

Light Water Reactor Sustainability Program

Simulator and Scenario Development for 10–30% Thermal Power Dispatch Concept of Operations Testing

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SUMMARY

Thermal power dispatch (TPD) provides flexible operating capabilities for existing commercial nuclear power plants that improve plant economics while maintaining the existing baseload generator role that the fleet of U.S. commercial reactors provide for electric grids. The TPD capability allows plants to offer thermal energy to nearby industrial processes that require large amounts of process heat, which would otherwise rely on less efficient electrical heating for an overall more efficient cost to the industrial user. Additionally, this allows the nuclear power utility to take advantage of an additional revenue stream during low-demand, wholesale electrical pricing. Recent trends are currently offsetting some of the low-demand and poor electricity pricing. However, maintaining grid balance between generation and demand will always remain a critical element of the electric grid operations, and this positions nuclear utilities to gain economic competitiveness with other forms of generation, such as natural-gas and renewable generators. Furthermore, military applications to establish energy independence strengthen the use case for advanced reactor TPD capabilities.

The work described here represents the latest TPD design, which has matured over the last several years. This work was performed as part of the Flexible Plant Operations and Generation Pathway project under the Light Water Reactor Sustainability program. The project aimed to develop and demonstrate a combined electric and thermal power dispatch the concept of operations that spans both normal and abnormal operations. Routine operation of the system entails transitioning the TPD from a hot standby to an online mode. This diverts steam from the turbine through the TPD in a coordinated manner. The converse sequence of operations is also envisioned to occur daily and over the same 10-minute timespan. Abnormal operations include detecting issues with the TPD system; most notably leaks between the extraction steam line to the delivery steam line to ensure the plant boundary is maintained.

Previous design and scenario validation efforts demonstrated the system to be safely operated during normal and abnormal operations. Furthermore, the TPD operated in tandem with existing plant operations, including fault response operations where a severe fault caused the plant to trip. During this event, operators performed typical emergency responses while the TPD system was in operation, and no significant safety issues were identified. This previous design extracted steam downstream of the high-pressure turbine and a small, less than 3% of the rated reactor thermal power. The current work evaluated a much larger system capable of supporting 17% thermal power equivalent of steam extracted through the TPD. To achieve this high extraction, the TPD was moved upstream

of the high-pressure turbine, which impacts the existing plant systems to a greater extent. As such, in tandem with the new TPD design, several additional technologies were advanced to ensure minimal impacts and smoother transitions between electric and combined electric-thermal generation plant modes of operation. A full-scope training simulator developed by GSE was modified to include the new TPD model, improved switchyard modeling for co-simulation with grid models, a new coordinated turbine control system and TPD controller, human-machine interface refinements, and a modified paper- and computer-based procedure to support scenario testing for evaluating the larger scale operation of this latest TPD design. The development and integration of these different elements is presented in this report to demonstrate how TPD operations can be developed and validated to aid industry in adopting this capability for existing commercial reactors.

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ACRONYMS

CBP	Computer-based procedure
COPS	Computerized Operating Procedure Systems
EOP	Emergency operating procedures
HITL	Human-in-the-loop
HPT	High-pressure turbine
HSI	Human-system interface
HSSL	Human systems simulation laboratory
HUNTER	Human Unimodel for Nuclear Technology to Enhance Reliability
MSLB	Main Steam Line Break
MSR	Main steam reheaters
NPP	Nuclear power plant
PBP	Paper-based procedures
PI	Proportional-integral
PV	Present value
PWR	Pressurized-water reactors
RCS	Reactor coolant system
RIPS	Rancor Integrated Procedure System
RNO	Response Not Obtained
RO	Response Obtained
SCR	Short-circuit ratio
SG	Steam generator
SGTR	Steam Generator Tube Rupture
TCS	Turbine control system

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1. INTRODUCTION

Thermal power dispatch (TPD) allows a nuclear power plant (NPP) to extract and use thermal power energy for purposes other than electricity generation. The TPD capability was originally pursued to bolster existing plant economics that were challenged by modern grid dynamics. Modern electric grids are far more variable than they were when the bulk of the U.S. nuclear fleet was built several decades ago. TPD affords NPPs with operational flexibility through an additional revenue stream enabled by providing process heat to a nearby industrial process during periods of low electrical pricing. At the same time, the plant maintains the ability to reduce or cease TPD to accommodate spikes in electrical demand and take advantage of the increased electrical pricing. The TPD achieves operational flexibility by accommodating the transition from electric to combined electric and thermal extraction modes of operation without affecting reactor power. This ensure steady-state operations are maintained, allowing the plant to follow well-known fuel burn-up cycles and avoid equipment degradation that would be required if they were to curtail power output by reducing reactor power. Indeed, this has been shown to be historically infeasible as several utilities have opted to pay other generators to curtail power in lieu of moving away from their own steady-state operations.

This document shares the research and development performed during the current fiscal year, which primarily focused on scaling the previously established TPD system to accommodate 10% and greater thermal power extraction. The following section describes the activities performed over each of the 5 years of the research project to provide context for this year's activities. Furthermore, as the final year of this research project, this section provides an integrated account of each disparate year's activities to illustrate the overall approach that generated the concept of operations for 10% and greater TPD capability.

1.1 Thermal Power Dispatch

Nationwide electrical demand projections recently underwent dramatic changes, which reduce the need for baseload nuclear power generators to contend with grid demand fluctuations. The dramatic rise in projected energy demand stems from chatbots and other forms of artificial intelligence, which are becoming ubiquitous and driving up the demand for electricity by data centers to provide the computational power supporting these artificial intelligence (AI) systems. Nonetheless, this spike in electrical demand may only provide temporary alleviation to the steady state inflexibility of currently operating nuclear power plants. Generation and load balance remain a challenge for existing commercial reactors as they cannot easily adjust their power without exiting their known operating band and inducing significant risk due to uncertainties around core integrity and equipment degradation. Therefore, the flexibility provided by the TPD will fundamentally remain relevant and valuable for existing light-water reactors into the foreseeable future.

Furthermore, the operating principles developed for gigawatt-scale light-water reactors are applicable to advanced reactor designs and expand TPD use cases. There is strong emerging demand for TPD applications like hydrogen production. In particular, the U.S. military has considerable energy demands placed on existing electrical and fossil-fuel infrastructure when available and otherwise supported by transporting portable diesel generators and fossil-fuels. The U.S. military has multiple initiatives aimed to achieve international energy independence as part of their combat readiness capability. For example, the U.S. Air Force recently announced a pilot project to use a microreactor to power the Eisel Air Force Base

located in Alaska (Warner 2025). This pilot project by itself does not provide evidence for a growing TPD need, but when considering it in conjunction with other U.S. military energy independence initiatives, it illustrates a clear potential use case for TPD to provide hydrogen for military vehicles. The military is developing technologies to transition air, land, and sea vehicles to use hydrogen fuel cells (Katalenich and Jacobson 2022). Their study reports long distance conversions are impractical, but short distance vehicles can be cost effectively converted to make use of hydrogen with numerous benefits, such as improved stealth characteristics due to lower noise emissions. The military interest in hydrogen for military vehicles and the development of infrastructure to support this reveals a large customer base that can be serviced by U.S. commercial reactors equipped with a TPD capability and partnered with HTSE producers. Further, military technology advancements routinely shape future public sector adoption which also indicates potential and emerging hydrogen markets in the future. Discussion of military applications for TPD is beyond the scope of this report and research effort, but it is important to acknowledge them as a source of emerging demand for commercial TPD.

1.2 TPD Research Program

The work reported here represents the most recent effort of a 5-year research project dedicated to developing and demonstrating a TPD capability. A project timeline mapping each year's activities with detailed reports can be seen in Figure 2, which is organized chronologically and topically to support interested readers in finding relevant reports. Research and development activities aimed to address increasingly realistic operational issues in tandem with system design refinements. The same general approach was used each year in which a full-scope simulator served as the testbed to evaluate and demonstrate concept of operations for the TPD system. Iterative TPD model, controller, and human-machine interface refinements were made each subsequent year to culminate in the final two-train TPD system design that served as the starting point for this current year's activities. A brief account of each year's activities and outcomes is presented below to provide context for the latest research and development reported in this document. Furthermore, details of the design for the TPD system as it evolved during each year can be seen in Table 1.

Table 1. TPD system design evolution across each fiscal year.

Fiscal Year	XSL/DSL	Extraction Location	TPD Scale	Design	Control System
2020	Steam/Oil	Main Steam	5–15%	Single Train	Manual
2021/2022	Steam/Steam	Main Steam	5–15% (5% evaluated)	Single Train	Manual
2023	Steam/Steam	Post-HP Turbine	~3%	Dual Train	AutoRamp
2024	Steam/Steam	Post-HP Turbine	~3%	Single and Dual Train	Integrated Automatic
2025	Steam/Steam	Main Steam	10–30%	Dual Train	Coordinated Automatic, Computer-based Procedure

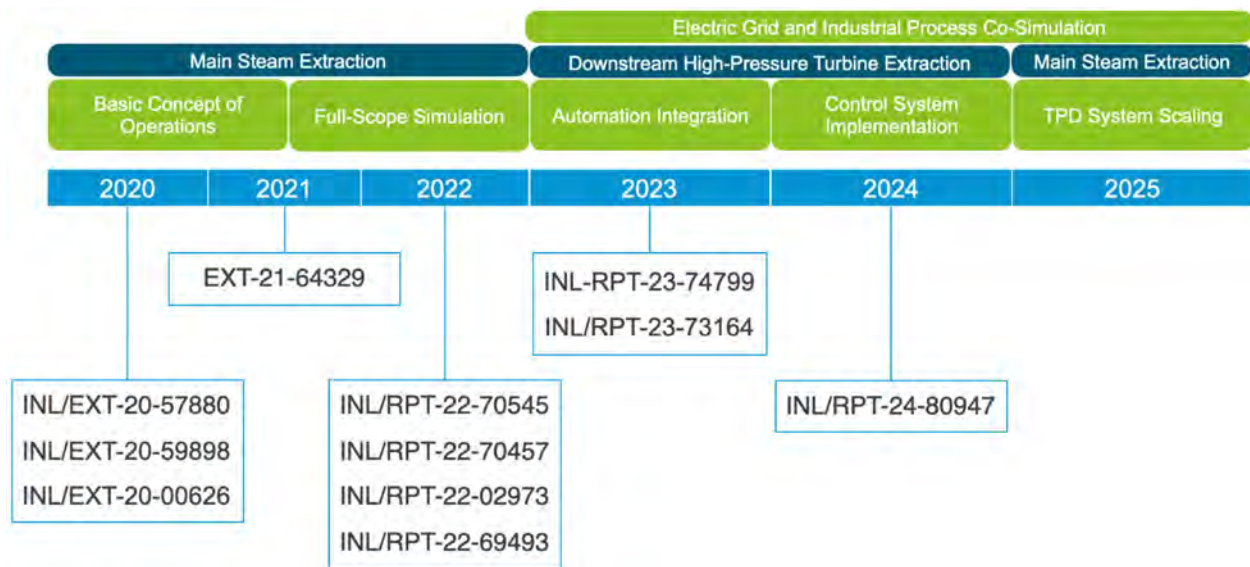


Figure 1. TPD research timeline depicting reports (LWRS n.d.).

The project began in 2020 with an initial conceptual design developed into the Generic Pressurized Water Reactor (GPWR) simulator developed by GSE Solutions. The proof-of-concept model was implemented natively in GPWR's JADE environment with JTopMerit to build and integrate the TPD into the existing plant models. The TPD design has matured throughout the project; however, the overall basic design has remained constant, which consists of an extraction and delivery loop that are thermally coupled through a reboiler heat exchanger. The heat exchanger and delivery loop maintain existing plant barriers encapsulating the main steam system to ensure radionuclides cannot be transferred to the industrial heat consumer. The extraction loop interfaces with the existing plants main steam system through an interface located downstream of the main steam header (see Option #1 in Figure 2 below) or the cross-under piping located downstream of the high-pressure turbine (see Option #2 in Figure 2 below). Once extracted, the diverted main steam passes through one side of a heat exchanger and is returned to the condenser after it has lost thermal energy through the heat exchanger. The delivery loop then transfers the thermal energy as steam to a nearby industrial user, such as a high-temperature steam electrolysis plant to make hydrogen (Ulrich et al. 2024).

The initial efforts, during fiscal year 2020, focused on developing the basic conceptual TPD design and implementing it in the simulator to support the development of operations to support normal routine functions. This first conceptual model used a single-phase oil secondary system as modeling is simplified with a steam-liquid heat exchanger configuration. This system was designed to support up to 30% thermal extraction in which 30% is defined as the equivalent steam flow representing 30% of total rated reactor power. Two former operators were engaged to support using this system to develop an initial and basic human-machine interface to control the TPD processes codified into mock procedures. Operator testing was quite limited, and therefore, they focused on a conservative 5% thermal power extraction to establish basic operations using recorded data from the simulator.

In 2022, a single-train steam-to-steam dual-phase heat exchanger TPD configuration was built into GPWR capable of 5–15% steam extraction. This model supported engineering analysis of the thermal efficiency and impacts of a TPD system. The full-scope simulator also provided the ability to support formal operator testing with a refined set of paper procedures providing instructions for operators to manually perform valve manipulations to offset turbine ramping at different speeds. The testing in 2022

focused on establishing the feasibility and impacts of TPD operations on existing operations. The testing included normal and abnormal scenarios. The critical outcomes identified the necessity of automation to transition the TPD system to hot standby and online modes and minimal impacts to handling abnormal plant operations.

In 2023, the GPWR model was revised to extract steam after the high-pressure turbine and reduced the total extracted steam to 3% across two trains. An AutoRamp controller was implemented as part of the TPD model. The AutoRamp controller ramped the extraction flow control valve of the TPD train for the hot standby and online transitions. The operation of the AutoRamp control had to be performed in conjunction with TCS, and the ramping of valve position was implemented due to instabilities with using a proportional-integral (PI) controller for extraction flow. In 2023, the Human-machine interface (HMI) matured with dedicated control panels for each of the four TPD controllers annunciating alarms.

In 2024, the GPWR TPD model was significantly refined based on specifications developed by Sargent and Lundy and documented in INL/RPT-23-71939 (Westover et al. 2023). Updating JADE versions improved the model fidelity allowing the PI flow controller to ramp extraction flow. The HMI implemented a setpoint controller for extraction flow with ramp rate and go/hold states. Operator testing confirmed both trains could be transitioned in a reasonable time window while maintaining reactivity. In 2024, we were also able to run a set of fault scenarios and demonstrate the HMI-supported identification, mitigation, and diagnosis of TPD faults. During 2024, a second simulator was used to evaluate a propriety high-fidelity implementation of the TPD control system with an established nuclear architecture and engineering firm. Due to the proprietary nature, the TPD system contained within that specification can support a 500-MWe HTEF. The TPD for this size HTEF is approximately 20 MWt, which represents less than 1% thermal power extraction. The 500 MWe TPD design specified in Westover et al. (2023) has a 120-MWt capacity, which is also quite small compared to the project objective of 10% thermal power extraction. Therefore, the components must be scaled to support significantly more steam flow to achieve the 10% target extraction value. Additionally, the current TPD model is a single loop. It may be possible to achieve the magnitude of extraction via a single loop. However, it would be beneficial to adopt the two-train design specified in Westover et al. (2023) .

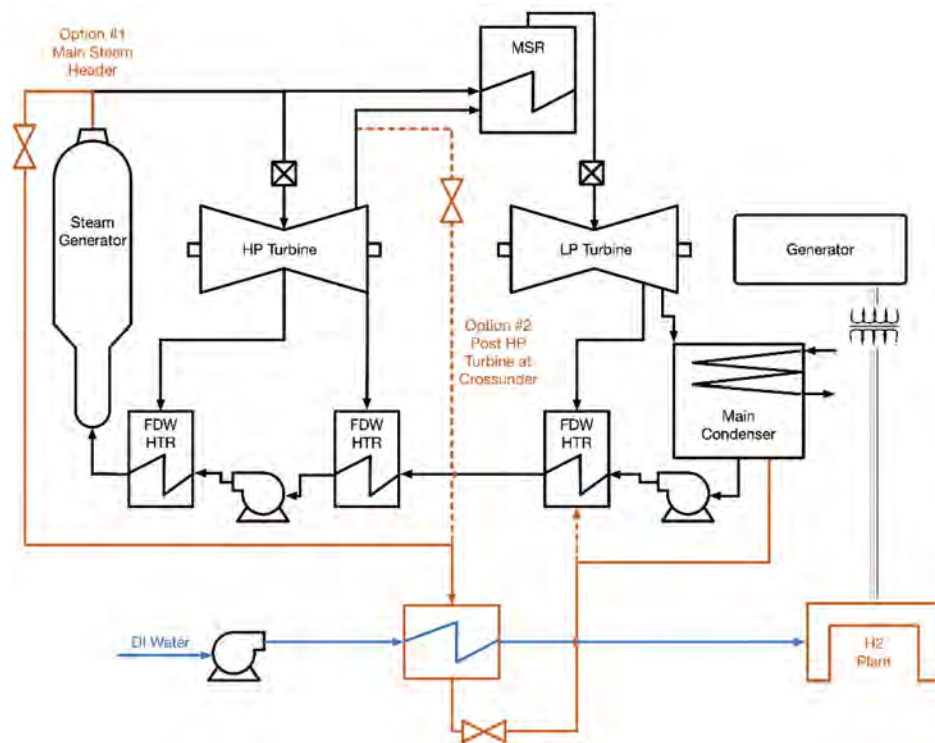


Figure 2. TPD extraction interface locations downstream of the main steam header and downstream of the high-pressure turbine at the cross-under piping.

1.3 Scope of Current Activities

The work in 2024 represents a successful design and associated concept of operations demonstration for a TPD capability suitable for hydrogen production represented with a 500-MWe high-temperature steam electrolysis (HTSE) facility (Ulrich et al. 2024). The current effort focused on modifying the TPD design and simulator implementation to support scenario testing with the pressurized-water reactor thermally coupled to a much larger HTSE facility capable of consuming 10–30% of reactor thermal power. The resulting design and simulator implementation supported 17% reactor thermal power capacity which falls within the 10-30% target. Extracting the required volume of steam to achieve this capacity is not feasible with the 2024 design's configuration, which required two important modifications. First, the TPD system model interface was repositioned to the main steam header to achieve the extraction flow volume needed for the increased capacity TPD. Second, components were rescaled to achieve sufficient heat exchange capacity flow rate for steam dispatched to the hydrogen plant for use as process heat. Scaling of components across the TPD specifically involved scaling the heat exchangers, piping, and valves.

In addition to modifications to the design and simulator models, several supporting control room technologies were refined or developed to streamline TPD operations *and* support scenario testing. An automatic control scheme was designed and implemented to support a coordinated control capability for the turbine governor valves and the primary flow controller modulating steam flow through the TPD system. The prototype HMI for the TPD system was modified to support the new automation functionality and leverage lessons learned from previous evaluations of the system. Second, the switchyard and electric grid models were modified both natively in the GSE Solutions environment and augmented through co-simulation with an external Simulink model representing the switchyard for the HTSE. Additionally, the Simulink model also contained the HTSE process to represent the dynamics and thermal load placed on the TPD. The electric grid-coupled to the generator was modified to support more realistic dynamics to support the load rejection scenarios planned for future validation activities. Last, procedures were modified to support the larger capacity and accommodate the change in extraction location from the main steam header. Paper procedures were drafted, but prototype computer-based procedures were also implemented to support evaluations that are representative of more advanced operational concepts similar to those found in an advanced reactor. The computer-based procedures served a dual-role as a powerful data collection tool that significantly increases the resolution of the human performance data collected during validation scenario testing.

1.4 Concept of Operations Simulator Testbed

1.4.1 Human Systems Simulation Laboratory

The human systems simulation laboratory (HSSL) supports research and development in support the existing U.S. nuclear fleet through the Light Water Reactor Sustainability program. The HSSL has hosted dozens of studies to develop digital control system upgrades and validate these modifications following the approach prescribed in Human Factors Engineering Program Review Model (U.S. Nuclear Regulatory Commission [NUREG-0711, Rev. 3], 2012). The HSSL has the infrastructure to host industry provided training simulators and display a virtual representation of the control room using a collection of computer bays. Each bay has three touchscreen displays that can be repositioned based on the physical characteristics of the actual control room it is emulating. Furthermore, the lab space is reconfigurable to support control rooms with different shapes including some European designs that can have an inner and outer row of control panels. The GSE Solutions GPWR simulator used in this study was hosted and displayed in the HSSL.

1.4.2 Full-Scope Training Simulator Approach

The approach to develop the concept of operations for thermal power dispatch has followed a scenario-based testing approach in which the operations of system are tested in live simulations using the HSSL and GSE Solutions GPWR simulator. Developing the concept of operations ultimately culminates in a validation activity with a high-fidelity control room simulation using licensed operators. To reach this stage, numerous simulations of varying fidelity are used to develop the procedures, human-machine interface, and scenarios for testing, but here the focus is on this year's activities, which were performed primarily on the GPWR system deployed in the HSSL. Basic system requirements, such as the magnitude of thermal energy extraction were known; however, scenarios were selected during the development process to identify any modifications that may be outside of the basic design specifications. This was particularly important for fault scenarios to ensure potential impacts of TPD operations on existing systems are considered while making modifications to the underlying simulator models. The scenarios in Table 2 were selected as a representative set of scenarios needed to validate the safe operation of the TPD system. In general, these scenarios fall under routine operations to evaluate impacts to workload and ensure a switch transition within the 10-minute target transition between hot standby to online and online to hot standby needed to ensure the plant has sufficient flexibility to respond to dynamic electric grid conditions in reasonable timeframe. The abnormal scenarios evaluate the system's ability to convey faults specific to the TPD with an emphasis on ensuring no steam escapes existing plant boundaries to stay within the licensing conditions for existing plants. The additional scenarios evaluate impacts of TPD operations within the context of existing plant operations, most notably significant fault conditions including main steam line breaks and steam generator tube ruptures.

Table 2. List of selected scenarios.

Scenario Group	Scenario
TPD Normal Scenarios	Hot Standby to Online
	Coordinated TPD/TCS Mode Online to Hot Standby*
<u>TPD Abnormal Scenarios</u>	<u>Tube Leak in the Reboiler – Small</u>
	<u>Tube Leak in the Drain Cooler Heater – Small</u>
	<u>Rupture Downstream of FT-1001/Upstream of the Reboiler</u>
Additional Scenarios	Load Rejection – TPD offline
	Load Rejection – TPD online
	HTSE Electric and Steam Trip
	Main Steam Line Break
	Steam Generator Tube Rupture

1.4.2.1 GPWR Simulator

The GSE Solutions GPWR simulator is a specialized nuclear power plant training tool developed by GSE Systems, Inc., designed to replicate the operation of a Generic Pressurized Water Reactor (GPWR). It is primarily used for training nuclear plant operators, engineering evaluation, and control room familiarization. This simulator served as the central simulation platform used to develop the TPD concept of operations.

1.4.2.2 Rancor Simulation Framework

Here we utilized the Rancor 3.0 Simulator framework and its integrated procedure system (RIPS) to implement concept of operations with computer-based procedure (CBP). Rancor has two-way communication support for GSE simulators using GSE’s SimAPI. The CBP can include live indications with logical evaluations and soft controls within the procedure. The procedures support single and two-column procedures with response obtained (RO) and response not obtained (RNO), like those typically found in the nuclear power industry. The procedures support substeps, place-keeping with timestamps, procedure path following to non-sequential steps, and other procedures.

1.4.2.3 TPD HMI

The HMI was first developed in Ulrich et al. (2021) and underwent significant refinements to support two trains (Ulrich et al. 2024). The refinements were based on usability testing with novice users and NRC personnel. Users were tasked with completing normal operations scenarios with written procedures. The HMI consisted of two displays for each train, an overview with alarm panel, piping and instrumentation diagram (P&ID), and mode status indicators as well as a control display (see Section 3.3).

