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Advancements in Development and Testing of Thermal Power Dispatch Simulators

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Advancements in Development and Testing of Thermal Power Dispatch Simulators

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SUMMARY

Flexible plant operations and generation (FPOG) offer nuclear power plants (NPPs) the chance to leverage alternative, non-electric revenue streams while ensuring their continued role as reliable, clean, and constant sources of baseload electrical power. The excess thermal energy generated from NPPs during periods of low electricity demand can be channeled to industrial processes via a thermal power dispatch (TPD) system. Hydrogen production via high-temperature steam electrolysis (HTSE) is an example use case based on technical and economic feasibility. Work performed at Idaho National Laboratory (INL) previously developed and implemented TPD system models within a GSE Solutions Generic Pressurized Water Reactor (GPWR) simulator to support human operator-in-the-loop (HOIL) scenario-based evaluations.

This report documents ongoing efforts to develop and test TPD operations within commercial full-scope NPP simulators. First, the report describes further modifications that have been made to the GPWR TPD model and human-machine interface (HMI) to align those tools with a new TPD design developed by Sargent and Lundy (S&L). The new modifications include an automatic control system for testing advanced control concepts. This report also contains a description of work performed in collaboration with Westinghouse using their three-loop pressurized water reactor (W3LPWR) simulator, which contains an industrial-grade automatic control system. The W3LPWR simulator was installed in the Human Systems Simulation Laboratory (HSSL) at INL in preparation for future work that will test a new version that will include TPD with automated controls.

Last, this report documents findings from a TPD integration and verification workshop that was conducted in the HSSL in August of 2023. The research team comprised INL human factors and TPD experts, a nuclear engineer from GSE Solutions who implemented the revised TPD model for GPWR, the HMI prototyping and human factors team from the University of Idaho, and personnel with operations experience with pressurized water reactors. The workshop provided time and expertise to conduct the final activities to bring the GSE Solutions simulator and associated HMI into a functional state. The goals of the integration and verification workshop were:

1. Install the revised GPWR TPD model at the HSSL
2. Verify the functionality of the TPD HMI prototype
3. Integrate the updated GPWR simulator with an HTSE Matlab/Simulink model.

The workshop and the corresponding NPP simulator development have laid the groundwork for a full-scope formal evaluation of TPD operations in the spring of 2024 using automated controls in a generic PWR simulator provided by GSE Solutions and a plant-specific three-loop PWR simulator provided by Westinghouse. Those formal simulator evaluations will test integrated operations between NPPs, a hydrogen production facility, and the electric grid with TPD scenarios.

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ACRONYMS

AST	automatic scenario tester
BoP	balance of plant
CLR	Common Language Runtime
CND	condenser
CRADA	Cooperative Research and Development Agreement
DOE	Department of Energy
DSL	delivery steam line
EDR	Exchanger and Design Rating
FPOG	Flexible Plant Operations and Generation
GPWR	generic pressurized water reactor
GSE	Global Simulation & Engineering
HDR	header
HIL	hardware-in-the-loop
HMI	human machine interface
HOIL	human operator-in-the-loop
HSSL	Human Systems Simulation Laboratory
HTSE	high-temperature steam electrolysis
HX	heat exchanger
HYSYS	Hyprotech Systems
IIJA	Infrastructure Investment and Jobs Act
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability
MSH	main steam header
MSR	moisture separator reheaters
NPP	nuclear power plant
NREL	National Renewable Energy Laboratory
P&ID	piping and instrumentation diagram
PEPSE	plant modeling and simulation software
PWR	pressurized water reactor
R&D	Research and development
RCS	reactor coolant system
ROM	Reduced order model
RTDS	Real-Time Digital Simulator

S&L	Sargent & Lundy
SOEC	Solid oxide electrolysis cell
TPD	thermal power dispatch
TPE	thermal power extraction
WPF	Windows presentation foundation
XSL	extraction steam line

ADVANCEMENTS IN DEVELOPMENT AND TESTING OF THERMAL POWER DISPATCH SIMULATORS

1. Flexible Plant Operations and Generation

Nuclear power has long been an important contributor to electricity generation with outstanding levels of reliability and safety. It has the highest capacity factor of any electricity generation source by a margin (Kozeracki et al., 2023) and is the nation's largest producer of carbon-free energy. However, despite this exemplary track record, nuclear power plants (NPPs) in the U.S. are under tremendous economic pressure, which has led to 13 early reactor closures in the last decade (US Department of Energy (DOE), 2020). Several more are in various stages of decommissioning (U.S. NRC, 2023).

