determinable without specific thermal requirements. The goal would effectively be to maximize the system's ability to produce a secondary product while still meeting the requirements of a primary product. For example, if the demand was for 30 MWth of steam at a minimum temperature of 300°C and a pressure of 15 bar (primary product), what would be the optimal thermal extraction method for maximizing electricity production (secondary product)? An equal but opposite problem set could be similarly defined. Thus, general rules could likely be developed, such as always remove thermal heat at its highest temperature/pressure and exchange heat to achieve the required levels, or always remove thermal heat as close to the desired application conditions as possible.

4.4 Matching Thermal Application Requirements to Reactors

The final knowledge base to be directly produced from this work is the ability to match thermal application requirements to specific reactor types. A general framework can be generated based on detailed physical modeling so as to characterize the impacts of interfacing thermal applications with various reactor types. This should enable analysts to determine which reactor type can best meet their thermal and electrical energy requirements. This knowledge base could be leveraged in industrial system use cases as well.

5. CONCLUSIONS

Thermal extraction work is well underway to meet the FY23 modeling goals and prepare for IES analyses in FY23 and beyond. Through increased BOP modeling capabilities, more questions can be answered with regard to optimal engineering integration design.

6. ACKNOWLEDGEMENTS

This work was supported by the IES program at Idaho National Laboratory under Department of Energy Operations contract no. DE-AC07-05ID14517.

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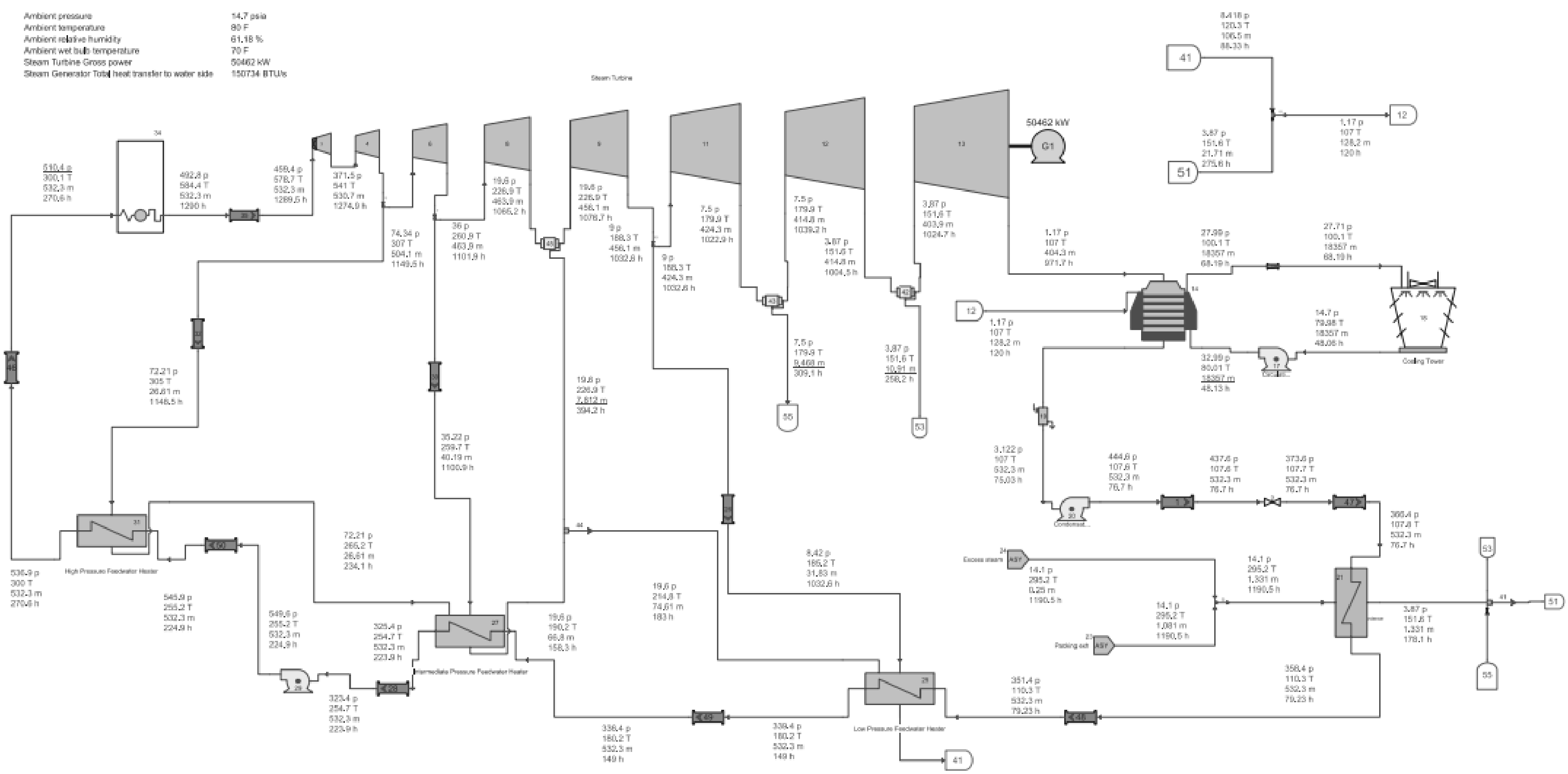
Appendix A

Figure 10.1-2: Flow Diagram and Heat Balance Diagram at Rated Power for Steam and Power Conversion System Cycle



For reference only – actual values are site dependent.