1.4.2.4 HTSE and Grid Model

The HTSE’s solid oxide electrolysis cell model comprises of the electrical, thermal, fluid and electrochemical dynamical equations that governs the operation of the HTSE’s stacks. Depending on the size of the HTSE, the cells are connected in series and parallel to form the solid oxide stacks. The thermal balance of plant contains heaters, recuperators, mass flow controllers, pressure regulators and others. The electrical balance of plant consists of AC-DC converters, transformers, circuit breakers and isolators. The grid model is developed to allow the coupling between the HTSE, GPWR and the rest of the grid. Properly sized transformers, isolators, high and low voltage lines, circuit breakers are modeled to allow bidirectional power flow between the HTSE, GPWR and the rest of the grid.

2. SIMULATOR MODIFICATIONS

2.1 Thermal Power Dispatch Model

Previously, the TPD system extracted steam from the cross-under piping of the high-pressure turbine. This configuration allowed the existing turbine control system (TCS) to modulate flow through the turbines and the system. However, it also severely limited the thermal extraction capabilities of the system, restricting previous iterations to 100 MWt and 500 MWe. This represents approximately 50% of the nominal 1,000-MWe NPP output and ~3% of the reactor's thermal power (Ulrich et al. 2024).

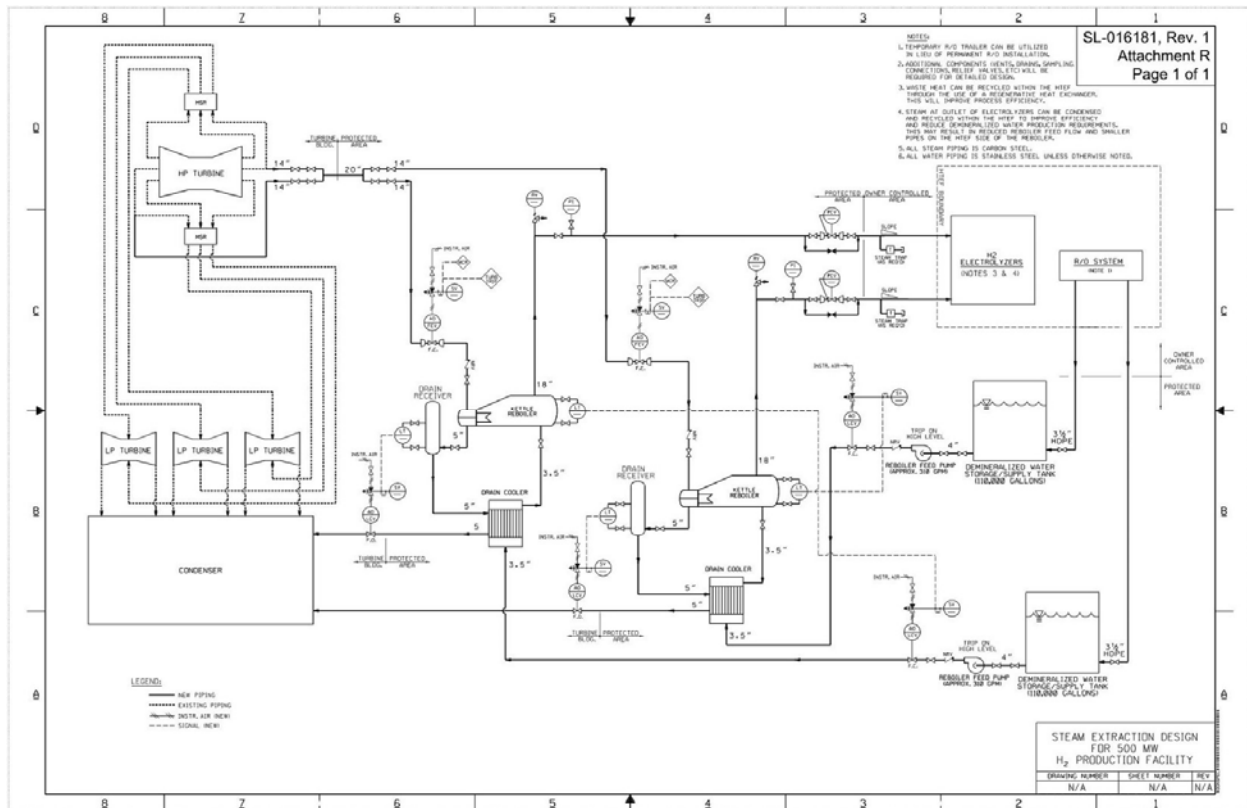


Figure 3. Piping and instrumentation diagram of the 500-MWe TPD system designed by Sargent & Lundy.

A primary objective for this activity is to modify the underlying plant models in the simulator to support thermal extraction in excess of 10% of the reactor's thermal energy, with future goals targeting up to 30% thermal energy extraction. Several changes were made to the system to achieve this goal; however, the overall design remains similar with respect to using the same components in a similar but scaled configuration.

2.1.1 Secondary System Interface Relocation

The first and most significant change to the system was relocating the connection upstream of the high-pressure turbine, branching off from the common steam header before the turbine throttle valves. This modification eliminates the previous limitations associated with being connected to the cross-under piping of the high-pressure turbine and enables the capability for complete transfer of thermal power from the turbines to the TPD system.

2.1.2 System Scaling to 10% and Beyond

Thermal power (Q) for the system can be calculated using the following equation, where mass flow rate ($\dot{m}$) and outlet enthalpy (h) are the unknown variables:

$$Q = \dot{m}(h_{in} - h_{out}).$$

To achieve greater than 10% thermal power extraction, a flow rate equal to 10% of the total steam flow was assumed—an intentionally conservative estimate likely to yield thermal extraction above the minimum requirement. The GPWR steam system is designed for a total steam flow rate of 3,572.2 lbm/s, which results in a standard TPD system flow of 360 lbm/s (split evenly at 180 lbm/s per loop of the two-loop design).

Given the system's significant and direct influence on reactor power, it was anticipated that one train may need to absorb some of the other trains flow during transient conditions. Each loop was therefore designed to sustain flow rates of 225 lbm/s—approximately 25% of the opposite loop's flow—to mitigate impact on reactor power. To support this, each loop was specified with a design margin of roughly 10%, yielding a design flow of 250 lbm/s per loop. The total design flow in the common piping was set at 500 lbm/s, while the control system's total trip setpoint was established at 480 lbm/s, with individual loop trips set at 250 lbm/s to ensure this value shall not be exceeded.

Once the mass flow rate was determined, pipe sizing for the extraction steam loop (XSL) system was performed. For the steam piping, it was assumed that flow velocity would remain constant, matching the main steam system velocity, which is selected to minimize both thermal losses to ambient and pressure drops within the pipe. Although ambient losses are more significant in the TPD system due to longer pipe runs, maintaining a high velocity helps limit these losses.

$$A = \frac{\dot{V}}{v},$$

$$\pi \left(\frac{d}{2}\right)^2 = \frac{\dot{m}V}{v},$$

$$v = \frac{4\dot{m}V}{\pi d^2}.$$

Since we want flow velocity to remain constant

$$\left[\frac{4\dot{m}V}{\pi d^2}\right]_{ms} = \left[\frac{4\dot{m}V}{\pi d^2}\right]_{xsl}.$$

At the point of connection, the specific volume (V) is constant since the conditions of the steam have not changed, the equation can be simplified to

$$\left[\frac{\dot{m}}{d^2}\right]_{ms} = \left[\frac{\dot{m}}{d^2}\right]_{xsl}.$$

Solving for d_{xsl} ,

$$d_{xsl}^2 \dot{m}_{ms} = d_{ms}^2 \dot{m}_{xsl},$$

$$d_{xsl}^2 = d_{ms}^2 \frac{\dot{m}_{xsl}}{\dot{m}_{ms}},$$

$$d_{xsl} = d_{ms} \sqrt{\frac{\dot{m}_{xsl}}{\dot{m}_{ms}}}.$$

This calculation resulted in a required XSL pipe diameter of 16.26 inches, which was rounded up to the next standard size of 18 inches to further reduce pressure drop through piping and valves.

The same approach was applied to size the pipes as the flow splits into Train A and Train B, leading to the equation

$$d_{xsl,A/B} = d_{xsl} \sqrt{\frac{\dot{m}_{xsl}}{\dot{m}_{ms}}}.$$

The required diameter for each train was calculated as 12.73 inches and rounded up to the standard 14-inch pipe size, again minimizing pressure losses through each train.

Before designing the heat exchanger, the conditions at the heat exchanger need to be determined. Since valves are present, pressure drop across each of the valves needs to be solved for and serves as input into GPWR. Since steam is compressible and the flow is not choked, Equation 6 from the ISA 75.01.01, “Flow Equations for Sizing Control Valves” can be seen below:

$$C_v = \frac{W}{N_6 Y \sqrt{\frac{\Delta P}{P_i}} P_i \rho_i}.$$

In this equation, the flow coefficient (C_v) is a function of the mass flow rate (W , lbm/hr), inlet pressure (P_i , psia), differential pressure (ΔP , psid), a conversion factor (N_6), the expansion factor (Y), and inlet fluid density (ρ , lbm/ft³). The expansion factor can be calculated using Equation 32 from ISA 75.01.01, “Flow Equations for Sizing Control Valves”:

$$Y = 1 - \frac{\Delta P / P_i}{3 F_Y x_T}.$$

Substituting the expansion factor equation into the equation for the flow coefficient yields the equation

$$C_v = \frac{W}{N_6 \left(1 - \frac{\Delta P / P_i}{3 F_Y x_T}\right) \sqrt{\frac{\Delta P}{P_i}} P_i \rho_i}.$$

Rearranging the equation to solve for outlet pressure (P_o),

$$\begin{aligned} \left(1 - \frac{\Delta P / P_i}{3 F_Y x_T}\right) \sqrt{\Delta P} &= \frac{W}{N_6 C_v \sqrt{\rho_i}}, \\ \Delta P^{3/2} - \frac{1}{3 F_Y x_T P_i} \Delta P^{3/2} &= \frac{W}{N_6 C_v \sqrt{\rho_i}}, \\ \Delta P^{1/2} - \frac{1}{3 F_Y x_T P_i} \Delta P^{3/2} - \frac{W}{N_6 C_v \sqrt{\rho_i}} &= 0, \\ (\Delta P^{1/2})^3 - 3 F_Y x_T P_i (\Delta P^{1/2})^1 + \frac{3 W F_Y x_T P_i}{N_6 C_v \sqrt{\rho_i}} &= 0. \end{aligned}$$

Since the cubic function is already depressed—when a quadratic in the form of $ax^3+bx^2+cx+d=0$ has $a=1$ and $b=0$ —Cardano’s method can be utilized to solve the root directly:

$$\begin{aligned} x &= \sqrt[3]{-\frac{d}{2} + \sqrt{\frac{d^2}{4} + \frac{c^3}{27}}} + \sqrt[3]{-\frac{d}{2} - \sqrt{\frac{d^2}{4} + \frac{c^3}{27}}} \\ \Delta P^{1/2} &= \sqrt[3]{-\frac{3 W F_Y x_T P_i}{2 N_6 C_v \sqrt{\rho_i}} + \sqrt{\frac{9 W^2 F_Y^2 x_T^2 P_i^2}{4 N_6^2 C_v^2 \rho_i} + \frac{27 F_Y^3 x_T^3 P_i^3}{27}}} \\ &\quad + \sqrt[3]{-\frac{3 W F_Y x_T P_i}{2 N_6 C_v \sqrt{\rho_i}} - \sqrt{\frac{9 W^2 F_Y^2 x_T^2 P_i^2}{4 N_6^2 C_v^2 \rho_i} + \frac{27 F_Y^3 x_T^3 P_i^3}{27}}} \end{aligned}$$

$$\begin{aligned}
\Delta P^{1/2} &= \sqrt[3]{-\frac{3WF_Y x_T P_i}{2N_6 C_v \sqrt{\rho_i}} + \sqrt{\frac{9W^2 F_Y^2 x_T^2 P_i^2}{4N_6^2 C_v^2 \rho_i} + F_Y^3 x_T^3 P_i^3}} \\
&\quad + \sqrt[3]{-\frac{3WF_Y x_T P_i}{2N_6 C_v \sqrt{\rho_i}} - \sqrt{\frac{9W^2 F_Y^2 x_T^2 P_i^2}{4N_6^2 C_v^2 \rho_i} + F_Y^3 x_T^3 P_i^3}} \\
P_i - P_o &= \left(\sqrt[3]{-\frac{3WF_Y x_T P_i}{2N_6 C_v \sqrt{\rho_i}} + \sqrt{\frac{9W^2 F_Y^2 x_T^2 P_i^2}{4N_6^2 C_v^2 \rho_i} + F_Y^3 x_T^3 P_i^3}} \right. \\
&\quad \left. + \sqrt[3]{-\frac{3WF_Y x_T P_i}{2N_6 C_v \sqrt{\rho_i}} - \sqrt{\frac{9W^2 F_Y^2 x_T^2 P_i^2}{4N_6^2 C_v^2 \rho_i} + F_Y^3 x_T^3 P_i^3}} \right)^2 \\
P_o &= P_i - \left(\sqrt[3]{-\frac{3WF_Y x_T P_i}{2N_6 C_v \sqrt{\rho_i}} + \sqrt{\frac{9W^2 F_Y^2 x_T^2 P_i^2}{4N_6^2 C_v^2 \rho_i} + F_Y^3 x_T^3 P_i^3}} \right. \\
&\quad \left. + \sqrt[3]{-\frac{3WF_Y x_T P_i}{2N_6 C_v \sqrt{\rho_i}} - \sqrt{\frac{9W^2 F_Y^2 x_T^2 P_i^2}{4N_6^2 C_v^2 \rho_i} + F_Y^3 x_T^3 P_i^3}} \right)^2
\end{aligned}$$

Approximate values of pressure differential ratio factor of a control valve without attached fittings at choked flow (x_T) for different valves were taken from ISA 75.01.01, “Flow Equations for Sizing Control Valves” and condensed to a single value for each valve type displayed in Table 3.

Table 3. Approximate values for x_T for each valve type.

Valve Type	x_T approximate value
Globe	0.70
Butterfly	0.40
Ball	0.40

For saturated steam, ISA 75.01.01, “Flow Equations for Sizing Control Valves” tells us that

$$0.893 \leq F_Y \leq 0.943.$$

For the purposes of valve calculations, it was assumed $F_Y = 0.925$. From Table 1 in the ISA 75.01.01, “Flow Equations for Sizing Control Valves” for our units,

$$N_6 = 63.3.$$

For the flow coefficient (C_v) Equation 6-96 from Perry’s *Chemical Engineering Handbook* (2019) was used to calculate standard values for use in the system definition:

$$C_v = 29.9 \frac{D^2}{\sqrt{K}}$$

K is the velocity head loss coefficient (see Table 4), and these values were obtained from Table 6-4 of Perry's *Chemical Engineering Handbook* (1999).

Table 4. K values for various valve types.

	Gate	Globe			Check	Butterfly
		Bevel	Composition	Plug		
K	0.17	6	6	9	2	0.24

The pressure drops in the XSL system from the main steam header to the inlet of the reboiler was calculated and are tabulated in Table 5 below.

Table 5. XSL conditions from connection to reboiler inlet.

Flow Rate (lbm/s)	Upstream Pressure (psia)	Valve Type	Valve Size (in)	Downstream Pressure (psia)	Specific Density (lbm/ft ³)
500	1,002.26	Gate	18.00	1,001.61	2.247842633
500	1,001.61	Gate	18.00	1,000.95	2.234716772
250	1,000.95	Gate	14.00	1,000.50	2.226581374
250	1,000.50	Globe-Plug	5.75*	566.93	2.221042602
250	566.93	Check	14.00	557.84	1.258402986
250	557.84	Gate	14.00	557.03	1.226886983

*Reduced-bore valve to facilitate flow control.

The same was done for the DSL system from the connection to the HTSE to the outlet of the reboiler was also calculated and can be seen below in Table 6.

Table 6. Pressure drop across valves in DSL downstream of the reboiler.

Flow Rate (lbm/s)	Upstream Pressure (psia)	Valve Type	Valve Size (in)	Downstream Pressure (psia)	Specific Density (lbm/ft ³)
205	96.51	Gate	18	95.50	0.24030490
205	95.50	Gate	18	94.47	0.23815194
205	94.47	Butterfly	18	93.04	0.23595535
205	93.04	Gate	18	91.99	0.23288364

Accurate design or evaluation of a heat exchanger requires detailed modeling to predict thermal performance, pressure drop, and vibration risk. Simplified approaches may not provide sufficient confidence, so rigorous calculations are often necessary. Aspen Exchanger Design and Rating (Aspen EDR) software enables this by accounting for exchanger geometry, materials, and precise operating conditions. Utilizing Aspen EDR to design the reboiler not only ensures reliable performance but can also help minimize capital costs. The reboiler was modeled with the input parameters listed in Table 7.

The inputs (depicted in Table 7) were entered into a kettle reboiler, shell and tube type as designated by the original Sargent and Lundy design. Table 8 indicates the relevant outputs for that process but more information on the design is available in Appendix A.

Table 7. Aspen Exchanger Design and Rating kettle reboiler inputs.

Input Parameter (units)	Input Value
XSL Region	
Mass Flow Rate (lbm/s)	180.00
Inlet Temperature (°F)	478.33
Outlet Temperature (°F)	400.00
Inlet Pressure (psia)	557.03
Allowable Pressure Drop (psi)	117.34
Design Pressure (psig)	1,185.00
Design Temperature (°F)	600.00
DSL Region	
Inlet Temperature (°F)*	310.00
Outlet Temperature (°F)	330.00
Inlet Pressure (psia)**	98.20
Allowable Pressure Drop (psi)	5.00
Design Pressure (psig)	350.00
Design Temperature (°F)	420.00

*Required feedback from drain cooler to achieve this input

**Required iteration to achieve input for desired exit conditions

Table 8. Aspen Exchanger Design and Rating kettle reboiler outputs.

Input Parameter (Units)	Input Value
XSL Region	
Outlet Pressure (psia)	549.50
DSL Region	
Mass Flow Rate (lbm/s)	165.90
Outlet Pressure (psia)	96.77

This allowed the calculation of the conditions downstream of the reboiler in the XSL system, where the fluid is assumed to be a liquid. Although there is a drain receiver between the reboiler and drain receiver, its presence is primarily to ensure that any remaining vapor in the system collects there and does not continue to the drain receiver until it condenses. It has minimal impact with respect to pressure drop in the system and was thus ignored for the purposes of calculating pressure drop across the two gate valves between the reboiler and drain receiver.

To calculate the drop in pressure, Equation 1 from ISA 75.01.01-2007 (IEC 60534-2-1 Mod) for non-compressible flow, as seen below, can be used:

$$C_v = \frac{Q}{N_1} \sqrt{\frac{\rho_i/\rho_0}{\Delta P}}.$$

Solving for P_o , knowing that $\Delta P = P_i - P_o$:

$$\begin{aligned} \sqrt{\frac{\Delta P}{\rho_i/\rho_0}} &= \frac{Q}{C_v N_1}, \\ \frac{\Delta P}{\rho_i/\rho_0} &= \left(\frac{Q}{C_v N_1} \right)^2, \\ P_i - P_o &= \frac{\rho_i}{\rho_0} \left(\frac{Q}{C_v N_1} \right)^2, \\ P_o &= P_i - \frac{\rho_i}{\rho_0} \left(\frac{Q}{C_v N_1} \right)^2. \end{aligned}$$

Outlet pressure (P_o [psia]) is a function of inlet pressure (P_i [psia]), inlet density (ρ_i [lbm/ft³]), density of water at 15°C (ρ_0 62.4 [lbm/ft³]), volumetric flow rate (Q [gpm]), valve flow coefficient (C_v), and a numerical constant (N_1 , 1 for the current units). The resulting pressure drops across the two gate valves in the XSL between the reboiler and drain receiver can be seen in Table 9.

Table 9. Calculated pressure drops in the XSL from the reboiler outlet to drain receiver inlet.

Flow Rate (lbm/s)	Upstream Pressure (psia)	Valve Type	Valve Size (in)	Downstream Pressure (psia)	Specific Density (lbm/ft ³)
250	549.50	Gate	5	548.35	53.74
250	548.35	Gate	5	547.21	53.74

Equation 1 from ISA 75.01.01-2007 (International Society of Automation, 2007) can also be used to calculate the inlet pressure from the outlet pressure of the gate valve in the DSL system. This allows the DSL system conditions to be calculated at the drain receiver outlet. Although the inlet conditions are not known for steam systems, when the fluid is incompressible, the inlet density (ρ_i) is entirely dependent on temperature. This allows the inlet pressure to be calculated via the equations below:

$$\begin{aligned} P_i - P_o &= \frac{\rho_i}{\rho_0} \left(\frac{Q}{C_v N_1} \right)^2, \\ P_i &= P_o + \frac{\rho_i}{\rho_0} \left(\frac{Q}{C_v N_1} \right)^2. \end{aligned}$$

The resulting conditions from the equation can be seen in Table 10.

Table 10. Calculated pressure drops in the DSL from the reboiler inlet to drain receiver outlet.

Flow Rate (lbm/s)	Upstream Pressure (psia)	Valve Type	Valve Size (in)	Downstream Pressure (psia)	Specific Density (lbm/ft ³)
205	98.93	Gate	5	98.20	56.99

In previous iterations of the TPD system, the drain receiver utilized a plate and frame heat exchanger. These exchangers have grown increasingly popular due to their compact footprint, high thermal efficiency, and straightforward maintenance, making them a common choice across various industries. However, the relocation of the connection from the high-pressure turbine (HPT) cross-under valve to the

MSS introduced substantially higher pressures and temperatures for this application. While it is conceivable that a custom plate and frame heat exchanger could be engineered to withstand these extreme conditions, publicly available information on such designs is scarce. The need for specialized construction would also eliminate much of the cost advantage typically associated with plate and frame units. Furthermore, Aspen EDR does not maintain validated design data for plate and frame exchangers at these elevated parameters, issuing a warning that calculated results are extrapolated and potentially unreliable.

For these reasons, a plate and fin heat exchanger were selected as the drain cooler. Plate and fin exchanges offer comparable benefits, high heat transfer rates, and space efficiency, while also being field proven under more demanding pressure and temperature conditions. The design was modeled in Aspen EDR using the input data presented in Table 11.

Table 11. Aspen exchanger design and rating plate and fin inputs.

Input Parameter (Units)	Input Value
XSL Region	
Mass Flow Rate (lbm/s)	180.00
Inlet Temperature (°F)	400.00
Outlet Temperature (°F)	200.00
Inlet Pressure (psia)	547.21
Allowable Pressure Drop (psi)	50.00
DSL Region	
Mass Flow Rate (lbm/s)	165.90
Inlet Temperature (°F)	85.00
Outlet Temperature (°F)*	310.00
Inlet Pressure (psia)**	108.73
Allowable Pressure Drop (psi)	10.00

*Required feedback from kettle reboiler to achieve this input

**Required iteration to achieve input for desired exit conditions

The solution method for the plate and fin type heat exchanger was design. Different solution methods within Aspen EDR require different inputs. The relevant outputs are available in Table 12, while the entirety of the design document is available in the Appendix B.

Table 12. Aspen Exchanger Design and Rating drain receiver outputs

Input Parameter (Units)	Input Value
XSL Region	
Outlet Pressure (psia)	538.82
DSL Region	
Outlet Pressure (psia)	98.93

In the XSL system, there is a globe valve that maintains level within the drain receiver followed by a gate valve and a check valve. The same formulas used for the region between the outlet of the reboiler and the inlet of the drain receiver on the XSL side can be used again here. Table 13 contains the resulting conditions for each valve prior to returning to the condenser.

Table 13. Calculated pressure drops in the XSL from the drain receiver outlet to the condenser.

Flow Rate (lbm/s)	Upstream Pressure (psia)	Valve Type	Valve Size (in)	Downstream Pressure (psia)	Specific Density (lbm/ft ³)
250	538.82	Globe	5	502.36	59.59
250	502.36	Gate	5	501.33	59.59
250	501.33	Check	5	489.18	59.59

The DSL system contains a globe valve, a gate valve, and a swing check valve before reaching a centrifugal pump. These items were solved using the same method as the region between the inlet of the reboiler and outlet of the drain receiver in the DSL. The results of these can be seen in Table 14.

Table 14. Calculated pressure drops in the DSL from the drain receiver inlet to drain receiver.

Flow Rate (lbm/s)	Upstream Pressure (psia)	Valve Type	Valve Size (in)	Downstream Pressure (psia)	Specific Density (lbm/ft ³)
205	140.63	Check	5	132.82	62.33
205	132.82	Gate	5	132.16	62.33
205	132.16	Globe	5	108.72	62.33

The final MW_{th} rating can be calculated using the same equation as stated at the beginning of the section:

$$Q = \dot{m}(h_{in} - h_{out}).$$

With a mass flow rate of 360 lbm/s, and return temperature to the condenser 213.639°F:

$$Q = \dot{m}(h_{in} - h_{out}),$$

$$\dot{m} = 360 \text{ lbm/s},$$

$$h_{in}(P = 1002.6 \text{ psia}, T = T_{sat}) = 1192.7 \left[\frac{\text{Btu}}{\text{lbm}} \right],$$

$$h_{out}(P = 328.11 \text{ psia}, T = 200.191 \text{ F}) = 169 \left[\frac{\text{Btu}}{\text{lbm}} \right],$$

$$Q = 360 \left[\frac{\text{lbm}}{\text{s}} \right] * (1192.7 \left[\frac{\text{Btu}}{\text{lbm}} \right] - 169 \left[\frac{\text{Btu}}{\text{lbm}} \right]),$$

$$Q = 368,532 \left[\frac{\text{Btu}}{\text{s}} \right] * 0.0010550559 \left[\frac{\text{MW}_{th}}{\text{Btu/s}} \right],$$

$$Q = 388.82 \text{ MW}_{th}.$$

The final MW_{th} rating for the system is ~389 MW_{th} during normal operation, or $\approx 13.4\%$ of the thermal power of the reactor.

2.1.3 Control System Modifications

Control systems form the backbone of modern automation, enabling machines and processes to operate with minimal human intervention while maintaining desired performance. By constantly monitoring outputs and making automatic adjustments based on input commands or setpoints defined by an operator, control systems ensure stability, accuracy, and efficiency across a wide range of applications—from manufacturing and robotics to transportation and energy management.

Among the various control strategies, the proportional-integral (PI) controller is particularly prevalent due to its balance of simplicity and effectiveness. A PI controller operates within a feedback loop to continually minimize the difference between a desired setpoint and the measured process variable. This is

achieved through two distinct actions: (1) the proportional component responds in real time to the current error, providing direct and immediate corrections, while (2) the integral component considers the cumulative history of error, making gradual adjustments that eliminate persistent offsets and ensure long-term accuracy. The combination of these effects allows PI controllers to deliver steady, reliable performance in regulating variables such as pressure, flow, and level, making them indispensable in both industrial and scientific contexts.

The general form of the control equation is dependent on several constants that can be set by the user such as the proportionality constant (K_c), the integral timescale (τ_i), and the derivative timescale (τ_D). It is also dependent on a simple error function that is the difference between the setpoint (SP) and the present value (PV). Both equations can be seen below (error first, followed by the control function):

$$\epsilon(t) = SP - PV,$$

$$u(t) = K_c \left(\epsilon(t) + \frac{1}{\tau_i} \int_0^t \epsilon(t) dt + \tau_D \frac{\delta \epsilon(t)}{\delta t} \right).$$

Since the TPD system uses PI controllers, the derivative timescale is zero. Although previous iterations of this system exist, these values need to be checked since the speed of the system can change, necessitating different controller settings to ensure proper system behavior, commonly referred to as controller tuning. The current values can be seen in Table 15.

Table 15. TPD system controller settings.

Controller	K_c	τ_i
XSL Flow Controller	0.0012	120
XSL Drain Receiver Level Controller	0.0075	400
DSL Demineralized Water Tank Level Controller	0.1000	400
DSL Reboiler Level Controller	0.0075	400
DSL Pressure Controller	0.0100	300

2.1.3.1 Level Controller Design

To increase the realism of the simulator, a new level controller was designed and modeled after error functions found in the steam generator water level control system. The graphical representation of the SGWLCS equation can be found in Figure 11.1-1 in the *Westinghouse Technology Systems Manual*, Section 11.1, “Steam Generator Water Level Control System” (Westinghouse Electric Corporation n.d.). There were some items that were not needed in the TPD systems implementation of the level controller, making the systems error equation dependent on two separate pieces. The first piece is the flow error, multiplied by the flow error constant (K_1), which is dependent on the mass flow rate of steam (Q_{steam}), the feed flow rate (Q_{feed}), and the max steam flow rate ($Q_{\text{steam, max}}$). The second piece is level error, multiplied by the level error constant, which is a function of the program level (L_{program}) and the current level (L).

$$\epsilon_{\text{Flow}}(t) = \frac{Q_{\text{steam}}(t) - Q_{\text{feed}}(t)}{Q_{\text{steam, max}}},$$

$$\epsilon_{\text{Level}}(t) = L_{\text{program}} - L(t),$$

$$\epsilon(t) = K_1 * \epsilon_{\text{Flow}}(t) + K_2 * \epsilon_{\text{Level}}(t).$$

The values of the constants bias the system toward being flow dominant or level dominant depending on system behavior. The value for K_1 was set to 0.8 and K_2 was set to 0.2 to make the system flow dominant. By making the system flow dominant, it allows the system to quickly respond to changes in flow while allowing accumulation of level error to prevent the system from drying out. This allows for a

new means of diagnosing detector or controller issues by seeing a deviation in steady-state level within the system; however, these controllers need further tuning to make that apparent.

This controller was implemented for both the drain receiver in the XSL and the reboiler in the DSL. For a real system, a dead band would also be implemented to prevent the premature wear of controller contacts.

2.1.3.2 Coordinated Steam Flow Controller

The goal of the system was to permit the transfer of thermal energy from the turbine generators to the TPD system in <10 minutes. Under normal circumstances, this would be very challenging for the operators and require very intense focus from the operator; therefore, an automatic transfer method was developed. This was done by doing a calorimetric on the secondary system of the nuclear reactor since, in the absence of rod motion, reactor power is tied to the secondary.

$$\dot{Q}_{Rx} = \dot{Q}_{Sec}.$$

This means if secondary power is held constant, then reactor power will be held constant. The secondary power is dependent on steam flow to various systems, namely the HPT, the main steam reheaters (MSR), the feedwater system (FW), and the TPD system. Since this system would be added to existing reactors, emphasis was placed on utilizing existing instrumentation and minimizing adding additional instrumentation to the maximum extent possible. This led to smaller steam flow systems, such as the gland exhaust system, being neglected. In doing so, the only transmitter that would need to be added to an existing system is a flow transmitter at the inlet of the HPT. This makes the control equation for the coordinated steam flow controller:

$$\begin{aligned}\dot{Q}_{Sec} &= H_{HPT} + H_{MSR} + H_{TPD} - H_{FW}, \\ H_{TPD} &= \dot{Q}_{Sec} + H_{FW} - H_{HPT} - H_{MSR}, \\ H_{TPD} &= \dot{m}_{TPD} h_{TPD}, \\ H_{HPT} &= \dot{m}_{HPT} h_{HPT}, \\ H_{MSR} &= \dot{m}_{MSR} h_{MSR}, \\ H_{FW} &= (\dot{m}_{1,FW} + \dot{m}_{2,FW} + \dot{m}_{3,FW}) * h_{FW}, \\ \dot{m}_{TPD} h_{TPD} &= \dot{Q}_{Sec} + (\dot{m}_{1,FW} + \dot{m}_{2,FW} + \dot{m}_{3,FW}) * h_{FW} - \dot{m}_{HPT} h_{HPT} - \dot{m}_{MSR} h_{MSR}, \\ \dot{m}_{TPD} &= \frac{\dot{Q}_{Sec} + (\dot{m}_{1,FW} + \dot{m}_{2,FW} + \dot{m}_{3,FW}) * h_{FW} - \dot{m}_{HPT} h_{HPT} - \dot{m}_{MSR} h_{MSR}}{h_{TPD}}.\end{aligned}$$

Since $\dot{Q}_{Sec}$ can be logged at the start of the transfer, and mass flow rates are available from transmitters, determining the enthalpy values remains the primary step. Enthalpy can be estimated using two main approaches: curve fitting of empirical data or applying the standardized formulas from the International Association for the Properties of Water and Steam (IAPWS-97). While the IAPWS-97 equations are highly accurate and suitable across a broad spectrum of conditions, their computational complexity can limit their practicality in embedded controller applications. Alternatively, polynomial curve fits demonstrate nearly identical accuracy ($R^2 = 0.9998$) over the full operational pressure range ($500 \text{ psia} \leq P \leq 1,050 \text{ psia}$). However, simpler linear fits have proven sufficiently accurate for specific subsystems, such as the HPT ($R^2=0.997$ for $700 \text{ psia} \leq P \leq 925 \text{ psia}$) and the MSR ($R^2=0.9997$ for $900 \text{ psia} \leq P \leq 1,000 \text{ psia}$). Consequently, the choice between these methods depends largely on processor resources, but for this study, linear fits as a function of pressure were chosen for their computational simplicity and satisfactory accuracy.

$$h_{TURB} = -0.0294 * P_{TURB} + 1222.9,$$

$$h_{MSR} = -0.0359 * P_{MSR} + 1228.7.$$

The polynomial is

$$h = -0.00003 * P^2 + 0.0179 * P + 1203.6.$$

A linear fit for the feedwater region at a pressure of 1,060 psia yields perfect correlation ($R^2 = 1$) over the temperature range of 400°F to 440°F, indicating more than satisfactory accuracy. In this case, enthalpy was linearly correlated with temperature within the specified range.

$$h_{FW} = 1.0859 * T_{FW} - 58.42.$$

This controller maintains the initial and final reactor power at equal levels, with reactor power deviating by no more than $\pm 0.1\%$ during transients, even as turbine power is ramped at a rate of 15 MWe/min through the existing TCS. Additional tests were conducted by bringing the TPD system online without feedwater tracking, which resulted in an increase in reactor power of approximately 0.5%. Similarly, failing to track the MSR system flow produced a reduction in reactor power of about 0.5%. However, since both feedwater and MSR systems already have appropriate instrumentation in place, neglecting to track these parameters should not be an issue in practical applications.

Additional controller functionality enables operators to designate a preferred train, allowing one train to be prioritized when brought online. This approach mirrors the common practice of alternating pump usage to balance equipment wear and is particularly useful when only one train is needed for modest power reductions.

To further support reactor stability in the event of a single TPD train trip, the control system is designed so that the remaining train can increase steam flow up to 225 lbm/s—maintaining a 10% margin below the 250 lbm/s trip threshold. During hot standby or single-train operation, this feature gives operators more flexibility to manage reactor conditions and minimizes the operational impact when transitioning to full TPD operation.

2.1.4 Electrical Grid Updates

GPWR also incorporates the ability to model an external electric grid through the JElectric program. To better represent grid-relevant impacts on the reactor, an AC source was introduced into the grid model as seen in Figure 4. The new grid load was specifically implemented to emulate the behavior of HTSE, carefully placed at a location in the network where changes would reasonably influence plant performance. For this study, the load was positioned on the bus just outside of the switchyard, simulating as close to direct electrical coupling to the turbine while being external to the plant, maximizing the sensitivity of plant response to grid fluctuations. The grid source that was originally provided was so large, changes to the electric grid were insignificant since it functioned essentially as an infinite source. To address this, the presumed capacity of the grid was reduced, increasing the relative influence of plant-induced changes and allowing for more realistic assessment of reactor-grid interactions under conditions where the external grid is not arbitrarily large.

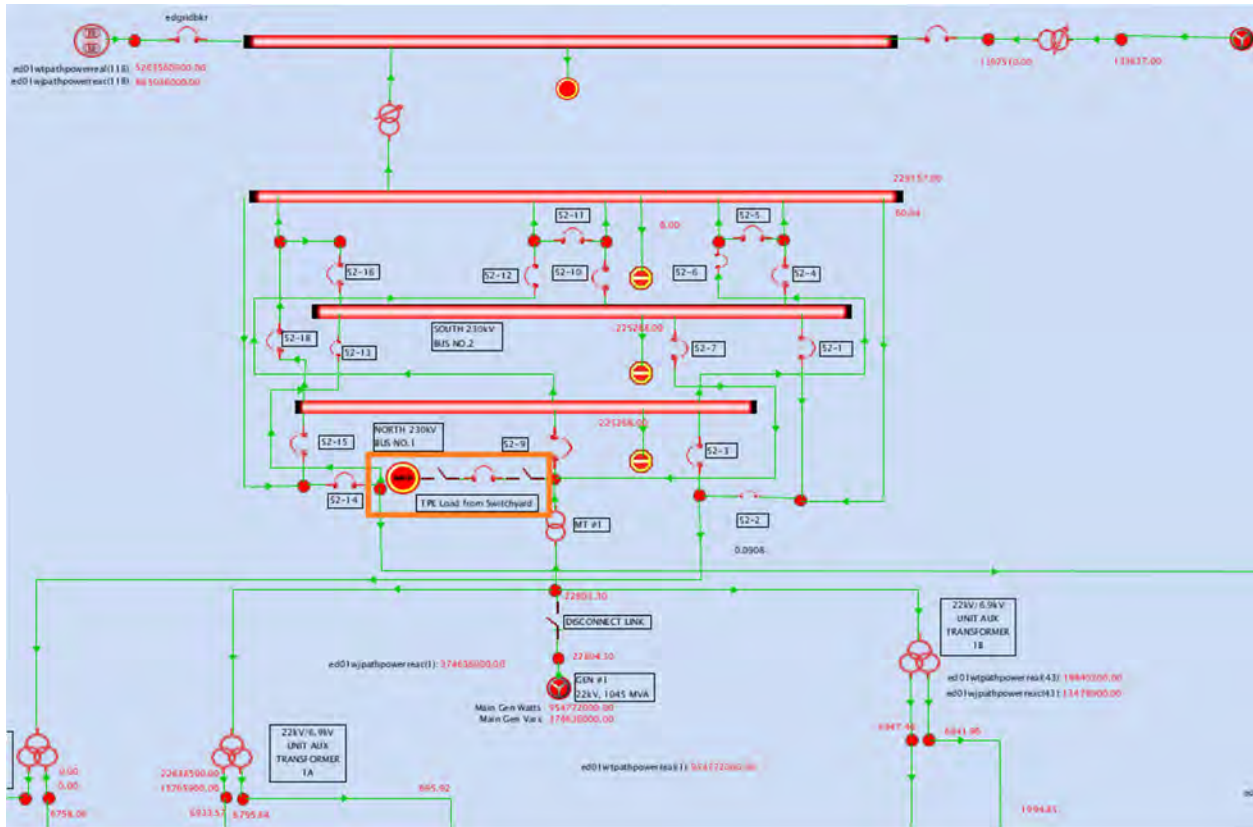


Figure 4. GPWR Electric Grid with modification to represent HTSE highlighted with an orange box in the middle of the figure.

2.1.5 Human-Machine Interface Updates for Main Steam Extraction and Controller

The HMI was updated to reflect main steam extraction from the main steam header, and a new coordinated TCS/TPD control panel was added to the HMI. This control panel allows the operator to place the TCS/TPD controller into the coordinated mode and set the preferred train. The controller also replicates the TCS target, ramp rate, go, and hold controls of the existing DEH system for GPWR. The HMI is discussed in more detail in Section 3.3.

2.2 Switchyard Model

The switchyard system for the NPP, integrated with an HTSE system, is developed to facilitate the supply of both electrical and thermal power generated by the nuclear plant. This supports the operation of the HTSE system for hydrogen production. The switchyard is set up to ensure flexible power generation from the NPP and efficient hydrogen production.

2.2.1 GPWR Simulator Switchyard Model Modification

GPWR generates electrical power at 22 kV, which is stepped up to 230 kV by a 22 kV/230 kV transformer and connected to a 230 kV bus. In-house electrical loads, such as pumps, are supplied via 6.9 kV circuits connected by 230 kV/6.9 kV step-down transformers, with these in-house transformers fed from the 20 kV bus. The HTSE system's electrical switchyard is tied to the GPWR switchyard via the 230 kV bus, positioning the HTSE load as close as possible to direct electrical coupling with the turbine, while remaining external to the plant. This maximizes the sensitivity of plant response to grid fluctuations.

To realistically model the impact of the HTSE’s electrical demand on both the NPP and the broader grid, the GPWR simulator’s switchyard representation is enhanced using the JElectric modeling platform. An AC grid source was introduced, and the new HTSE grid load was specifically implemented at the bus just outside the switchyard. Since the original grid capacity in the model was effectively infinite—rendering plant-induced changes insignificant—the grid’s presumed capacity was reduced, allowing plant and HTSE electrical loads to have a meaningful influence on overall grid dynamics and plant performance.

Both the size and power factor of the HTSE are defined as variables at the GPWR switchyard. The parameters of the external AC power source, representing the rest of the grid, are also modified. Together, these modifications enable the HTSE’s changing electrical demand to influence both the NPP, its yard, and the broader grid, thereby providing a more realistic assessment of reactor-grid interactions under non-idealized external conditions.

2.2.2 Simulink Switchyard Model

The 230-kV bus in the NPP’s switch yard is connected to a 500-m transmission network while the other end of the line is connected to the 200-kV bus on the HTSE’s switch yard. At the HTSE boundary, the voltage is stepped down using transformers from 230 kV to 34.5 kV, and from 34.5 kV to 13.8 kV. The 13.8 kV is supplied to the HTSE’s AC/DC converter. The transmission lines are modeled as series impedance with their resistance and inductance characteristics, while transformers are represented by their turns ratio and impedance values. At each voltage conversion point in the switch yard, isolation and protection devices are modeled appropriately.

The dynamic electrical model of the HTSE and its switch yard developed and modeled in MATLAB-Simulink as shown in Figure 5.

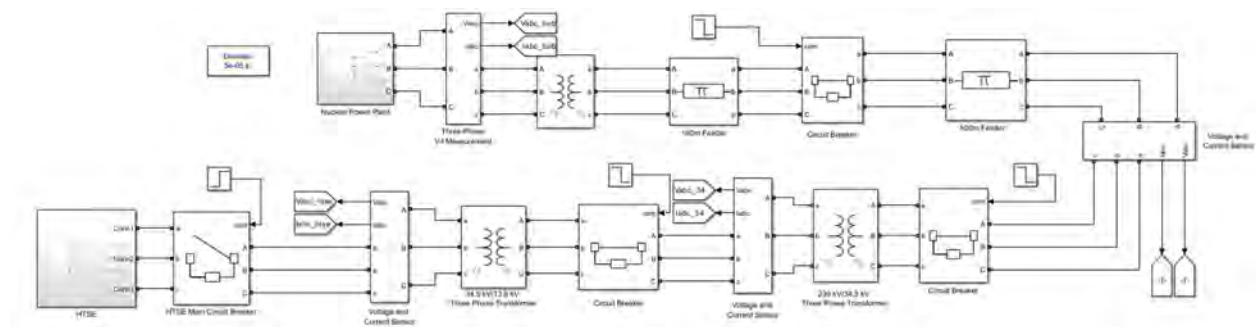


Figure 5. Switchyard model coupled to the existing GPWR generation and grid model and the Simulink HTSE model.

2.2.3 API Development for Simulink-GPWR Integration

To enable bidirectional communication between Simulink and the GPWR model, GSE’s SimAPI application programmable interface (API) was utilized. The API allows the exchange of necessary steady-state variables between both platforms.

A MATLAB script was designed to interface the HTSE Simulink model with a real-time GPWR simulator to control via a SimAPI interface. The developed script starts by defining the HTSE’s allowable operating power range and ensures that the input setpoint stays within these limits. The setpoint is then passed to a MATLAB function that communicates with an external GPWR simulator via a RESTful API. This function writes the power setpoint to the simulator, waits for a predefined delay to let the system settle, and then retrieves updated electrical data such as power, voltage, and frequency from two bus points. These measurements provide feedback on the HTSE and power grid’s operational status.

After acquiring the real-time simulation data, the script loads a predefined HTSE's Simulink model and runs it using the updated parameters. The HTSE's simulation output, particularly the electrical and thermal dynamics, is extracted from the model's output for further analysis or control actions. Supporting MATLAB functions are used to send and retrieve variable values from the GPWR simulator. The developed MATLAB code to interface the HTSE's Simulink model and the real-time GPWR simulator demonstrates a co-simulation architecture, where MATLAB coordinates external API interactions with real-time hardware-in-the-loop or software-in-the-loop simulations, enabling closed-loop testing of HTSE control strategies.

3. SCENARIO DEVELOPMENT

Scenarios were developed to support the evaluation and demonstration of increased scale of TPD operations. Two main criteria were used to select candidate scenarios for operating the TPD under normal and abnormal conditions. Scenario representativeness and worst cases envisioned were used as criteria for selecting the normal and abnormal scenarios, respectively. The TPD is not expected to undergo startup and shutdown scenarios frequently, as it would only be shut down during outages, which occur on average every eighteen months. During most of its operation, the TPD system will be in either hot standby or online modes. Therefore, the most representative operating scenarios under normal operating conditions involve transitioning from Hot Standby to Online and from Online to Hot Standby.

The potential worst-case scenarios that may result from the current enhancement of the TPD system to support up to 10% of thermal energy extraction from the plant were considered and used in abnormal scenario development. Considering the TPD physically couples the NPP to the H2 plant by exchanging main steam thermal energy flowing through a heat exchanger to generate demineralized steam in the delivery loop for use at the H2 plant over ~ 1 km, leaks along the steam line are considered worst-case scenarios and were used as the basis for determining fault conditions. The operator's ability to effectively diagnose and localize precise fault locations is of utmost safety significance. Additional well-known plant fault scenarios were included to assess the potential impacts of TPD operations. Overall, a total of X scenarios was selected across three groups: Normal TPD Scenarios, Abnormal TPD Scenarios, and Additional Plant Scenarios (see Table 16).

Table 16. Selected scenarios for human-in-the-loop testing depicting the focus of the scenario for testing purposes, the type of evaluation performed, and the specific procedures used in the scenario.

Scenario Group	Scenario	Purpose	Test Type	Note
TPD Normal Scenarios	Hot Standby to Online	TPD and TCS	CPB Validated	TPD-02
	Coordinated TPD/TCS Mode Online to Hot Standby	TPD and TCS	Simulator Validation	TPD-03
TPD Abnormal Scenarios	Tube Leak in the Reboiler – Small	TPD Fault Detection	CBP Validated	TPD-AOP-01
	Tube Leak in the Drain Cooler Heater – Small	Plant Impacts	Simulator Validation	TPD-AOP-01
	Rupture Downstream of FT-1001/Upstream of the Reboiler*	TPD Fault Detection	Simulator Validation	TPD-AOP-01 No data recorded from sim, just ops data
Additional Scenarios	Load Rejection – TPD offline	Plant Impacts	Paper Tested CBP Verified	AOP-15

Scenario Group	Scenario	Purpose	Test Type	Note
	Load Rejection – TPD online	Plant Impacts	Paper Tested CBP Verified	AOP-15
	HTSE Electric and Steam Trip	Plant Impacts	Paper Tested CBP Verified	AOP-15
	Main Steam Line Break	Plant Impacts	Paper Test CBP Verified	EOP-0, EPP-14, EPP-15
	Steam Generator Tube Rupture	Plant Impacts	Paper Test CBP Verified	EOP-0

3.1 Existing Scenarios

Since the operations of TPD have been explored in prior work, suitable scenarios were reused and modified to accommodate the larger scale TPD system.

3.1.1 TPD Normal Scenarios

Operating the TPD for daily, routine, transitions between traditional all electric and combined electric and thermal operating configurations spans two basic scenarios, which are hot standby to online and online to hot standby. Startup and shutdown scenarios are also required for the TPD, but since the TPD will be held in a hot standby state between usage, these scenarios are performed rarely and have no time-sensitive aspects. In contrast, the hot standby to online and online to hot standby transitions must be executed expediently to take advantage of predicted wholesale electrical pricing.

3.1.1.1 *Hot Standby to Online*

Each train of the TPD will be held in a hot standby state when steam is not required in the HTSE. In hot standby, a marginal heat extraction rate of 9 lb/s from the nuclear plant is maintained to keep the TPD steam lines heated. The Hot Standby to Online scenario involves transitioning from the hot standby state by increasing the heat extraction rate from the nuclear plant to the HTEF from 9 lb/s to 180 lb/s, thereby bringing the two TPD trains online one after the other. The sequence of transition of TPD Trains A and B to Hot Standby is set by the *preferred TPD train* button on a new HMI feature—Coordinated TCS/TPD Controller—implemented in the current TPD iteration and discussed in detailed in the following sections. The selected *preferred TPD train* is ramped to hot standby first, followed by the second train.

3.1.1.2 *Online to Hot Standby*

The Online to Hot Standby scenario is the opposite of the Hot Standby to Online scenario. This scenario entails returning the extraction flow to the marginal flow rate of 9 lb/s. To curtail the dispatch of thermal and electrical energy, the TPD is transitioned to hot standby when steam is not required in the HTSE. The *preferred TPD train* is used to perform the same function of selecting the TPD train to be ramped first from online to hot standby, with the evolution following the prescribed order.

3.1.2 TPD Abnormal Scenarios

Abnormal conditions during TPD operation may involve various events such as tube leaks, ruptures, and valves failing open or closed. Most of these scenarios were reviewed during the previous human-in-the-loop (HITL) testing study on the smaller scale TPD system. In this current work, only the scenarios related to tube leak in the reboiler, tube leak in the drain receiver, and rupture downstream of FT-1001/upstream of the reboiler are analyzed, as illustrated in Figure 6. Current efforts focus on verifying compliance with the digitalized TPD trouble procedure (TPD-AOP-01) and validating the simulator’s response under increased steam flow conditions.

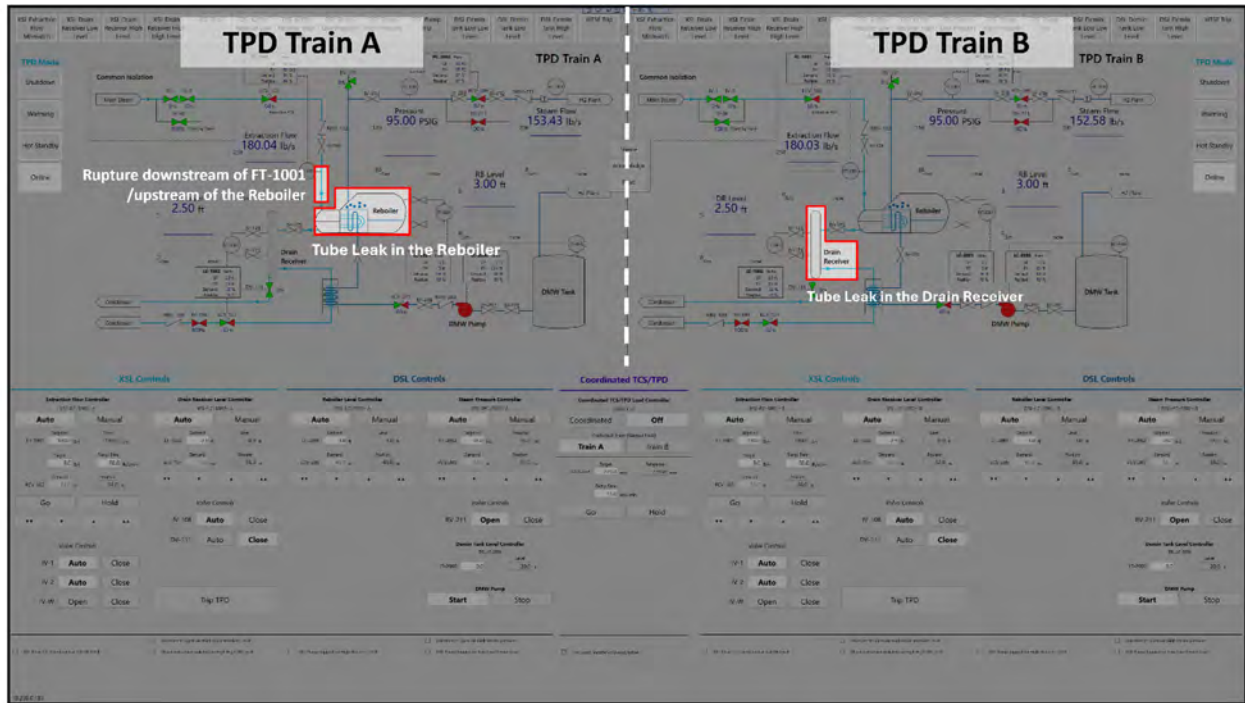


Figure 6. Fault locations for affected components included in the TPD abnormal scenarios.

3.2 Additional Scenarios

3.2.1 Steam Generator Tube Rupture

A steam generator tube rupture (SGTR) is a critical event in which one or more tubes of a steam generator (SG) break, releasing radioactive coolant from the primary loop into the non-radioactive secondary side. Control room indicators of a potential SGTR include a combination of alarms and abnormal readings. The SG high-radiation alarm is the first to go off and is shortly accompanied by other radiation alarms, a lowering pressurizer level, and a rising SG level. These indicators prompt a series of diagnostic steps to identify the ruptured SG, mitigate the release of radioactive material, and protect the reactor core.

Upon confirming an SGTR, operators follow emergency operating procedures (EOP) to isolate the faulted SG(s) by shutting associated steam and feedwater valves. The reactor is manually tripped if it has not already shut down automatically, and cooldown operations begin using unaffected steam generators. The primary goal is to stop the leak path, maintain core cooling, and minimize radiological releases. The affected generator is depressurized and isolated, and long-term cooling is established using intact systems.

3.2.2 Main Steam Line Break

Main steam line break (MSLB) is one of design basis accidents (DBAs), which are a widely analyzed accident scenario used for safety evaluation and simulation performance benchmarking among research institutes across many countries (Todorova et al. 2003; U.S. NRC 2003; Franklin Research Center 1982). In particular, under TPD operation, where steam produced from the SGs is utilized, the MSLB may be considered a significant and interesting case.

This scenario assumes the rupture of a main steam line, resulting in a sudden pressure drop in one of the SGs. Consequently, excessive heat is removed to the secondary side through the broken SG, causing abnormal overcooling in the reactor coolant system. Due to the effect of positive reactivity, the reactor core power may rise sharply, triggering the signal of an overpower trip and initiating a reactor shutdown.

Simultaneously, overcooling leads to coolant contraction in the primary loop, which causes a drop in the pressure of the pressurizer. This pressure drop may activate the high-pressure injection system and result in multiple alarms and automatic reactor trip signals. Additionally, the location of the break, whether inside or outside the containment, can affect evaluation of containment integrity and offsite consequence.

Operators are expected to take early actions to control leakage through the break to minimize the release of radioactive materials and prevent overfill damage in the affected SG. The MSLB is diagnosed through the EOP-E-0 (“Reactor Trip OR Safety Injection”) procedure, and proper action such as broken steam generator isolation and overfill prevention are taken following the EPP-14 (“Faulted Steam Generator Isolation”) and EPP-15 (“Uncontrolled Depressurization of All Steam Generators”) procedures. During these procedures, reactor coolant system cooldown and depressurization may also be initiated to assist in controlling break flow and mitigating this scenario.

3.2.3 Load Rejection

Load rejection is directly relevant due to the nature of TPD extracting steam. Generally, load rejection refers to the phenomenon where electrical power generation is partially or completely interrupted due to abnormalities in the electrical system, such as generator faults or malfunctioning circuit breakers. However, in the case of NPPs, since electrical power generation is proportional to steam flow, load rejection can occur due to a decrease in steam flow resulting from turbine system anomalies. In a load rejection scenario, the thermal generation of the reactor coolant system (RCS) exceeds the load, causing an excessive amount of energy in the RCS. This is a safety threat to NPPs in terms of the failure to remove heat through the SG and can lead to a reactor trip, resulting in significant economic losses due to the interruption of electric generation or additional fees and penalties.

A load rejection scenario was performed with the TPD system offline and online to observe differences in the plant caused by the TPD system. When the TPD system is offline, steam is not extracted by the TPD, so the NPP conditions are at 100% power, and the turbine load is approximately 920 MW. On the other hand, when the TPD system is online, 360 lb/s of steam is extracted by the TPD, so the plant power remains at 100%, but the turbine load is approximately 770 MW.

To simulate the load rejection, turbine runback malfunction was input. In the previous simulation, a feedwater pump trip was induced to implement load rejection. However, in the case of the GPWR simulator, this caused a reactor trip, making it impossible to handle the load rejection scenario. Additionally, the operators must respond to both the load rejection and the partial loss of feedwater. This makes it difficult to accurately assess the impact of the load rejection scenario on the operators.

If a turbine runback occurs due to a malfunction, the operator enters AOP-15 to verify whether the functions to mitigate load rejection are operating correctly and take necessary actions according to AOP-15. These procedures include verifying the proper operation of the digital electrohydraulic control (DEH), confirming appropriate reactivity control in primary system, ensuring the proper functioning of the electrical system, and verifying adequate flow supply on the secondary system. Through these procedures, the reactivity is gradually reduced, minimizing the temperature transients in the RCS. This gradual reduction in secondary system’s steam demand allows the NPP to reach a stable state. Finally, stability is confirmed by either the main feedwater pump running (Step 19) or maintaining the reactor power above 20% (Step 21). Then, the scenario concludes by identifying the cause of load rejection (Step 32) and transitioning to other procedures to address it.

3.3 Human-Machine Interface Modifications

The revised TPD model extracts main steam before the HPT. The P&ID HMI display was updated to reflect this extraction point (Figure 7). The HMI controls remained largely the same from last year with the incorporation of a new coordinated TCS/TPD controller. The purpose of this controller is to coordinate transitioning main steam from the turbine and TPD system. The controller allows transitioning

from hot standby to online and from online to hot standby while maintaining total extracted steam flow and thereby reactor power.

The controller is remarkably simple with just three functions:

1. A two-button toggle group to set the controller in coordinated mode or turn off the coordinated mode. A digital indicator at the bottom provides a redundant indication that the controller is in coordinated mode.
2. A two-button toggle group to set the preferred TPD train. The preferred TPD train is the first to ramp up to 180 lb/s or down from 180 lb/s. At total extraction flows greater than 360 lb/s the coordinated TCS/TPD controller ramps both trains in unison.
3. TCS target load, reference load, ramp rate, go-and-hold controls. These replicate the TCS controls of the main DEH system in GPWR. For an actual plant with a TPD, control would likely be performed from the DEH HMI, and the TPD HMI could be integrated with turbine control.

The coordinated TPD/TCS controller represents an achievement of user-centered design and this 5-year project (see Figure 8). The simplicity of the controller is enabled by a robust engineering design, well-tuned PID controllers, and control schemes evolved through numerous iterations of engineering and HITL testing. The result is the ability of a TPD system that can load follow the turbine while not changing reactor power. We also demonstrated this scheme can function across multiple TPD trains.

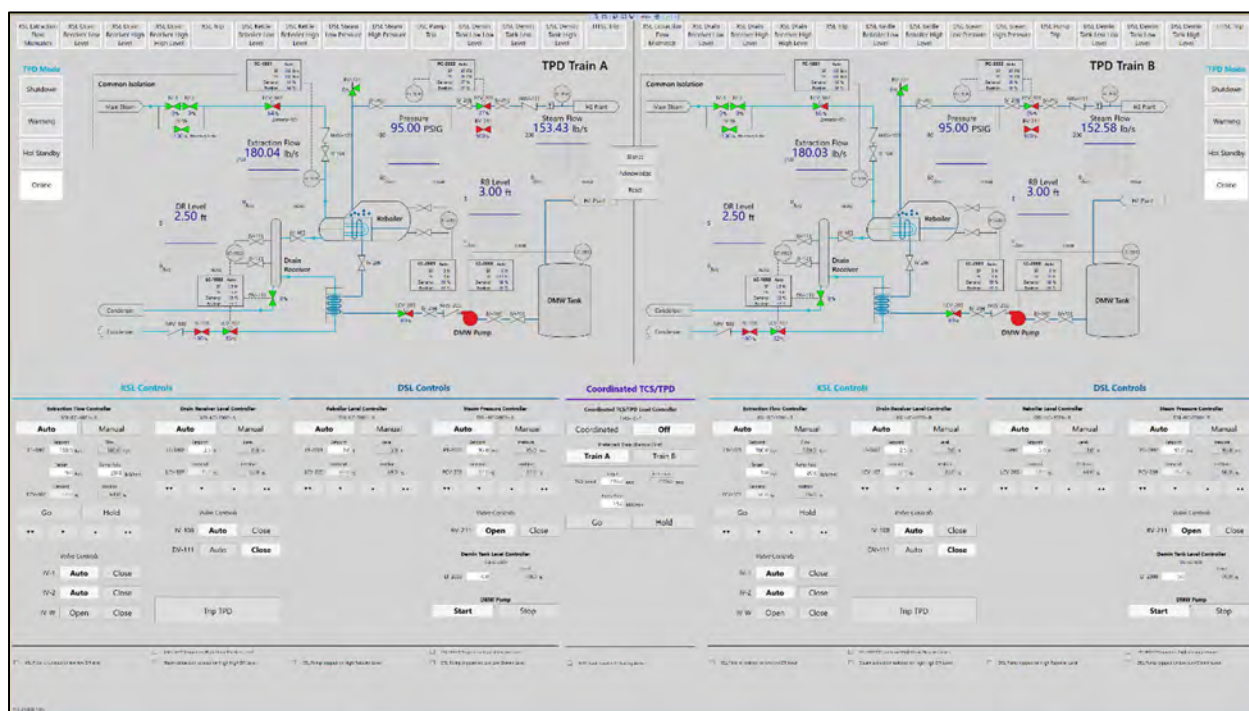


Figure 7. Revised HMI depicting the P&IDs for both trains and the controls.

Coordinated TCS/TPD

Coordinated TCS/TPD Load Controller
TPD-FC-1

Coordinated
Off

Preferred Train (Ramps First)

Train A
Train B

Target

TCS Load 770.0 MW

Reference

770.0 MW

Ramp Rate

15.0 MW/min

Go
Hold

☐ TPD Load Transfer Following Active

Figure 8. New coordinated TCS/TPD controller for the TPD system.

3.4 Procedure Development

Procedures are a central element in any concept of operations, as they ensure operational tasks are conducted in a consistent and controlled manner, guaranteeing predictable outcomes. Reactor operators closely follow written operating procedures, which provide step-by-step guidance to diagnose conditions and respond with actions to change plant states. Therefore, procedure development considerations must be factored into the development of new operational concepts, such as those to be used for operating the TPD, to prevent them from constituting error traps that can potentially compromise plant safety and efficiency. According to the NRC, errors and difficulties in following procedures are associated with most reportable events at NPPs (NRC 1995); hence, the need to develop procedures that support operator performance optimally.

Traditionally, paper-based procedures (PBPs) have been employed in nuclear power operations for decades, providing immense value in promoting safe and effective operations. However, certain inherent limitations of PBP may compromise safe and effective operation, especially during emergency operations. For example, the Three Mile Island (TMI) accident investigations revealed confusing EOPs as contributing factors to the accident. Lately, efforts to explore potential opportunities for leveraging the capabilities of digital technology to develop CBPs have received considerable attention. The shift away from PBP to CBP is anticipated to mitigate the safety concerns associated with PBP in control room operations.

CBP utilizes computer systems to support the presentation and use of procedures (U.S. Nuclear Regulatory Commission, 1999). Several characteristics of CBPs support operator supervisory control performance in ways that eliminate or mitigate the challenges posed by PBPs. For example, anecdotal evidence has shown that CBPs support more effective task monitoring while implementing EOPs (Lin et al. 2016), enhance the ease of following procedures with more seamless transitions (Le Blanc, Oxstrand, and Joe 2015), and enable faster fault recovery (U.S. Nuclear Regulatory Commission, 1999). According to IEEE-1786 (2022), three types of CBPs are described in order of increasing digitalization: Type 1, Type 2, and Type 3. The progressive order of digitalization implies that the characteristics of each type of CBP include those of the previous lower levels. For example, Type 2 includes all Type 1 capabilities. The three different types of CBP have different levels of digitalization. Type 1 recreates the PBPs in digital form using computer-generated visual displays, while Type 2 includes live process indicators embedded within procedure steps with place-keeping. Type 3 procedures extend the functionality of Type 2 by adding embedded soft controls, allowing the operator to perform the prescribed actions without the need for dedicated controllers on the human-system interface (HSI). Boring et al. (2023) expanded on the formal explanation of the characteristics of CBP, suggesting that some capabilities are optional, and their absence need not preclude a CBP system from qualifying for the group to which they belong (see Table 17).

Table 17. Characteristics of digitalized procedure.

Index	Characteristics	Type 1	Type 2	Type 3
1	Select and display procedure on computer screen	✓	✓	✓
2*	Provide navigation links within or between procedures	✓	✓	✓
3	Display process data in the body of procedure steps	×	✓	✓
4	Process step logic and display results	×	✓	✓
5*	Provide access links to process displays and soft controls that reside on a separate system	×	✓	✓
6	Provide embedded soft controls	×	×	✓
7*	On operator command, initiate procedure-based automation	×	×	✓

*Characteristics from IEEE-1786 that should be optional

The need for a simulation platform that supports flexible implementation and testing of advanced concepts of operations and different CBP attributes made Rancor Microworld a suitable candidate for the current project. Initially conceived as a simplified, reduced-scope simulator for conducting basic nuclear process control research with operator surrogates like college students, Rancor evolved to include additional capabilities enabling the implementation of the characteristics of different CBP types stipulated by the IEEE-1786. Implementing the CBP types in Rancor Microworld is a significant step in testing CBPs in an operational context. The latest iteration of Rancor further expanded its capability to function as a simulation framework and as an integrated procedure authoring system, discussed in the following sections.

3.4.1 Rancor Simulation Framework

Over the last year, the Rancor Microworld Nuclear Power Plant Simulator has evolved from being a simplified NPP simulator to a simulator framework. Rancor now incorporates a server/client framework for running the Rancor Plant Simulator of a single unit or multiple units (Boring et al. 2024). The server/client architecture features a Web API server and client integrated into the Rancor Simulation Framework as schematically shown in Figure 9, with both the server and the client contained in the Rancor executable application. Following the start of every simulation run in Rancor, the simulator references a WebAPI.ini file to identify whether to run as the server or as the client. On the one hand, when running as server, the simulation update loops are run to model the plant. On the other hand, when run as a client, Rancor obtains the state of the plant and units from the Web API, and operator actions are sent to the simulation model via the Web API. Both the Rancor server and client can be configured to display the HSI windows.

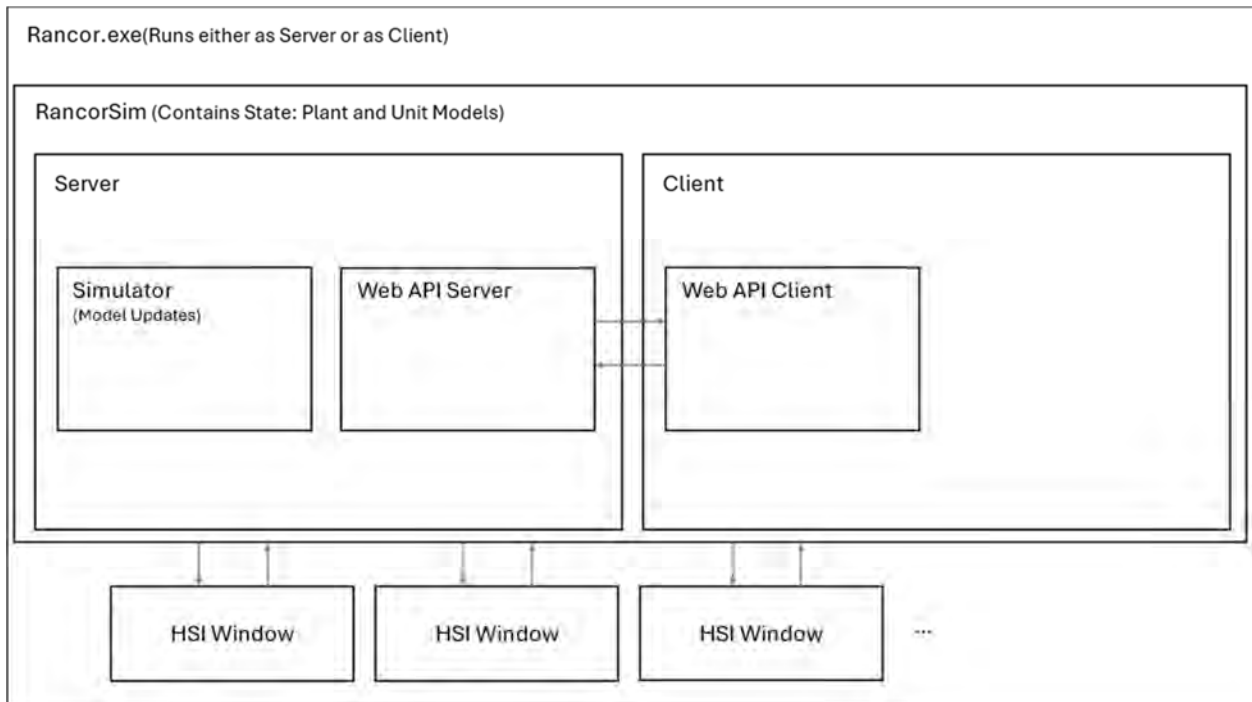


Figure 9. Rancor Simulator Framework Rancor Server-Client Architecture. The Rancor.exe contains both the server and client.

3.4.2 Rancor Integrated Procedure System

The Rancor architecture was adapted to enable two-way communication with full-scope simulators. This functionality enables bidirectional communication between the TPD and GPWR simulators. Two-way communication makes it possible for operators to perform control room TPD maneuvers manually or digitally while observing the impact on the plant in real time. Rancor Simulation Framework includes digital procedure implementation via a full-featured digital procedure system called the Rancor Integrated Procedure System (RIPS). RIPS enables operators to execute CBP in the correct sequence of plant maneuvers while maintaining safety margins throughout, in the same manner as with the use of PBPs.

The structure of traditional PBPs was used as a foundational basis for designing RIPS, extending the features beyond what is obtainable in traditional procedures. Two basic PBP structures are used in existing U.S light-water reactors: single-column and two-column structures. A single-column structure provides a single course of action within a well-defined set of conditions that do not require the operator

to deviate from a predetermined path or sequence of procedure steps. The two-column structures, commonly used in pressurized-water reactors (PWRs), are arranged across the two columns and contain textually explicit and implicit logic procedure steps. The two columns include a RO column on the left and a RNO column on the right. Operators follow procedures in a stepwise manner by evaluating the logic of steps in the left column to determine whether it is met or can be met by prescribed actions. When the plant state matches the condition described in the left column, the step is marked RO, and the operator proceeds to the successive step. In contrast, a mismatch between the plant state and the condition described in a given step is considered an RNO with the operator moving to the corresponding right side of the step. Both single-column and dual-column procedure structures are included in the RIPS feature set.

RIPS supports IEEE-1786 Type 1, 2 (live indications), and 3 (live indications and soft controls) procedures. Type 1 procedure is a static digital rendition of the PBP and contains only textual instructions. The operator performs all monitoring of plant parameters on the P&ID and control actions on the control panel, as is the case with traditional procedures. Type 2 procedures include the indicator as embedded and color-coded live data value that updates as the plant state changes. Although the embedded live values updates relieve the operator of the need to perform monitoring on the P&ID, control actions must still be executed outside of the procedure through the control panel. Type 3 procedures build on these prior levels by adding soft controls that allow the operators to take action as prescribed by the step instruction text without the need for the P&ID or control panel display. Despite the advanced capabilities of Type 3 procedures, operators are not expected to rely solely on the digital procedure but are expected to consider the P&ID and controllers to maintain situation awareness.

3.4.3 Dynamic ViewModels and GPWR Client

The Rancor Microworld Simulator Framework is a modern .NET WPF application. WPF applications commonly employ Model-View-ViewModel architecture. The model is the simulation model, the view(s) are the displays or HMIs, and the ViewModels are .NET instances that are bound to the views and update the display contents through property update notifications. The ViewModel also handles control actions when there is interaction with HMI. The challenge in interacting with full-scope simulators is that they contain tens-of-thousands of points and including them all in a hard-coded ViewModel would be extremely difficult and simulator specific. To circumvent this challenge, a .NET DynamicViewModel was developed.

A .NET DynamicViewModel class that compiles properties representing simulator point at runtime as defined through JSON ViewModel configuration files using Reflection was developed (see Figure 10). From Rancor's perspective, these dependency properties are first class properties of the DynamicViewModel instances. They asynchronously update through a Web-API client and raise IPropertyNotification to update the HMI just like normal ViewModel properties in a hard-coded WPF application. At start up, the user can select the ViewModels file they would like to load into the Rancor Microworld Simulator. The ViewModel files define a set of ViewModels. The procedure author can decide how to segregate the View model definitions. For the TPD system, we have two ViewModels. One is for Train A, and the other is for Train B. They both define the same set of properties that are bound to RIPS.

```

1  {
2      "ViewModels": [
3          {
4              "DynamicViewModelName": "TPD_TrainA",
5              "Title": "TPD - A",
6              "StringResources": {
7                  "train_id": "A",
8                  "other_train_id": "B"
9              },
10         > "Properties": [ ...
1136     ]
1137     },
1138     {
1139         "DynamicViewModelName": "TPD_TrainB",
1140         "Title": "TPD - B",
1141         "StringResources": {
1142             "train_id": "B",
1143             "other_train_id": "A"
1144         },
1145         > "Properties": [ ...
2271     ]
2272     }
2273 ]
2274 }

```

Figure 10. DynamicViewModel in the ViewModel.

The author defines meaningful PropertyNames and the corresponding PointNames in the simulator. These properties define indication points to use for conditional checks in the CBPs as well as control points for taking plant actions. Each ViewModel has a set of properties (see Figure 11).

```

102     "PropertyName": "Alarm_XSL_trip",
103     "PointName": "xsl1trip_alarm",
104     "PropertyType": "bool"
105 },
106 {
107     "PropertyName": "DSL_2001_FastLower",
108     "PointName": "tpe01water1lc_am_Pb_f_Lower",
109     "PropertyType": "double"
110 },
111 {
112     "PropertyName": "DSL_2001_FastRaise",
113     "PointName": "tpe01water1lc_am_Pb_f_Raise",
114     "PropertyType": "double"
115 },

```

Figure 11. A set of properties of ViewModel.

The ViewModels also allow the author to define StringResources for replacement in the CBPs. This allows for the procedures to be specific (like specifying Train A vs. Train B) without needing to largely redundant procedures.

3.4.4 Digital Procedure Authoring

3.4.4.1 Digital Procedure Structure

To develop a CBP, it is essential to convert existing PBPs into a digital format. Figure 12 presents the procedure schema used in Rancor Microworld Simulator. This scheme defines the structure and attributes of the procedures, including steps, conditions, actions, RNO column, transitions, and primitives. The digitalized procedure is created as a YAML file, which conforms to the defined procedure schema. Some attributes within the procedure reference external configuration files, such as **ViewModel.json** and **DynamicViewModel.cs**, which provide the necessary data and dynamic behavior definitions that support the procedural content. The completed procedure can be validated using the **Validate_procedure** python code and the **ProcedureEditor**. The python code identifies any structural issues or errors within the procedure, while the **ProcedureEditor** allows for detailed modifications and updates by executing Rancor simulator.

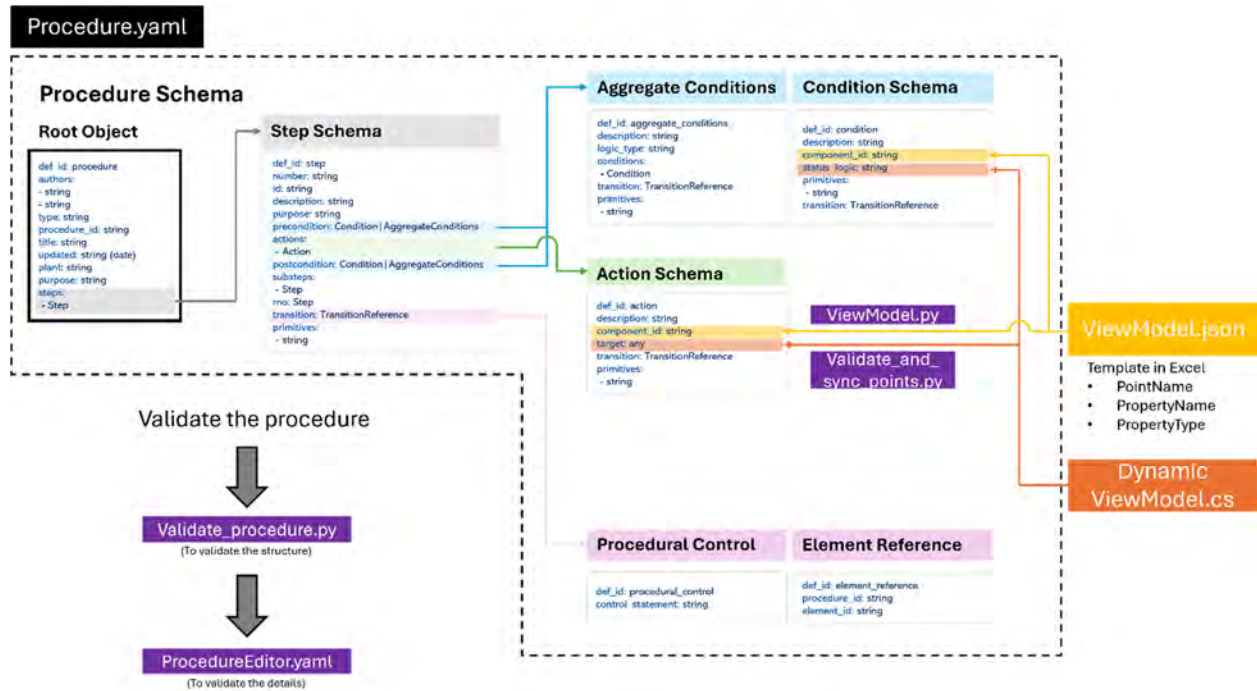


Figure 12. Digital procedure structure.

The procedure schema begins with a **root object** representing the entire procedure. Within this root, key attributes of the procedure can be defined. Before the main step starts, it is possible to include an introductory memo or context setting section. This section may contain metadata such as the author's name, the type of procedures, including:

- *def_id*: Always "procedure" for the root object
- *authors*: Array of strings containing author names (string)
- *type*: Type of procedure (one of: "OP", "AOP", "EOP", "ContinuousAction") (string)
- *procedure_id*: Unique identifier for the procedure (string)

- *title*: Human-readable title of the procedure (string)
- *updated*: Last update date in string format (string)
- *plant*: Name of the plant this procedure is for (string)
- *purpose*: Description of the procedure's purpose (string)
- *steps*: Array of Step objects (Step).

The **Step** schema serves as the core structure for defining each step in a procedure. The *def_id* is always “step,” and the *number* represents the step number, possibly with substep notation. An optional *id* serves as an identifier of the step. While the *description* provides a human-readable explanation, *purpose* and *note* are optional attributes for additional context. Especially, the *note* is presented in a boxed format to highlight important information or precautions that the operator should take into account while executing the step. Conditions required before (*precondition*) and after (*postcondition*) execution are specified. The step includes an array of *actions*. If a condition is not met or an action fails, a *rno* step is provided in the right-hand column. This enables the procedure to manage exceptions or transition to an alternate flow. Nested steps are listed under *substeps*. The *transition* is used to navigate to other steps or procedures, typically indicated by the expression “go to” along with the procedure designator, and *primitives* can be listed for HUNTER data. The attributes included in a **Step** are as follows:

- *def_id*: Always “step”
- *number*: Step number—can include substep notation like “1.1” (string)
- *id*: Optional identifier for the step (string)
- *description*: Human-readable description of the step (string)
- *purpose*: Optional description of the step's purpose (string)
- *note*: Optional description of the step's note (string)
- *precondition*: Optional condition that must be met before executing the step (Condition|AggregateConditions)
- *actions*: Array of actions to be performed in this step (Action)
- *postcondition*: Optional condition that must be met after executing the step (Condition|AggregateConditions)
- *substeps*: Array of nested steps (array)
- *rno*: RNO step to be executed if the step fails (Step)
- *transition*: Specifies what to do after the step completes (TransitionReference)
- *primitives*: Array of primitive operations associated with the step (string).

Each step can specify *precondition* and *postcondition* to check and validate certain conditions of a plant parameter, setpoint, switch position, or system. These conditions are often accompanied by questions that the operator is to answer with YES or NO (Carolina Power & Light Company 1999). Within the **Condition schema**, two types can be defined: *Condition* and *AggregateCondition*. *AggregateCondition* enables evaluation of multiple conditions collectively such as requiring all conditions to be met or any of them to be true. This allows for more complex logical checks within a step. Each *Condition* includes *component_id* and *status of logic*. Up to four *component_id* can be specified per condition, namely, *component_id_x* (x), *component_id_y* (y), *component_id_z* (z), and *component_id_w* (w). The value of *component_id* is referenced from the *PropertyName* specified in the ViewModel.json file. Logical relationship between these components can be expressed using *status of logic* such as OR (||) and AND (&&), which define how the individual *component_id* are combined and evaluated.

The *Condition* includes the following attributes:

- *def_id*: Always "condition"
- *description*: Human-readable description of the condition (string)
- *component_id*: ID of the component to check (string)
- *status_logic*: Logic expression to evaluate (string)
- *primitives*: Array of primitive operations for checking the condition (string)
- *transition*: What to do based on the condition result (TransitionReference).

The *AggregateCondition* includes the following attributes:

- *def_id*: aggregate_conditions
- *description*: Human-readable description of the condition (string)
- *logic_type*: Logic expression to evaluate (string)
- *conditions*: Array of conditions (Condition)
- *transition*: What to do based on the condition result (TransitionReference)
- *primitives*: Array of primitive operations for checking the condition (string).

A step may also define an *Action*, representing a task that the operator actively performs. In the CBP interface, this is typically linked to an “Execute” button that triggers the task. The attributes included in the *Action* are mostly similar to those in previous schema. However, the target is notable in that it can be assigned to either a static value or a dynamic parameter defined in *DynamicViewModel.cs*. For example, dynamic parameters can represent operations, such as a switch changing its state from 1 to 0. An *Action* includes the following attributes:

- *def_id*: Always "action"
- *description*: Human-readable description of the action (string)
- *component_id*: ID of the component to act on
- *target*: Target state or value (e.g., 50) OR "MomentaryPush" to Setcomponent_id to 1 and then to 0 (any)
- *transition*: What to do after the action (TransitionReference)
- *primitives*: Array of primitive operations for the action (string).

The **Transition Reference schema** defines how the procedure progresses either to the next sequential step or to a designated target step or procedure. There are two types of transitions: *Procedural Control* and *Element Reference*. While *Procedural Control* includes attributes such as proceeding, exit, break, return, and continue to the next element, *Element Reference* allows direct transitions to a designated procedure or a specific step, providing greater flexibility in managing procedural navigation.

The *Procedural Control* includes the following attributes:

- *def_id*: procedural_control
- *control_statement*: For procedural control, one of
 - *next*: Standard sequential flow, moves to the next element in the procedure
 - *exit*: Terminates the current procedure execution
 - *break*: Break out of the current sequence (useful in loops or nested steps)

- *recurse*: Returns execution to the nearest parent step
- *continue*: Similar to next but skips any remaining substeps in the current context.

The *Element Reference* includes the following attributes:

- *def_id*: element_reference
- *procedure_id*: For element reference, the target procedure ID
- *element_id*: For element reference, the target element ID.

The *component_id* references *PropertyName* defined in the **ViewModel.json** file. The **ViewModel** establishes a mapping between user-defined *PropertyName* and actual parameter of the simulator (*PointName*), while also specifying the associated *PropertyType*. The **ViewModel** supports multiple *DynamicViewModels*, allowing for flexible swapping of component trains. As shown in Figure 13, this structure enables dynamic configuration of parameter mappings. For instance, in a system with three components trains (e.g., Train A, B, and C), it is possible to define three different *DynamicViewModels*. In *DynamicViewModel 1*, *train_X_id*, *train_Y_id*, and *train_Z_id* may correspond to each component of Train A, Train B, and Train C, respectively. In *DynamicViewModel 2*, the same logical variables may instead map to each component of Train B, Train C, and Train A. In *DynamicViewModel 3*, the mapping could be each component of Train C, Train A, and Train B. By switching between *DynamicViewModels*, the value assigned to logical variables, such as *train_X_id*, *train_Y_id*, and *train_Z_id*, can be dynamically linked to different physical components depending on the selected train configuration. This provides a high degree of flexibility.

ViewModel.json

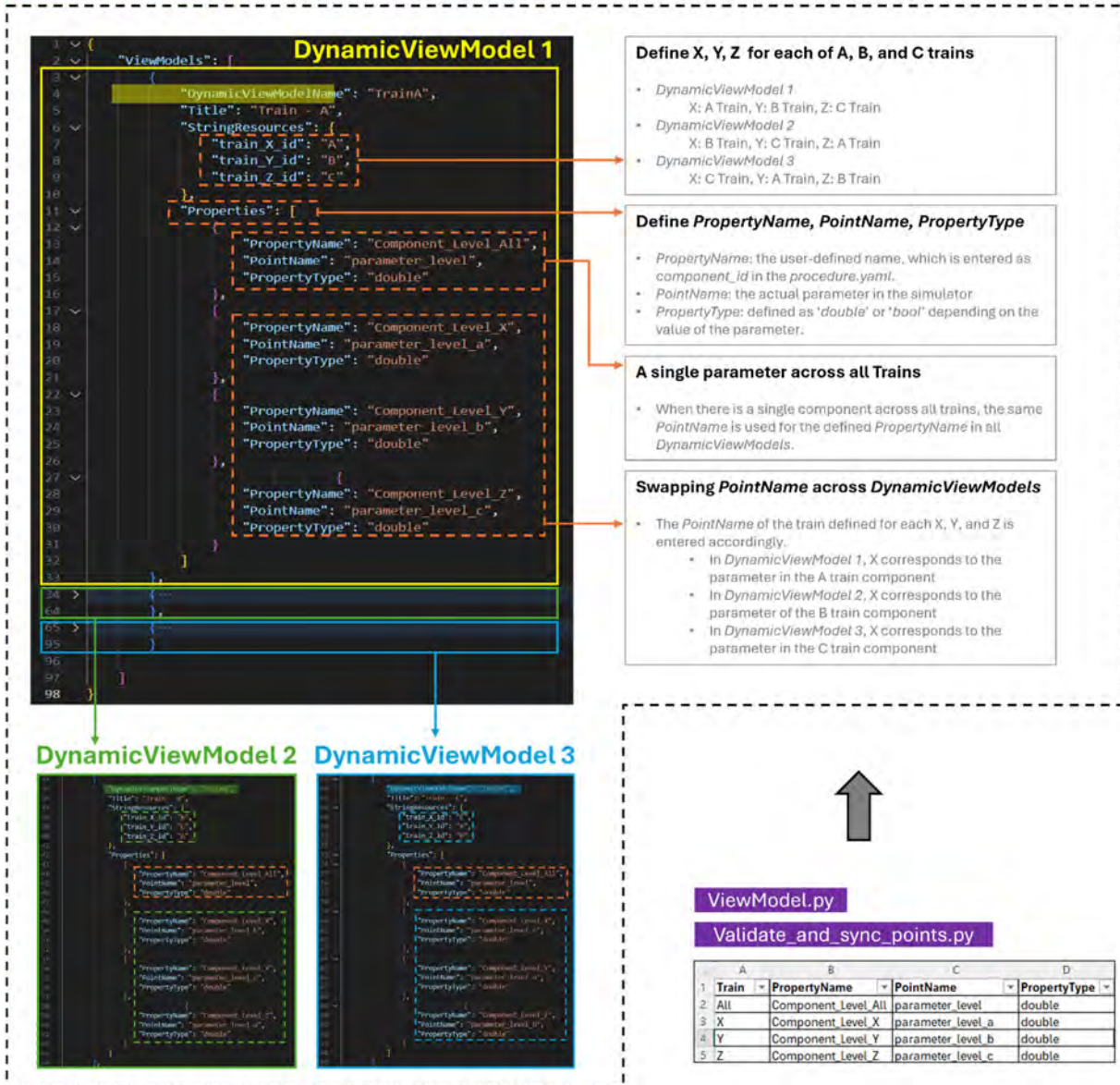


Figure 13. ViewModel structure.

3.4.4.2 Digital Procedure Workflow

The **ViewModel** can be automatically generated using an Excel-based input (as illustrated in Figure 13) along with supporting python scripts such as **ViewModel.py**. The resulting can be also validated through tools like **Validate_and_sync_points.py** to endure structural and logical integrity.

Figure 14 shows the window that appears when launching Rancor simulator, where the user is prompted to select the **ViewModel**. The name of each **DynamicViewModels**, as defined in the **ViewModel** configuration, should be aligned with the corresponding **WindowLayout** configuration to endure consistency between the data structure and the user interface.

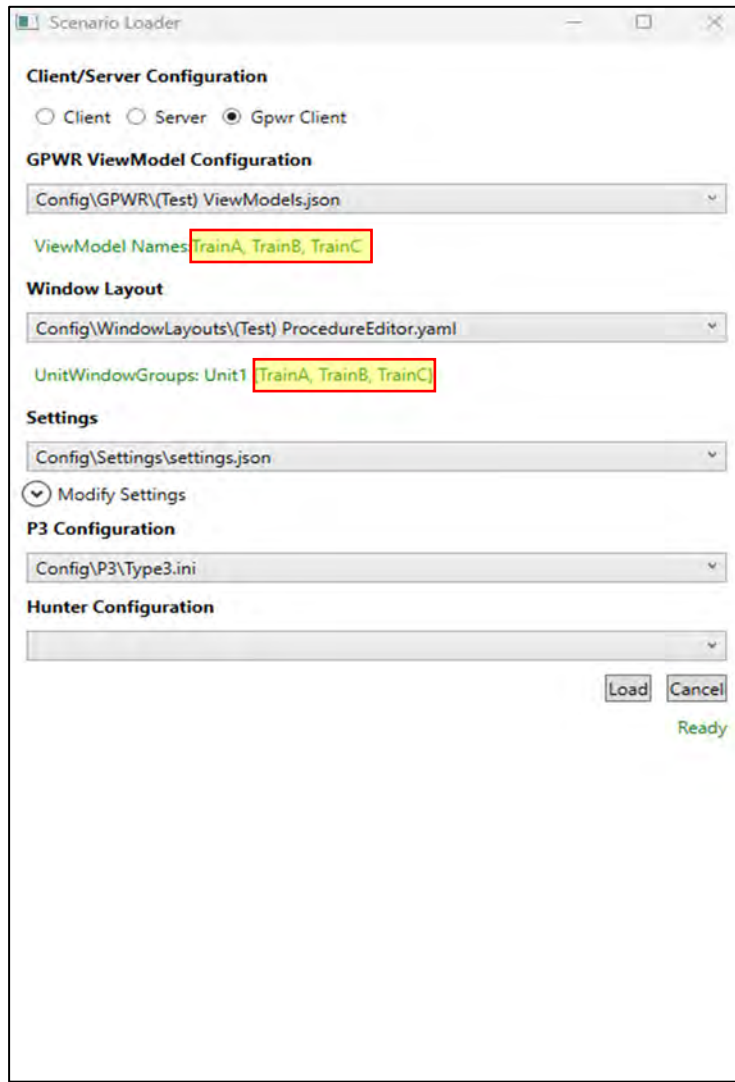


Figure 14. Scenario loader in Rancor Simulator.

Figure 15 illustrates an example of Step 1 from the EOP-E-0 procedure. Before entering the step, a note provides the operator with considerations or precautions that should be observed. In the condition of Step 1, each condition can be verified as True/False, and these are linked to the actual simulator parameters. In this example, when all conditions are met, an operator can proceed to Step 2. If the conditions are not met, the operator proceeds to the right column, which is the RNO step. In this rno step, manual action can be performed by using the execute button. When the execute button is pressed, the connected simulator parameter is activated. The RNO Step 1.2 shows that if the action is still not executed, the procedure can be exited and transitioned to another procedure.

Figure 15. Example of digital procedure in Rancor Simulator.

steam flow at a rate of roughly 30 lbm/s per minute. The operational results for this procedure are presented in Figure 16.

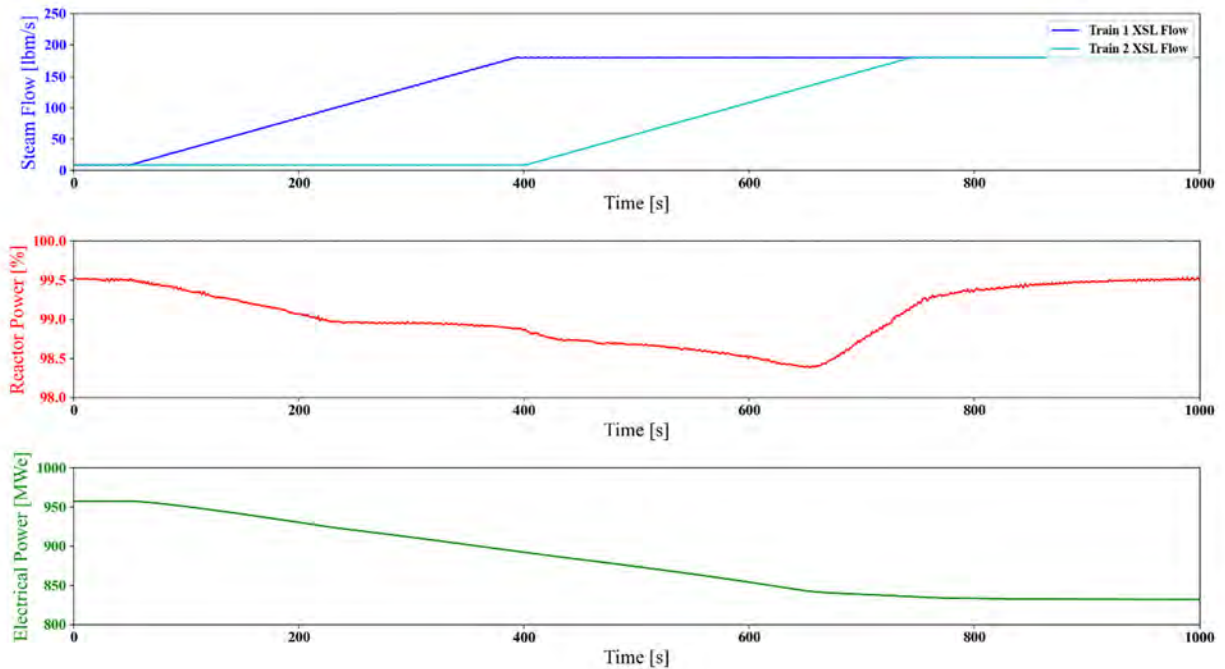


Figure 16. Hot standby to online without coordinated TCS/TPD controller.

Although the plant could complete the transition within 10 minutes, operational procedures required the operator to remain at the TPD panel to manually initiate the transition of the second train after the first train was fully online. This approach reduced overall situational awareness, as it prevented the operator from monitoring the broader plant response during the evolution.

Consequently, reactor power temporarily dropped by just over 1%, from approximately 99.5% to slightly below 98.5%, before returning to its nominal value as the plant stabilized. The precise parameters for configuring the system were available solely due to prior testing conducted on the GPWR.

The same procedure was used when transitioning from online to hot standby, utilizing the same set points. During this process, steam flow to the turbine increased slightly faster than the reduction achieved by the TPD system, resulting in a transient rise in reactor power. While this effect could be minimized by slowing the transition, doing so would have exceeded the 10-minute transfer target. The results of these operations are shown below.

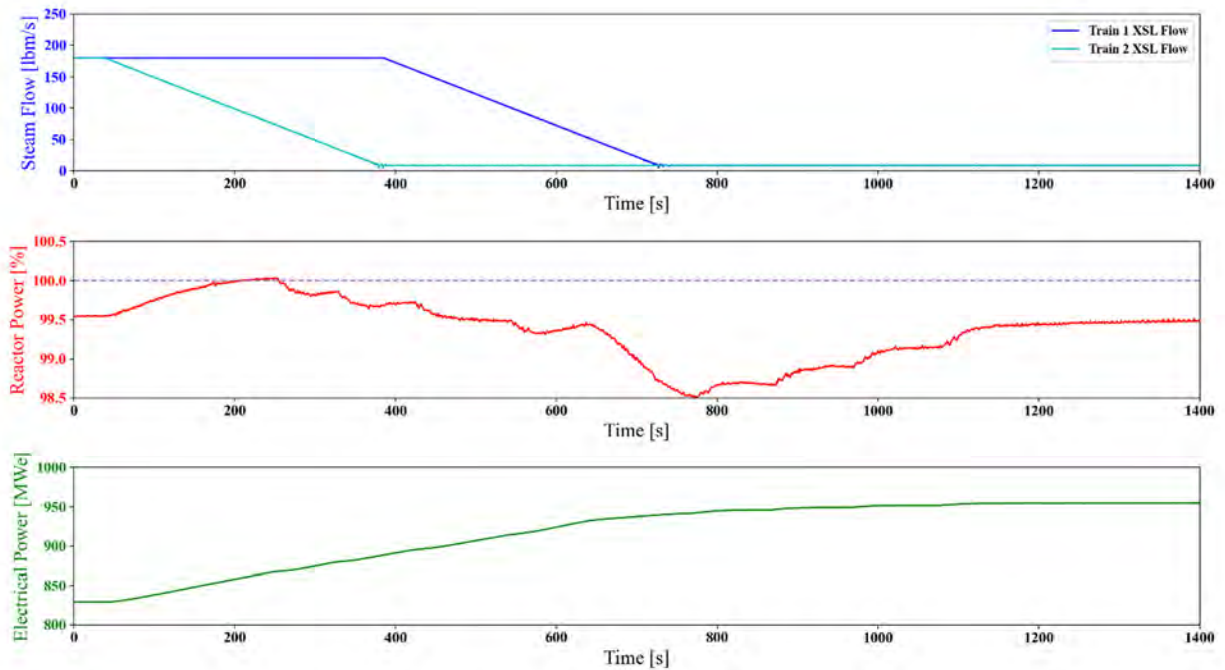


Figure 17. Online to hot standby without coordinated TCS/TPD controller.

The transient observed during the transition from online to hot standby was more pronounced than when bringing the TPD system online, with reactor power temporarily exceeding 100% for 20–30 seconds. This surge was followed by a sharp drop to approximately 98.5% power once the TPD system was fully offline, after which reactor power gradually returned to its previous level.

Managing this sequence required even greater operator attention than the transition to online, as any delay in initiating the second train's transition could result in an excessive increase in reactor power. This heightened demand on the operator detracted from overall plant oversight, contradicting the study's objective of seamless integration into existing reactor operations.

To address these challenges, an automatic controller, described previously in section was developed. The controller reduces operator cognitive load, minimizes plant transients, and enables the operator to focus on plant monitoring by simply initiating the transfer while the sequence is managed automatically. The improved performance of this approach during the transition from hot standby to online is illustrated in Figure 17.

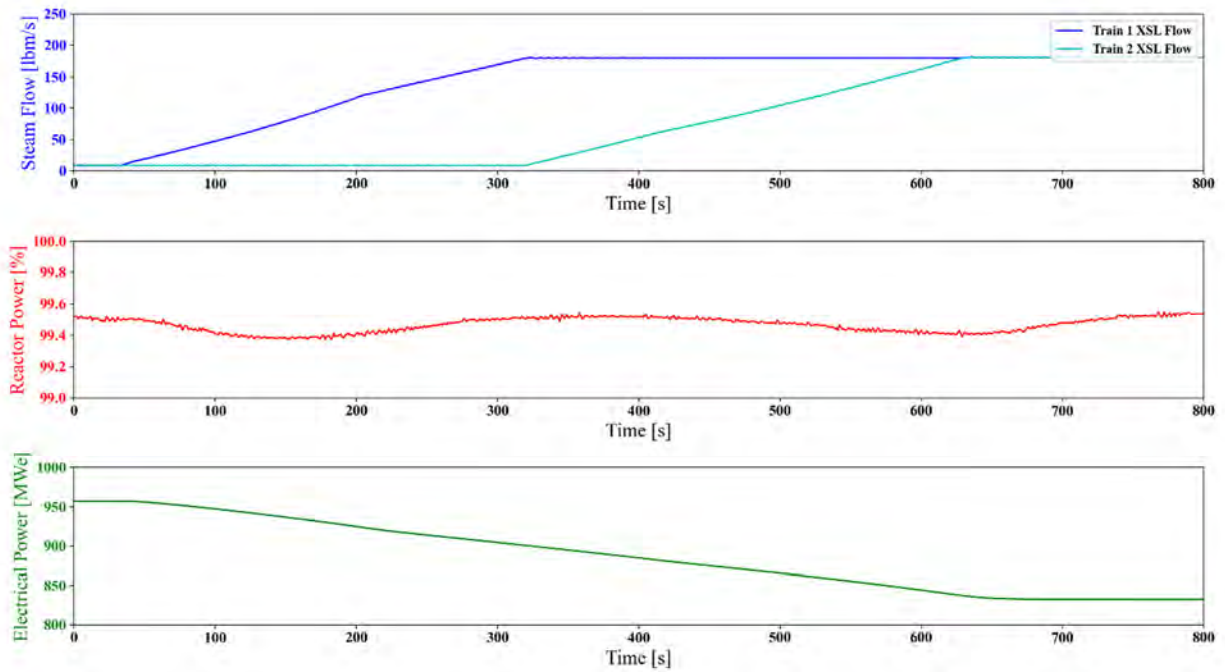


Figure 18. Hot standby to online with coordinated TCS/TPD controller.

With the coordinated controller, the reactor power transient is significantly reduced, permitting the y-axis range in the figure to be narrowed from 2% to 1%. This adjustment highlights the much smaller fluctuation in reactor power—now barely above a tenth of a percent. The steam transfer is completed precisely within the 10-minute target, and the reactor returns to steady-state conditions more rapidly than

with manual operation. Notably, the severe transient seen during the manual online to hot standby transfer is almost eliminated using the coordinated TCS/TPD controller as seen in Figure 18.

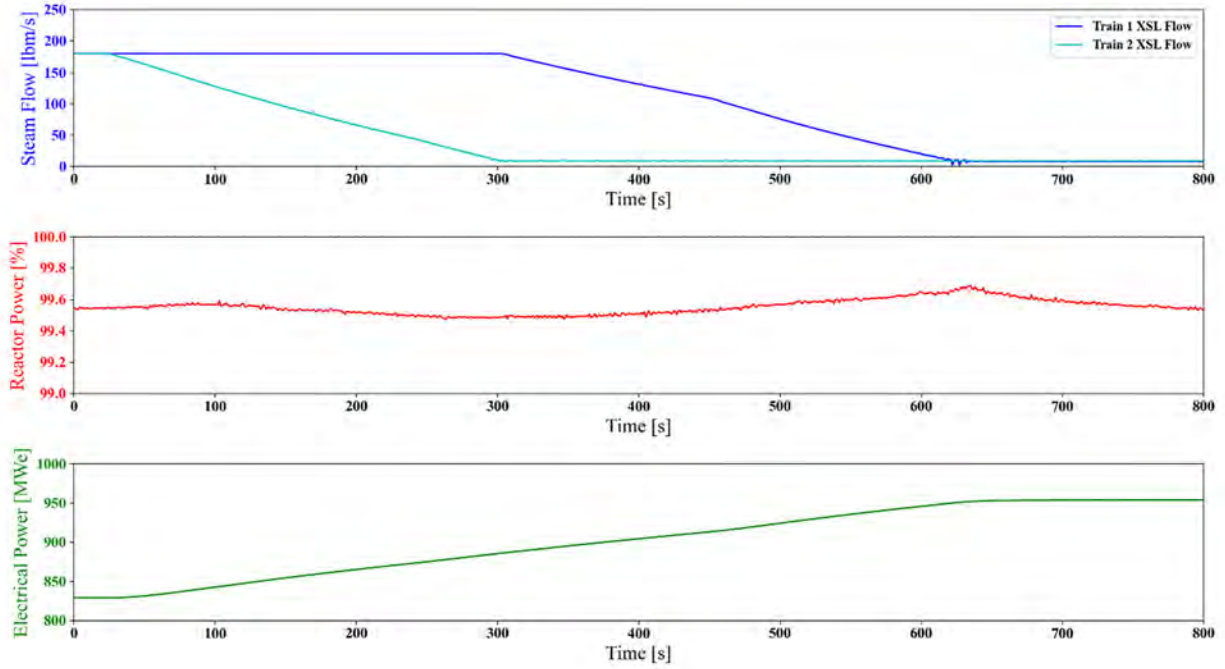


Figure 19. Online to hot standby with coordinated TCS/TPD controller.

Similarly, during the transition from online to hot standby with the coordinated controller, reactor power varies by less than two tenths of a percent (see Figure 19). The transient resolves and the system returns to steady-state conditions in approximately ten minutes less than with the prior method.

4.1.1.2 Limitations and Continued Simulator Development

The simulation's accuracy could be improved to better represent what this system would look like in the real world. One such improvement would be implementation of accurate pressure drop within the piping between valves. Accuracy is important, but a functional simulator that can approximate operations to support the development and demonstration of a TPD capability were the priority for this project, and therefore, emphasis was not placed on this since there is no existing plant or model data to emulate the pressure drop. One route to achieving this is the Darcy-Weisbach equation (as seen below) since the flow is expected to be turbulent. The Darcy-Weisbach equation calculates pressure drop as a function of the density (ρ [lbm/ft³]), pipe length (L [ft]), average fluid velocity (V [ft/s]), gravitational force (32.174 [ft/s²]), pipe diameter (D [ft]), and the Darcy friction factor (f).

$$\Delta P = f \frac{\rho L V^2}{2gD}.$$

The average fluid velocity (V) can be calculated since mass flow rate ($\dot{m} = 500$ [lbm/s] for design flow rate), density, and pipe diameter.

$$V = 4 \frac{\dot{m}}{\pi \rho D^2}.$$

Substituting into the Darcy-Weisbach equation yields:

$$\Delta P = f \frac{\rho L \left(4 \frac{\dot{m}}{\pi \rho D^2} \right)^2}{2gD},$$

$$\Delta P = f \frac{16\rho L \dot{m}^2}{2\pi^2 \rho^2 g D^5},$$

$$\Delta P = f \frac{8\rho L \dot{m}^2}{\pi^2 \rho^2 g D^5}.$$

The Darcy friction factor (f) can be solved using the Swamee-Jain Approximation for a solution to Colebrook-White Equation. This approximation was chosen due to its wide range of applicability and ease of implementation, while still maintaining satisfactory accuracy ($\pm 1.0\%$). The equation for the turbulent region can be seen below ($Re \geq 5000$). For the Swamee-Jain Correlation, the Darcy friction factor is a function of pipe roughness (ϵ), the pipe diameter (D), and the Reynolds number (Re).

$$f = \frac{0.25}{\left[\log\left(\frac{\epsilon/D}{3.7} + \frac{5.74}{Re^{0.9}}\right) \right]^2}.$$

Pipe roughness is characteristic of the material for the pipe, making pipe roughness and diameter constant for the same pipe. The Reynolds number, however, is a function of the fluid density (ρ), flow velocity (v), pipe length (L), and the dynamic viscosity (μ).

$$Re = \frac{\rho v L}{\mu}.$$

Although the conditions in this system are likely to lead to turbulent flow, the other flow regimes—laminar and transition—were still calculated if they occurred. The Darcy friction factor in laminar flow ($Re \leq 2000$) was calculated using the equation below.

$$f = \frac{64}{Re}.$$

The Darcy friction factor in transition region ($2,000 < Re < 5,000$) can be calculated by interpolating between the two equations previously stated and can be seen below.

$$f = \frac{64}{Re} * \left(1 - \frac{Re-2000}{5000-2000}\right) + \frac{0.25}{\left[\log\left(\frac{\epsilon/D}{3.7} + \frac{5.74}{Re^{0.9}}\right) \right]^2} * \frac{Re-2000}{5000-2000}.$$

Table 18 below shows pressure drop in various sections with some assumed plant geometry.

Table 18. Pressure drop in the XSL for assumed geometry.

Pipe Diameter (ft)	Pipe Length (ft)	Pressure (psia)	Density (lbm/ft ³)	Dynamic Viscosity (lbm/ft·s)	Mass Flow Rate (lbm/s)	Pressure Drop (psi)
1.50	200	1,000	2.242	0.045576	500	4.345
1.17	50	1,000	2.242	0.045576	250	1.001
0.417	200	300	60.18	0.0002037	250	31.67

When considering pressure drop in the pipe, it may be necessary to size up the pipe on the liquid side. Substituting the 5-inch pipe with an 8-inch pipe would reduce the pressure drop to a more reasonable 1.686 psi for the same conditions.

During the system testing, it appeared that the pressure downstream of the pressure control valve is partially dependent on the temperature of fluid exiting the reboiler and heading to the drain receiver. This leaves two items that may need to be done: (1) optimization of the enthalpy exchanged to the DSL system and (2) proximity to choked flow may require choked flow modeling.

Choked flow is modeled in GPWR; however, it must be selected. This makes flow area the primary controlling method the controlling method. This equation is applicable when the when the ratio of pressure differential to inlet absolute pressure is greater than or equal to the product of the pressure

differential ratio factor of a control valve (x_T) and the specific heat ratio factor (F_γ) (International Society of Automation, [ISA 75.01.01], 2007).

$$\frac{P_i - P_o}{P_i} \geq F_\gamma x_T.$$

Using the same assumption as in Section 2.1.2 System Scaling to 10% and Beyond, F_γ is assumed to be 0.925 and $x_T = 0.70$ for globe valves as seen in Table 18. Solving for the outlet pressure:

$$P_i - P_o \geq F_\gamma x_T P_i,$$

$$P_o \leq P_i - F_\gamma x_T P_i.$$

If the inlet pressure is 1,000.50 psia if outlet pressure is less than 352.676 psia, choked flow conditions would need to be considered. Since the downstream pressure while in hot standby is less than this, choked flow conditions would need to be evaluated. The control valve can be sized can be done using Equation 12 from “Flow Equations for Sizing Control Valves” (ISA 75.01.01).

$$C_v = \frac{W}{0.667 N_6 \sqrt{F_\gamma x_T P_i \rho_i}}.$$

Using the relationship discussed previously from Perry’s *Chemical Engineering Manual*, the flow coefficient (C_v) can be used to determine the approximate valve size to achieve the flow rate.

$$C_v = 29.9 \frac{D^2}{\sqrt{K}},$$

$$29.9 \frac{D^2}{\sqrt{K}} = \frac{W}{0.667 N_6 \sqrt{F_\gamma x_T P_i \rho_i}},$$

$$D^2 = \frac{W \sqrt{K}}{29.9 * 0.667 N_6 \sqrt{F_\gamma x_T P_i \rho_i}},$$

$$D = \sqrt{\frac{W \sqrt{K}}{29.9 * 0.667 N_6 \sqrt{F_\gamma x_T P_i \rho_i}}}$$

With a flow rate (W [lbm/hr]) of 32,400 lbm/hr, 9 lbm/s, while in hot standby, a velocity head loss coefficient (K) of 9, an inlet pressure of 1,000.5 psia, and an inlet density (ρ_i) of 2.221 lbm/ft³, the valve would need to have an effective diameter of approximately 1.42 ft, which is currently not only larger than the control valve, but also larger than the pipe in that location.

4.1.1.3 Grid Model

To emulate a practical scenario where the system dynamics is influenced by that of the GPWR and the HTSE, the short-circuit Mega Volt Amps (MVA) contribution of the rest of the grid, where the GPWR is connected to, is reduced. The default short-circuit MVA value set in the simulator was reduced to lower the short-circuit ratio (SCR) at the point of interconnection as described by the following formula:

$$SCR = S_{SCMVA} / P_{RMW}.$$

where S_{SCMVA} is the short-circuit MVA and P_{RMW} is the rated megawatt value of the new connected source.

Short-circuit power, while primarily a measure of voltage stiffness, also significantly influences frequency dynamics. A low SCR indicates a weak grid with high source impedance, which limits the grid’s ability to absorb or deliver sudden changes in power, making it more sensitive to power imbalances. These imbalances result in faster and larger frequency deviations, particularly in systems with low rotational inertia.

Hot Standby to Online Scenario

The HTSE is both electrically and thermally coupled to the GPWR. While on hot standby, the HTSE power consumption is set at 10% of its nominal power demand. For this scenario, when the HTSE goes fully online, it consumes its nominal power for hydrogen production. The grid-coupled switch yard frequency and voltage response are shown in Figure 20. As seen in the figure, as soon as the HTSE goes online after 1 minute of simulation, the system frequency dips. This causes the GPWR frequency control to start regulating the frequency by minimizing the error between the nominal 60Hz frequency and the instantaneous frequency of the system. After approximately 13 minutes, the system's frequency was able to recover to its nominal value. The voltage response of the system on the 6.9 kV bus and 230 kV bus is shown on the left plots in Figure 20.

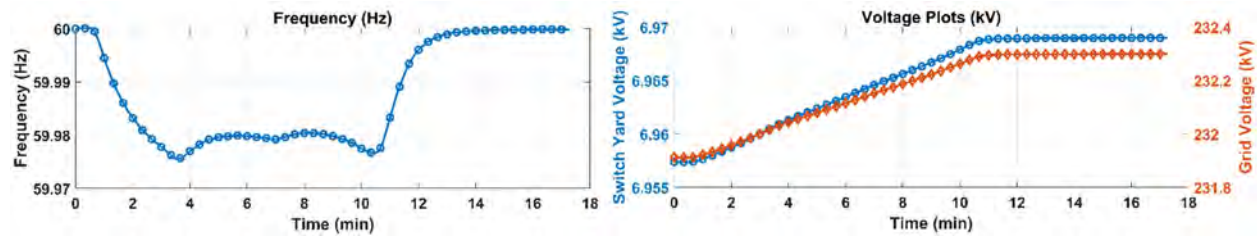


Figure 20. Frequency and voltage response for hot standby to online.

Online to Hot Standby Scenario

For the online to hot standby scenario, the HTSE is placed in hot standby. The grid-coupled switch yard frequency and voltage response for the scenario are shown below in Figure 21. As seen in the figure, when the HTSE is placed in the standby, the system frequency begins to rise starting at minute one and rises above 60 Hz. Similar to the hot standby to online scenario, the GPWR frequency controller is activated to regulate the system frequency. After approximately 18 minutes, the controller recovered the system's frequency to its nominal value. The voltage response of the system on the 6.9 kV bus and 230 kV bus is shown on the right plot in Figure 21.

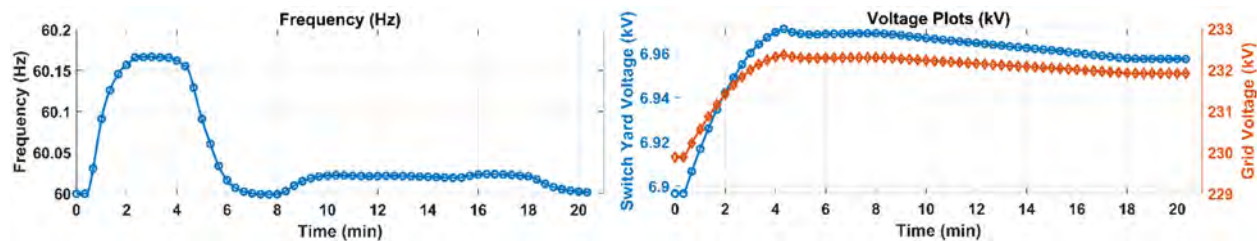


Figure 21. Frequency (left) and voltage (right) response for the online to hot standby scenario.

4.2 Human-in-the-loop Scenario Testing

This section introduces the TPD testing results of the normal and additional scenarios. These tests were conducted at INL's HSSL during the integration workshop. The aim of this week long workshop was to verify whether the TPD system operated as intended, validate the impact on the TPD system during representative DBA event scenarios currently considered in existing NPPs, and verify that the CBP for each scenario accurately reflected and the simulator state. The CBP verification specifically focused on ensuring the correct GPWR simulation database points were properly referenced within each tested CBP step. Several hundred simulation points were mapped to CPB elements and therefore it was important to ensure the proper mapping was performed both in terms of connecting the proper values and control variables or functions. In sum, the HITL testing served to ensure the simulator models, coupled

co-simulations, human-machine interfaces, and computer-based procedures were functioning properly together.

4.2.1 Testing Protocol

The simulator was administered using one computer for the instructor station to configuration and control the simulation. Another computer displaying the RIPS CBP system, was positioned on a table near the HSSL bay displaying the TPD HMI. This positioning was done to aid datapoint checks since the HMI has been validated several times and serves as an accurate reference for TPD database variables. A video recorder was used to capture a historical record that could be viewed later for reference to observe physical interactions with the TPD HMI and CBPs. Additionally, Microsoft Teams was used to support a remote team member acting as a test participant. The video recording feature was used to capture both HMI and CBP display interactions.

The workshop researcher team included individual performing the following duties and roles:

- **Instructor** – Responsible for configuring scenario initial conditions, initiating malfunctions on event related equipment, and saving process parameter recordings.
- **Operator** – Directly performed the test scenario tasks according to the procedures. In the TPD scenarios, the operator used CBPs to execute the scenario. In the additional scenarios, the participant used the HSSL glasstop touchscreens to manipulate virtual representations of existing analog control boards to execute each scenario. For expediency, the CBP author acted as the operator executing the paper procedure, while being observed by the workshop team, to validate the simulator response.
- **Recorder** – Since the operator directly manipulated the simulator in the additional scenarios, the recorder followed the operator to record notes of the simulator's variables and operations.
- **Observers** – Records and evaluates any anomalies during the test. Unless they are assigned another specific role, all researchers participate as evaluators. In the additional scenarios, an assistant evaluator monitored whether the CBP accurately reflect the current state of the simulator while the operator performs the scenario and records any anomalies.

The test was conducted in the following four main stages:

1. **Preparation** – In this stage, the initial conditions and malfunctions are entered according to the scenario. The RIPS is launched, and printed copies of the procedures to be used in the scenario are provided to all researchers.
2. **Start** – All recording devices and software are activated, and the simulator is running.
3. **Duration** – The operator performs the scenario, while the evaluators carry out their assessments. When an alarm is triggered by a malfunction, the operator enters the proper procedures and continues the test until the end conditions are satisfied. During the test, the operator verbalizes the procedures being followed and the actions being taken.
4. **End** – The scenario concludes when the predefined end condition is met. The simulator and recordings are then stopped, and the data is recorded.

During each test scenario, operators executed the procedure while verbalizing the instruction text, explicitly pointing at indication and controls required for each step. Instructions requiring field operators or other personnel external to the control room, such as the chemistry department, were verbalized and then assumed as appropriately executed. Furthermore, steps that involved control room systems with no functional representations on the HSSL bays were acknowledge and omitted.

4.2.2 TPD Scenarios

The TPD system was designed to function in conjunction with the existing plant's TCS in a coordinated fashion. An increase in the TPD extraction flow decreases steam flow and subsequently turbine load, such that the reactor power remains constant during both normal operating scenarios and transient conditions between modes of operation. The tight coupling between the TPD and TCS systems requires a coordinated monitoring and control functionality that enables the operator to toggle between TPD online and offline modes while monitoring both systems' parameters in tandem. The "Coordinated TCS/TPD Controller" was introduced on the TPD HMI control panel to support this function (see Figure 8).

The TPD HMI and the CBPs were examined during all testing, but the normal and abnormal scenarios placed different emphasis on testing the TPD HMI or CBPs as the method of executing the required tasks within each scenario. Previous work evaluated the coordinated operation, but this was achieved without a coordinated controller. The testing focused on using the TPD HMI with the coordinated TCS/TPD controller to perform the normal scenarios. As previously stated, scenario representativeness and worst-case, design-basis related events were used as criteria for selecting the four abnormal TPD scenarios tested under varying conditions. The CBPs

4.2.2.1 Normal Scenarios

Hot Standby to Online

Routine TPD operations were evaluated by performing the transition from Hot Standby to Online procedure using with coordinated thermal energy extraction between the TCS and TPD, controlled by manipulating the coordinated TCS/TPD controller. The scenario was executed using the CBP with procedure steps performed by monitoring live values and executing actions using embedded soft controls within the procedure steps. The sequence of steps for this scenario begins by verifying the general plant and TPD initial condition are in the appropriate configuration. The coordinated TCS/TPD controller is first placed in the "Coordinated Mode". The operator then selects train A or B ("preferred TPD train") to designate which train should be ramped to the target setpoint first as this is performed sequentially in the controller logic. The coordinated TCS/TPD controller target and ramp rate is then set to 770 MW and 15 MW/min, respectively. The controller's go button is then clicked to initiate the transition to online. The coordinated TCS/TPD controller uses the logic from the existing digital electrohydraulic TCS within the simulator to change the turbine load to the input setpoint target. The preferred train is programmed to ramp to 180 lb/s, followed by the non-preferred train ramping to 180 lb/s. For extraction flows greater than 360 lb/s, both trains will ramp simultaneously. The operator then monitored the system as the extraction flow rate rose to 180 lb/s and the turbine load approached the 770 MW target. Once these values were observed and the TPD online mode indicator was illuminated, the scenario was deemed completed and terminated.

Online to Hot Standby

The Online to Hot Standby scenario is identical to the hot standby to online scenario, only the sequence of actions is in reverse. As in the Hot Standby to Online scenario, TPD initial conditions were verified. Then, the coordinated TCS/TPD controller was placed in the "Coordinated Mode," and the preferred TPD train was selected. Afterward, the coordinated TCS/TPD controller target and ramp rate were set to 920 MW and 15 MW/min, respectively, followed by the controller's go button selected to begin the TPD system ramp down. The system was monitored as the extraction flow rate dropped to 9 lb/s and turbine load approached 920 MW. Upon observing these values, the transition was verified as complete when TPD in Hot Standby mode indicator was illuminated.

4.2.2.2 Abnormal Scenarios

The TPD abnormal scenarios were tested by following a digitalized procedure based on the existing paper-based TPD trouble procedure. The initial steps focus on diagnosing the event by checking the presence of alarms, such as XSL trip, HTSE trip, and XLS extraction flow mismatch, along with monitoring the behavior of associated flows. In Steps 5 and 6 of the procedure, the affected train is identified, and appropriate XSL trip actions are taken to isolate the faulted TPD train.

It was identified during abnormal scenarios that the existing TPD trouble procedure lacks clear distinction between TPD Train A and Train B. Although the identification of affected train is made in Step 5 of XSL trip, it was confirmed that train-specific identification is necessary in earlier steps as well. Without this, operators may experience delays or errors in diagnosis and response during abnormal scenarios. Therefore, updating the operating procedure to incorporate the identification of the affected train from the initial steps is recommended to improve clarity and operational effectiveness.

Tube Leak in the Reboiler

A tube rupture occurs in the reboiler which results in a leak from the XSL to the DSL. This is indicated by the drain receiver level dropping significantly, as well as an increase in steam flow despite the reboiler level remaining balanced and high. The steam flow increases and pressure control valves at 100% further support the presence of a leak upstream. As shown in Figure 22, the operator can determine that a rupture has occurred in the Train A reboiler by monitoring the parameters.

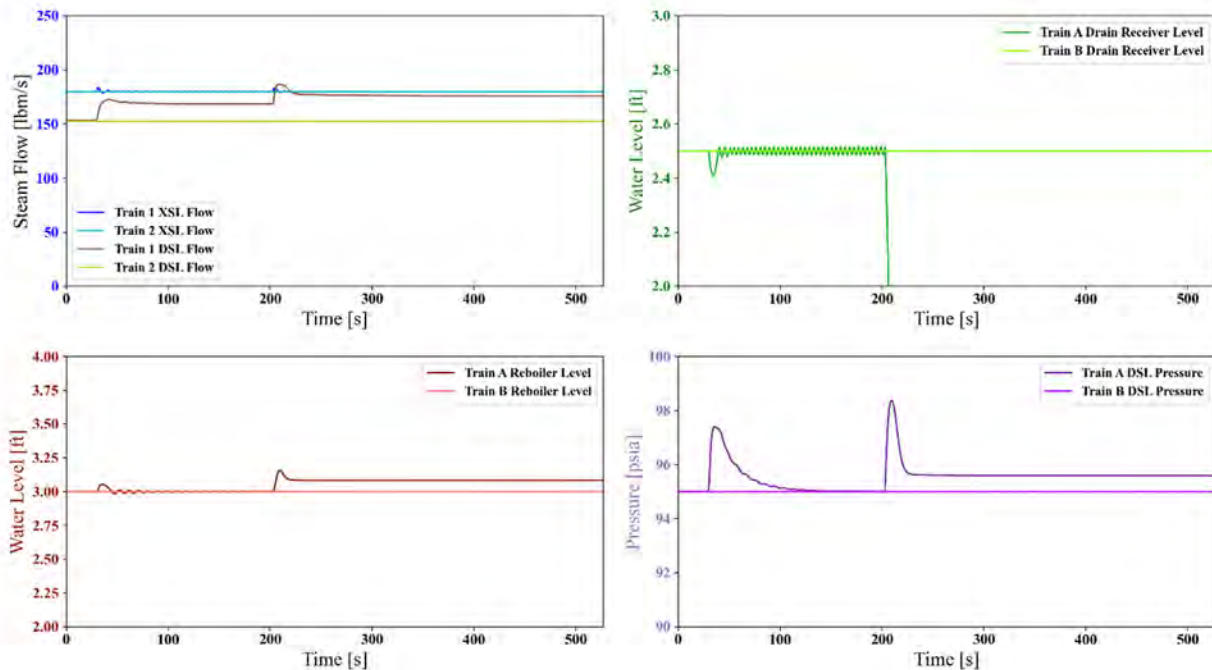


Figure 22. Monitored parameters in the scenario of the tube leak in the reboiler.

Tube Leak in the Drain Receiver

When there is a leak in the drain receiver, the operator can observe the following phenomena: the valves will open and close repeatedly due to fluctuating pressure caused by the leak. High-pressure water from the leaks, causing pressure spikes. These spikes result in a slight reduction in the leak flow rate, which temporarily allows the valves to open. As the pressure in the DSL increases, the leak flow rate decreases slightly, which can be seen as the pressure oscillates between higher and lower values. This

oscillation causes the reboiler level to drop when the pressure is high and rise when the pressure drops. The level control valve responds to these fluctuations by opening to drain the receiver when the level rises.

As shown in Figure 23, this cyclical pattern of pressure changes, leak flow adjustments, and valve movements create a back-and-forth dynamic that the operator can monitor. By observing these parameters, the operator can determine that there is a leak in the Train B drain receiver and take appropriate action to address the issue.

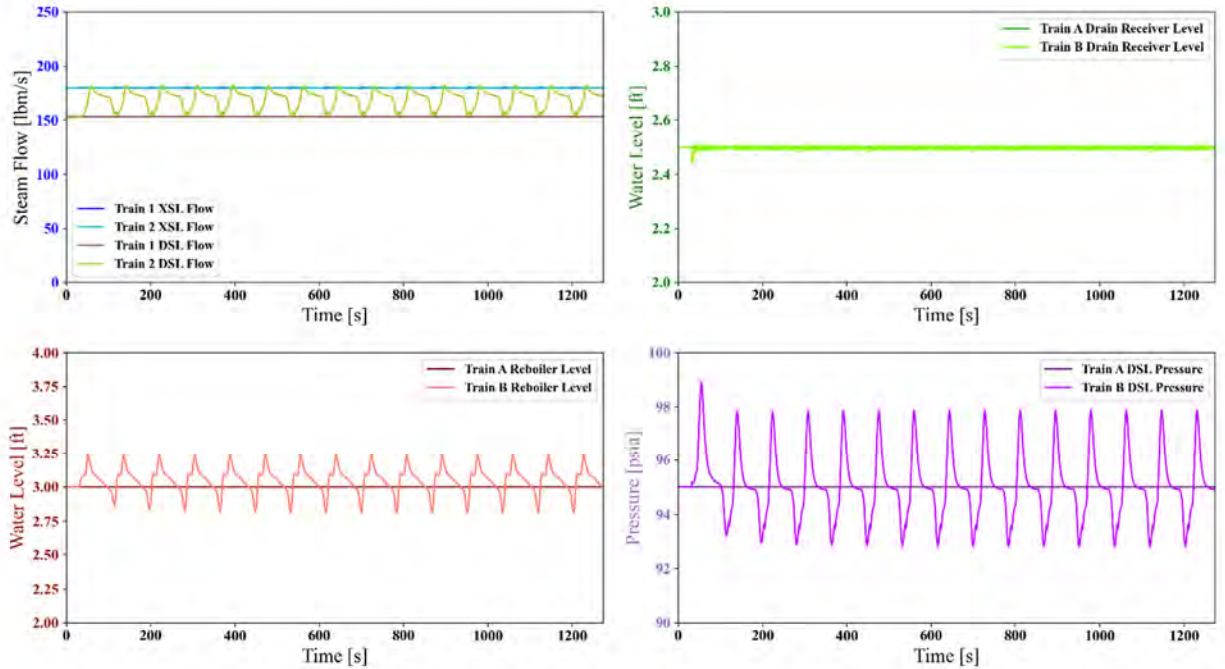


Figure 23. Monitored parameters in the scenario of the tube leak in the drain receiver.

4.2.2.3 Rupture Downstream of FT-1001/Upstream of the Reboiler

The operator can determine that there is a leak after the flow transmitter and before the reboiler in Train A by observing several key indicators. First, the level control valve is completely closed, yet the steam flow continues to decrease. The pressure drops initially but then rises again as the valve shuts to build pressure back up. This behavior indicates an issue in the system. Additionally, the reboiler level remains unaffected until the system trips, suggesting that the problem is not downstream of the reboiler. If it were downstream, the steam flow would remain constant, and the flow control valve would maintain the flow at around 180 lb. Furthermore, by comparing the performance of Train A and Train B, the operator can see that while Train B's steam flow remains constant, Train A's steam flow decreases, confirming that the issue is specific to Train A. These observations point to a leak located after the flow transmitter and before the reboiler on Train A (see Figure 24).

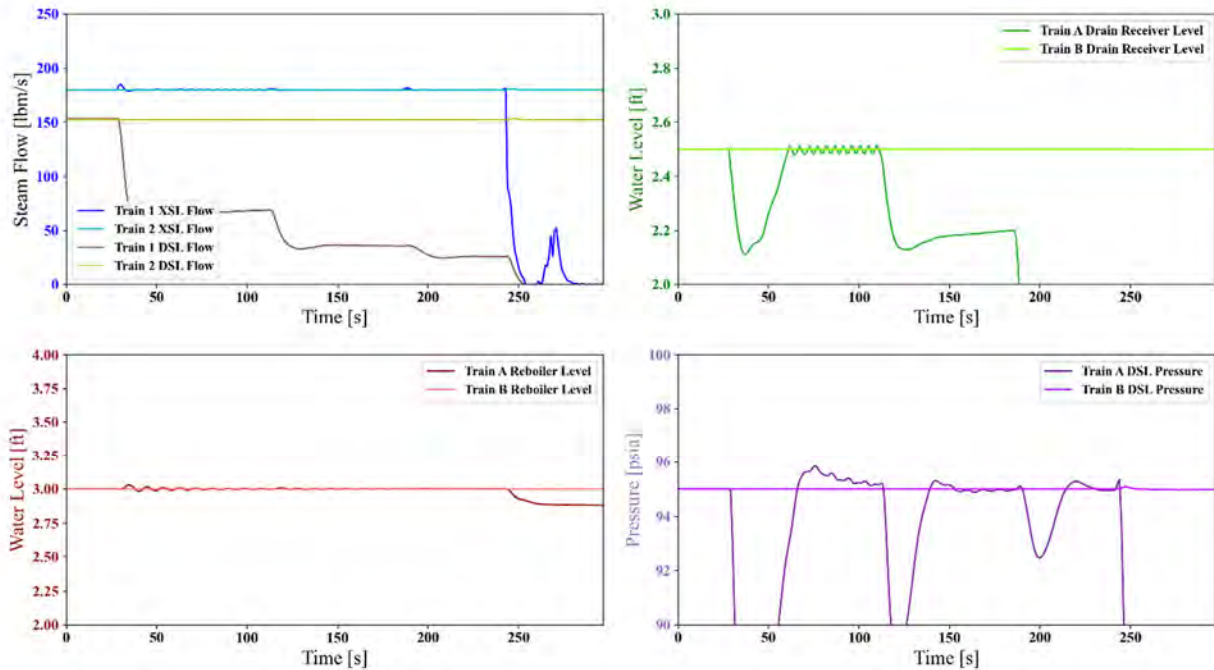


Figure 24. Monitored parameters in the scenario of the rupture downstream of FT-1001/upstream of the reboiler.

4.2.3 Additional Scenarios

4.2.3.1 Steam Generator Tube Rupture

The SGTR scenario was entered from the “Reactor Trip and Safety Injection” (EOP-E-0). Following a reactor trip, verification of the reactor and turbine trips was performed by walking through the initial steps of EOP-E-0, followed by confirmation of safety injection (SI) on both injection pathways. Key parameters were monitored to assess core cooling and the proper alignment of the emergency core cooling system, determining whether to continue the SI. Upon stabilizing the plant, a series of diagnostic logic steps were followed to determine the cause of the event, leading to the SGTR scenario from EOP-E-0 Step 29.

The SGTR scenario was performed using EOP-E-3 with the primary goal of identifying and isolating ruptured SG(s) and regulating the AFW flow to stabilize the RCS temperature. The initial procedure steps identified the ruptured SG, with subsequent steps focused on isolating the faulted SG by shutting associated steam and feedwater valves. The reactor was manually tripped, and cooldown operations began using unaffected steam generators. Following the identification and isolation of the faulted SG, subsequent steps maintained core cooling and minimized radiological releases. Thereafter, the affected SG was depressurized and isolated, and long-term cooling was established using intact systems.

4.2.3.2 Main Steam Line Break

In the MSLB scenario, the reactor automatically trips, triggering entry into the EOP-E-0 procedure. As the procedure progresses, the transition to EPP-14 occurs at Step 16 of EOP-E-0. This step is following the confirmation that the pressure of any SG is either dropping in an uncontrolled manner or has completely dropped. In the EPP-14, Step 3 checks the pressure of any SG, but it is observed to be neither stable nor increasing, leading the operator to follow the RNO Step. Then, the procedure transition to EPP-15, in which only the isolation actions specified in Step 2 were executed during this testing.

4.2.3.3 Load Rejection

The load rejection scenario was performed with the TPD system offline and online with no discernible impacts on the existing plant systems reported by the operators. The operator, upon identifying the turbine runback alarm, enters AOP-15 for secondary load rejection.

4.2.3.4 TPD Offline

Upon entering AOP-015, the NPP has both main FW pumps and heater drain pumps running. Also, the turbine load is approximately 900 MW, which is about 97.8% of the normal state of 920 MW and decreasing. Therefore, based on AOP-015 Step 1, the use of the AOP-015 procedure and the turbine runback malfunction is appropriate for this load rejection scenario.

Regarding AOP-015 Step 2, since the DEH is operating in turbine runback oper mode, Step 3, which involves operating the DEH, is skipped. Additionally, it was confirmed during the test that the termination condition for Step 3, Turbine Valve transient TERMINATED, has already been satisfied.

In the subsequent procedures, to control the reactivity on the primary system and maintain the integrity of the secondary system, the status of the PORV control and SG levels are checked. Specifically, the insertion status of the control rods for reactivity control is verified in conjunction with Step 6 and Step 13. If the conditions specified in these steps are not met, the RNO for the respective steps must be performed, requiring manual operation of the equipment. However, during this test, it was confirmed that all conditions were satisfied.

In AOP-015 Step 11 and Step 12, the verification of the electric system is required. However, since it is not possible to check the HMI of the power system in this test, these steps were skipped.

When the start in AOP-105 Step 19, the turbine load is 472 MW, which is approximately 51.3% of the normal state. Therefore, according to Step 19, the RNO should be entered to stop one of the two main FW pumps. However, due to an error by the operator during the test, the stopping of the main FW pump was omitted.

Ultimately, this scenario satisfied the condition of reactor power being above 20% as specified in AOP-105 Step 21, transitioned to Step 32, and then concluded. At the termination timing, the reactor power was approximately 60%, which is a 40% decrease from the normal state. **Error! Reference source not found.** shows the number of tasks actual performed in this scenario compared to the total number of tasks in the AOP-015, "Digital Procedure" used for this test.

4.2.3.5 TPD Online

When the TPD is online, the scenario proceeds almost identically to when the TPD is offline. However, 360 lb/sec of steam is consumed for TPD operation, resulting in differences in the initial and termination states.

Upon entering AOP-015, the NPP has both main FW pumps and heater drain pumps running, which is the same as when the TPD is offline. However, since steam is already being consumed by the TPD, the turbine load is approximately 720 MW, which is less than TPD offline scenario. Nevertheless, this is about 93.5% of the initial condition 770 MW. Therefore, the use of the AOP-015 procedure and the turbine runback malfunction is also appropriate for the load rejection scenario with the TPD online.

As a result of this test, scenario flow was very similar regardless of whether the TPD was offline or online. Specifically, the turbine load at the scenario termination timing was 472 MW and 460 MW, respectively, showing no significant difference. However, with the TPD online, since the initial turbine load was 770 MW, the turbine load at the end of the scenario was approximately 59.7%. This satisfies the condition of AOP-015 Step 19, so unlike the TPD offline scenario, the scenario transitioned to the termination step (i.e., AOP-015 Step 32) regardless of reactor power.

At the end of each scenario with the TPD online and offline, the reactor power was 60% and 73% respectively. This difference is likely due to the additional steam consumption by the TPD system, which operated during the TPD online scenario and thus could consume more energy from the RCS which represents mitigation of the load rejection with the TPD system acting as a buffer.

4.3 Observations from Human-in-the-loop Scenario Testing

The effective use of procedures is highly correlated to the process employed in their development. Many reported incidents involving procedures are due to a deficiency in the procedure development process, chief among them being domain experts working in silos to prepare procedures (Marsden 1996). To circumvent the issues associated with procedure development and optimize procedure quality and reliability, a standardized and collaborative approach that enables correct procedure interpretation by the intended users was proposed by Embrey (1986). The process comprises six discrete steps (see Figure 25), starting with a formal task analysis to decompose the task into subgoals and specify the combination approach of the subgoals to achieve the task objectives. Following a detailed task analysis is the selection of the appropriate format to be used in presenting the procedure. The third step in the procedure development process is the preparation of a draft procedure, where the initial layout is verified against applicable human factors guidelines before proceeding to the quality assurance stage.

The quality assurance stage involves qualified inspectors conducting a series of validation tests in the actual task operating environment. Findings from quality assurance testing should be documented in a structured way to enhance the drafting process, and Steps 1 through 4 may be conducted in more than one iteration when incremental refinements are necessary. The last two stages include approval of final draft procedure for operational use and maintenance of the procedure through its lifecycle.

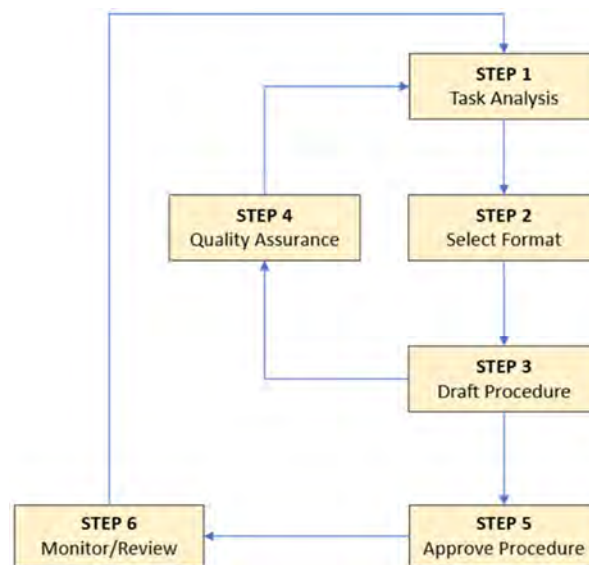


Figure 25. Procedure development process (based on Embrey 1986).

The HITL scenario testing corresponds to stage four of the procedure development process with operator surrogates. However, observations and findings went beyond the testing stage to include other stages prior within the context of the standardized procedure development process. The CBPs used in the HITL testing were translated from existing GPWR PBPs, skipping the first stage of task analysis in the procedure development process. Therefore, observations related to a lack of an initial CBP-based task analysis were not included in this report. Anecdotal observations comparing the CBP to traditional PBP were captured and documented. The observations captured will serve as a first step in the iterative development of CBP as proposed by Embrey (1986).

4.3.1 Efficient Transition Between Steps

The CBP enabled a sequential presentation of information in a way that supports a seamless transition between procedure steps. The cognitive tasks involved in following control room procedures can be broadly categorized as primary and secondary tasks (O'Hara, Stubler, and Nasta 1997). Primary tasks are a set of actions directly targeted at achieving the task objective, such as "IF turbine ramp rate exceeds 1800 RPM, THEN latch the turbine." The secondary tasks are actions not directed at the primary task but toward operator interactions with HSIs, such as navigating through the procedure itself. Overall, primary and secondary tasks require cognitive resources for effective performance. Observations from the HITL test revealed that the CBP enables efficient transitions between steps compared to paper-based procedures (PBP). Transitioning between steps in the CBP was achieved by a single button (GO TO...) press to specify an exact target step. In the PBP, operators had to deal with the onerous secondary task of flipping through the pages of procedure documents to navigate between steps, which may impact performance. The cognitive resources freed up by relieving the operator of the task of manually transitioning between steps lowers the cognitive workload involved in following procedures.

4.3.2 Effective Place-Keeping

Place-keeping when following procedures is the practice of tracking one's position within a sequence of procedure steps to ensure that no steps are skipped or repeated. While executing scenarios in the HITL test, the salient highlighting of current procedure steps in the CBP made it easy to know exactly the position in the execution sequence of the procedure at any given time. Effective place-keeping may improve efficiency by supporting logical path following control room operations.

4.3.3 Ineffective for Performing Diagnostics

Timely and effective diagnosis is a critical safety imperative in nuclear process control. Operators are trained to integrate information from multiple indicators, alarms, and trends of essential parameters representing different systems to deduce an emergent state of the plant. Trained operators can match the emergent state with their mental models of the functional plant state to make a swift diagnosis. The presentation of live indicators in silos on a stepwise basis did not enable the integration necessary to make swift diagnosis compared to what is obtainable using PBPs when the operator is required to consider all relevant pieces of information available on the control boards. Although CBPs are not intended to substitute operators' manual confirmation of values on the control board, the natural tendency to take the path of least effort may be driving the use of CBP as substitutes instead of their intended use as supplements.

4.3.4 Difficult to Represent Trends

The CBP lacked representations of trends and made it difficult to follow the progression of essential operating parameters, especially during fault scenarios. Trend graphs play a vital role in controlling room operations by enabling operators to monitor the evolution of key plant parameters over time. Trends are highly effective visual tools for identifying gradual deviations or abnormal patterns that may not trigger immediate alarms but can lead to issues down the line. A lack of trends made it very difficult to analyze progressions of variables to understand evolving issues and take early corrective actions.

4.3.5 Ineffective for Integrating Multiple Redundant Indicators

NPPs often employ redundancy in essential process variables to enhance reliability. It is common practice to have more than one indicator measuring the same process variable (e.g., the steam generator line-A level, indicated by "SG Level Narrow Range Change has four redundant indicators: LI-474 SA, LI-475 SB, LI-476 SB, LI-473 SB." Stability of the process does not imply the exact same reading on all redundant indicators. Trained operators can interpret stability within a given range of variability in values across redundant indicators. Referring to the description of the CBP ViewModel in prior sections, point names corresponding to variables are mapped to property names in the ViewModel to enable their

functioning in the CBP. Point names corresponding to multiple redundant values of the same variable are hard to integrate into a single property name in the ViewModel. While an operator could easily perform these integrations using PBPs, specifying a logic that performs such operations in a CBP is not easily achievable.

4.3.6 Tedious Elaboration of Simple Steps

The digitization of monitoring and control functions in CBPs requires that every procedure step be translated into logically operable forms. The translation process sometimes results in a single step, well understood by a human operator when described simply, becoming an elaborate sequence of substeps when implemented in CBP. For example, an operator knows exactly what to do after reading EOP-E-0 Step 21.3, which reads, “Control Feed flow.” However, implementing this step in the CBP environment requires breaking it down into twelve different actions (Figure 26). The process of elaboration may make a simple step appear more tedious in CBP than it is in PBP form.

For example, in the digital procedure, it could be difficult to configure action with just one execute button in situations where specific setpoints are not predetermined. In such cases, all possible executions should be created, and the operator should decide and perform them as needed. In Step 21.3, as shown in Figure 26, the auxiliary feedwater flow should be adjusted to maintain the RCS temperature between 555°F and 559°F. The operator should select the proper SG from Trains A, B, or C and choose whether to operate the motor-driven pump or turbine-driven pump. Additionally, the flow control valve should be adjusted up or down to control the flow rate. While a paper procedure might present this as a single action, a digital procedure should break it down into detailed steps, including the selection of proper component, the up and down adjustments of the valve setpoint, and monitoring the variables to see how much each action has changed.

Figure 26. An example of digital procedure step.

4.3.7 Translating Tables with Multiple Logic

There are some difficulties in implementing the table from the paper procedure into the digital procedure. The table can represent different approaches of execution depending on each condition, which, unlike the parallel representation in the paper procedure, should be shown sequentially in the digital procedure. However, even in such cases, it is possible to implement this by verifying each condition and moving to a specific step if the condition is not met. For example, in the table of Step 21 shown in Figure 27, Condition 1 indicates that the RCS temperature is less than 557 or is decreasing. If this condition is met, Conditions 2 and 3 do not apply, so Steps 21.1 to 21.5 in Figure 28 can be performed. If the condition required in Step 21.5 is satisfied, the process can exit Step 21 and proceed to the next step. However, if Condition 1 is not met initially, the process moves to Step 21.1 RNO, then skips to Step 21.6 to check Condition 2. Similarly, if Condition 2 is met, Steps 21.6 to 21.9 can be performed. If Condition 2 is not met, the process proceeds to Step 21.10 via the RNO step to perform the procedure for Condition 3.

21. Stabilize AND Maintain Temperature Between 555°F AND 559°F Using Table 1.			
TABLE 1: RCS TEMPERATURE CONTROL GUIDELINES FOLLOWING RX TRIP - Guidance is applicable until another procedure directs otherwise. - IF no RCPs running, THEN use wide range cold leg temperature.			
	RCS TEMPERATURE TREND		
	Condition 1	Condition 2	Condition 3
	LESS THAN 557°F AND DROPPING	GREATER THAN 557°F AND RISING	STABLE AT OR TRENDING TO 557°F
OPERATOR ACTION	- Stop dumping steam - Control feed flow - Maintain total feed flow greater than 210 KPPH until level greater than 25% [40%] in at least one intact SG - IF cooldown continues, THEN shut MSIVs AND BYPASS valves	- IF condenser available THEN transfer steam dump to STEAM PRESSURE mode using OP-126. Section 5.3 AND dump steam to condenser - OR - - Dump steam using intact SG PORVs - Control feed flow to maintain SG levels	Control feed flow and steam dump to establish and maintain RCS temperature between 555°F AND 559°F

Figure 27. An example of table as depicted in a paper procedure with complex logic.

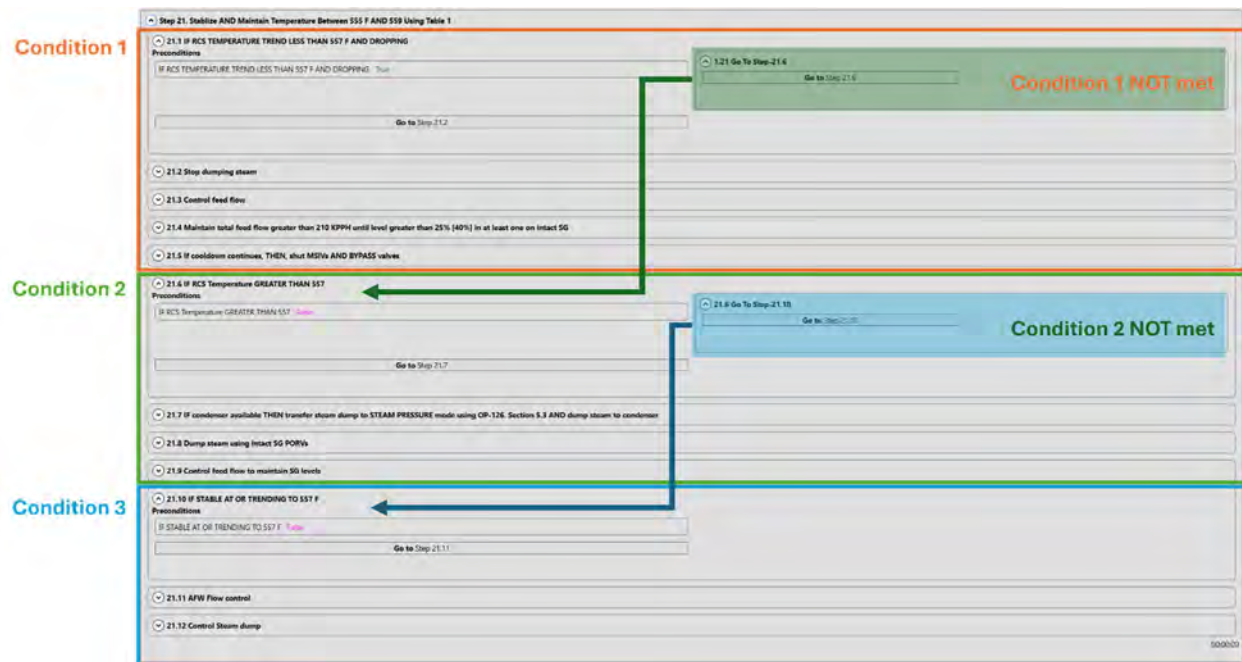


Figure 28. An example of steps in digital procedure corresponding to the table depicted in Figure 27.

5. DISCUSSION

5.1 Lessons Learned

A full-scope training simulator was successfully modified with a much larger TPD system. The Rancor Microworld Nuclear Power Plant Simulator evolved into the Rancor Simulator Framework including generalized support for full-scope simulators, HUNTER, and RIPS. The integration workshop yielded several lessons learned with respect to integrating the new operational capability. Furthermore, insights were made concerning the supporting technologies that aid operators to monitor and control the TPD system. Though these implementations were specific to the TPD, the lessons can be broadened to general efforts to digitize and integrate automation into existing nuclear control rooms. Additionally, some of the operator support technologies are representative of advanced reactors and have implications beyond the existing fleet of U.S. commercial reactors.

5.1.1 Where Should New Control Capabilities Be Integrated with Existing Systems?

The TPD system impacts the flow of steam through the turbine, which has direct feedback to the reactor control system to modulate reactor power. The functionality to dispatch thermal energy is a new unique functionality and should have dedicated controls. However, it should also be integrated into the existing control scheme, so that when operators interact with the TPD, they understand the context of the other systems, which are important to reactivity. The most probable hierarchy to organize the responsibilities of the control systems in terms of precedence is to situate the TPD system as subsystem of the TCS.

5.1.2 Task-based Automation Integration

When working with full-scope simulators, we have a great deal of flexibility in how CBPs and prototype HMIs can be implemented because all the data points are readily available and the control systems can be augmented through simple code changes. However, plants may not have some of these points available in a digital format or may not be able to easily adapt control schemes due to safety, cost,

engineering, and regulatory constraints. Type 3 CBPs have the potential to replace existing control boards and procedures through direct integration with the control system interface itself. In theory, plants could be operated completely from Type 3 procedures. This leads to the questions: is this desirable, is more capability in CBPs always better for operations and situational awareness, and alternatively, should CBPs always be considered as supplemental to existing HMIs, whether analog or digital? Conversely, embedded procedures within the interface are an alternative format in which the procedure functionality is made available through the selection of controllable actions. This is a bottom-up approach in which during diagnosis the operator can visually search through the indication and select items that may be amiss or in an unexpected state with prompting for additional diagnostic or mitigating functions that can be selected by the operator. A top-down or task-based display region is still needed to serve as a dedicated place to track active tasks similar to how procedures are executed in a CBP format.

The constraints of modernization will dictate CBPs as supplemental or hybrid with existing HMIs. However, new plant designs with modern instrumentation and control could support CBP first or CBP only designs. It is arguable that the philosophical concept of operations for existing plants versus new plants could diverge rather than converge.

That said, CBPs do have some potential benefits with place-keeping, logical path following checks, and redundant indications across all deployments. CBPs may also have some unique weaknesses compared to traditional PBPs, such as complacency in following suggested paths or situational tunnel vision into the procedure. Traditional HMIs have the benefit of consistently placing indications and controls and have established interaction paradigms for displaying information and trends. Interaction paradigms with CBPs are not yet well established, and the dynamic structure of CBPs makes the displayed indications inconsistent.

5.1.3 Scalable Task-based Automation Strategy

The overall observation in the procedure development process and HITL scenario testing provides immense insight for CBP development in new and existing plants. Some of the encumbrances encountered in the CBP used for the HITL testing were carryover effects from the existing structure of PBPs from which the CBPs were translated. Developing a CBP for new plants provides the opportunity to start from the ground up by conducting a detailed CBP-based task analysis to understand the underlying task to be performed. The task analysis will employ a structured approach to decomposing complex tasks into manageable procedure steps, starting from the highest level of task analysis, describing subgoals, to the lowest level where a sequence of fine-grained steps can be implemented using CBPs. In some, the enhanced features of CBP could allow for sequences to be automated or simplified.

Additionally, several CBP development and training considerations apply to both new and existing plants. CBPs should be designed to enforce their use as supplementary tools in control room operations and not as substitutes. Specifically, operators should be trained to avoid tunnel vision with CBPs. Operators should be trained to actively seek information from existing HMI and controls and CBPs. They should be capable of operating the plant with or without the aid of CBPs. Such training could aid fault diagnoses where mimic displays or trends are needed to identify complex faults. Also, conventions for handling multiple redundant indicators do not translate to computer-based procedures. With existing analog control systems with multiple channels, the operator is needed to aggregate the redundant indications. With modern digital systems, the control systems can have a voting or median mechanism to create a virtual indication from the redundant channels.

To effectively control an NPP, operators must be familiar with hundreds of controllers scattered across dozens of plant subsystems. Often controllers must function in a coordinated manner with other controllers and depend on the state of other components in the system. Each controller has unique setpoints, process values, and control characteristics that must be understood for effective control. Proceduralizing control system operations in CBP has significant potential to reduce human error, ensuring the correct setpoints are entered to the correct controller in the correct sequence.

5.2 Future Directions

The fidelity supported with these hand calculations is sufficient for a training simulator used to validate the concept of operations, but for more accuracy, a higher fidelity modeling approach using TRACE, RELAP, or CFD models is prudent. Implementing a higher fidelity model to represent frictional pressure drop may allow the training simulator to be used for engineering activities as well as its traditional role as a operational training and validation tool. While calculating the frictional pressure drop by hand is an important part of the design process, a high-fidelity model could serve as validation of the simulator and provide data that could be used to enhance the realism of the simulator.

A formal operational test was not performed since the scope of the activities for this fiscal year was to develop the capability to support concept of operations development for TPD. Future activities can use this simulator capability to further refine the TPD operations established over the last several years of this research project. At this point, there is no pending operator study planned for the next fiscal year; however, related activities, especially those focusing on electric grid integration operations with gigawatt-scale reactors, are planned, and this platform will be suited to support those future activities. The simulator capabilities were developed on GSE's GPWR, which is under export control but is accessible to the public. As such, the simulator models and configuration can be made available upon request with the hope to support industry and university researchers to continue to establish additional use cases and optimize operations for the TPD system.

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Appendix A

Kettle Reboiler Heat Exchanger Analysis

Design Status
Near
(OK)
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Figure 29. Heat exchanger design ratings analysis.

TEMA Sheet

Heat Exchanger Specification Sheet

1	Company:										
2	Location:										
3	Service of Unit:					Our Reference:					
4	Item No.:					Your Reference:					
5	Date:		Rev No.:		Job No.:						
6	Size:		23 / 45.9756 - 192		in		Type:		BKU Horizontal		
7	Surf/unit(eff.)		5192		ft²		Shells/unit		3		
8	Surf/shell(eff.)		1730.7		ft²		Connected in:		3 parallel 1 series		
PERFORMANCE OF ONE UNIT											
9	Fluid allocation					Shell Side			Tube Side		
10	Fluid name										
11	Fluid quantity, Total					lb/h			597248		
12	Vapor (In/Out)					lb/h			0		
13	Liquid					lb/h			597248		
14	Noncondensable					lb/h			0		
15											
16	Temperature (In/Out)					°F			310		
17	Bubble / Dew point					°F			327.71 / 327.24		
18	Density Vapor/Liquid					lb/ft³			/ 53.572		
19	Viscosity					cp			/ 0.174		
20	Molecular wt, Vap								18.02		
21	Molecular wt, NC								18.02		
22	Specific heat					BTU/(lb-F)			/ 1.1471		
23	Thermal conductivity					BTU/(ft-h-F)			/ 0.396		
24	Latent heat					BTU/lb			923.5		
25	Pressure (abs)					psi			98.2		
26	Velocity (Mean/Max)					ft/s			26.56 / 52.85		
27	Pressure drop, allow./calc.					psi			5		
28	Fouling resistance (min)					ft²-h-F/BTU			0		
29	Heat exchanged					564253200			BTU/h		
30	Transfer rate, Service					759.82			Dirty 1773.44		
31	CONSTRUCTION OF ONE SHELL								Sketch		
32						Shell Side			Tube Side		
33	Design/Vacuum/test pressure:g					psi			350 / /		
34	Design temperature / MDMT					°F			420 /		
35	Number passes per shell								1		
36	Corrosion allowance					in			0.125		
37	Connections					In			1 10 / -		
38	Size/Rating					Out			1 0.5 / -		
39	Nominal					Out - Vapor			1 18 / -		
40	Tube #: 325 U's					OD: 0.625			Tks. Average 0.065		
41	Tube type: Plain					Insert:None			Fin#: #/in		
42	Shell Carbon Steel					ID 23			OD 24		
43	Channel or bonnet					Carbon Steel			Shell cover Carbon Steel		
44	Tubesheet-stationary					Carbon Steel			Channel cover -		
45	Floating head cover					-			Tubesheet-floating -		
46	Baffle-cross Carbon Steel					Type Unbaffled			Cut(%d)		
47	Baffle-long -					Seal Type			Spacing: c/c		
48	Supports-tube					U-bend			Inlet		
49	Bypass seal					Tube-tubesheet joint			Expanded only (2 grooves)(UW-20 'i')		
50	Expansion joint					-			Type None		
51	RhoV2-Inlet nozzle					190			Bundle entrance 3		
52	Gaskets - Shell side					Flat Metal Jacket Fibe			Bundle exit 603		
53	Floating head					-			lb/(ft-s²)		
54	Code requirements					ASME Code Sec VIII Div 1			TEMA class R - refinery service		
55	Weight/Shell					14735			Filled with water 28207.6		
56	Remarks								Bundle 4789.5		
57									lb		
58											

Figure 30. Heat exchanger specification sheet.

Setting Plan

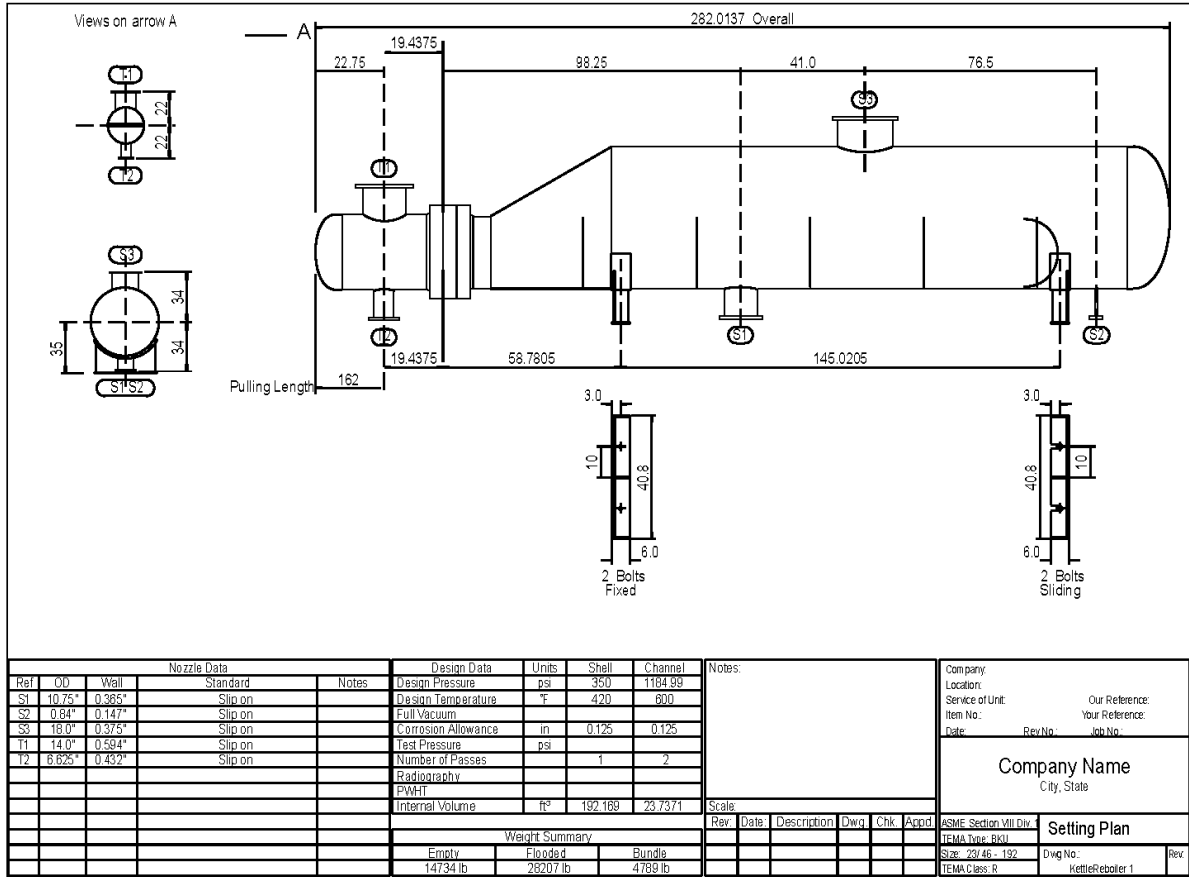


Figure 31. Heat exchanger setting plan.

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Appendix B

Plate and Fin Aspen Analysis

Overall Geometry

Number of exchangers in parallel		2
Number of exchangers per unit		1
Number of layers per exchanger		68
Orientation	Vertical, end A at top	
Core length	in	53.7094
Core width	in	19.3604
Core depth(stack height)	in	21.4842
Number of X-flow passes		0
Number of layer groups		1
Distributor length - end A	in	9.035
Main heat transfer length	in	37.7624
Distributor length - end B	in	6.912
Internal (effective) width	in	18.4549
Side bar width	in	0.4528
Parting sheet thickness	in	0.0591
Cap sheet thickness	in	0.1969
Exchanger metal	Aluminum	
Exchanger weight - empty	lb	2541.8
Exchanger weight - full of water	lb	3614
Exchanger weight - operating	lb	3582.1

Figure 32. Plant and fin overall geometry.

Stream Geometry

		Stream 1	Stream 2
Stream type		Hot	Cold
Flow direction		End A to B(down)	End B to A (up)
Number of layers per exchanger		23	45
Main fin surface area (total)	ft2	2144.8	4702.1
Main primary surface area (total)	ft2		
Main secondary surface area (total)	ft2		
Length - before stream	in	0.4528	0.4528
Length - end A distributor	in	8.5822	8.5822
Length - main fin	in	37.7624	37.7624
Length - end B distributor	in	6.4592	6.4592
Length - after stream	in	0.4528	0.4528
Inlet distributor: Type		Indirect (side)	End (central)
Outlet distributor: Type		End (corner)	Full end
Inlet header location		Right	Central
Outlet header location		Left	Central
Number of layers (redistributed)			
Main fin number		1	2
Main layer internals			
Main fin type		Plain	Serrated (offset)
Main fin height	in	0.252	0.252
Main fin thickness	in	0.02	0.016
Main fin frequency	#/in	18.01	19.99
Hold-up (total)	ft3	5.217	11.958

Figure 33. Steam geometry.

Fin Geometry

	Fin 1	Fin 2	Fin 3	Fin 4
Fin code/bank number	1	2	3	4
Fin used in exchanger	Yes	Yes	Yes	Yes
Layer internals				
Fin type	Plain	Serrated (offset)	Plain	Perforated
Fin height in	0.252	0.252	0.252	0.252
Fin thickness in	0.02	0.016	0.024	0.024
Fin frequency #in	18.01	19.99	14.99	14.99
Fin porosity (fraction)				0.05
Fin serration length in		0.1181		
Subchannel aspect ratio	6.53	6.93	5.34	5.34
Blockage fraction	0.41	0.36	0.42	0.42
Hydraulic diameter in	0.0616	0.0595	0.0719	0.0719
Flow area per unit width in	0.1484	0.1606	0.1459	0.1459
Primary perimeter per unit width	1.28	1.36	1.28	1.28
Secondary perimeter per unit width	8.35	9.43	6.83	6.49
Hydraulic diameter (hardway) in				
Flow area per unit width (hardway) in				

Figure 34. Fin geometry.