These economic pressures are both internal and external. Internal forces include a labor-intensive business model compared to other utilities that can operate with a smaller workforce, and the increasing costs associated with replacing obsolete equipment, much of which was installed when the plants were commissioned several decades ago (Thomas et al. 2020). External forces stem from changing market conditions. Most notably, the introduction of intermittent renewables in recent decades and accompanying shifting market dynamics has threatened baseload, wholesale electricity providers such as nuclear. This is compounded by production processes that favor renewables (Hancock et al., 2023). In addition, some states have moved to deregulated markets making it difficult for NPPs to cover fixed costs. This, coupled with recent historic levels of inflation and Russian fuel supply uncertainties, are all challenges to the industry and a plant's bottom line (Remer et al., 2023). Together, these factors put at risk the continued operation of the remaining NPPs within the domestic reactor fleet.

Despite this, nuclear power's role in the decarbonization of the economy has brought about renewed support for the industry. In pursuit of the U.S. Government's pledge to decarbonize energy by 2035 (White House Briefing Room, 2023), federal incentives and actions are aligning to expand the role of nuclear power as a viable and more flexible contributor to the national clean energy portfolio. These include initiatives, such as nuclear loan guarantees, the Inflation Reduction Act's clean nuclear electrical, steam, and hydrogen incentives, and the Infrastructure Investment and Jobs Act (IIJA). The IIJA directly funds the Civil Nuclear Credit program, which is targeted towards preserving the existing fleet (US DOE, 2023a). Further, $1 billion is allocated for the Clean Hydrogen Electrolysis Program, slated to reduce the cost of hydrogen produced from clean electricity, such as nuclear power. The DOE's Hydrogen Shot initiative, launched in 2021 seeks to reduce the cost of clean hydrogen by 80% by 2031 (US DOE, 2023b).

Researchers at Idaho National Laboratory (INL), under the DOE's Light Water Reactor Sustainability (LWRS) program, are developing ways to support hydrogen production using the existing nuclear fleet. Within the Flexible Plant Operations and Generation (FPOG) pathway, innovations are being tested that allow NPPs to dispatch thermal power in service of a coupled industrial process, such as high-temperature steam electrolysis (HTSE) that produces hydrogen. Existing reactors are optimally poised to deliver both the clean electrical and thermal energy required for HTSE (Figure 1). The flexible operations research and development (R&D) at INL has the twofold advantage of using the abundant thermal energy capabilities of NPPs for clean hydrogen and improving their profit margins by taking advantage of a non-electric revenue stream, all the while continuing to serve as clean baseload generators of electrical power for the grid. Together, this holds promise to shore up the existing fleet by defraying the substantial economic pressures faced by NPPs in today's energy marketplace.

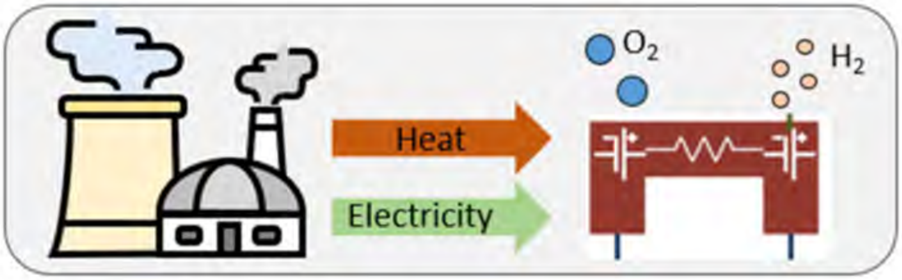


Figure 1. Heat and electricity dispatch from an NPP to a hydrogen production plant

1.1 Graded Simulation-based Research Approach

A graded simulation-based research approach was adopted to develop and demonstrate engineering systems and control concepts to dispatch thermal and electrical power to an industrial user. The graded approach describes the process of beginning with simple, individual conceptual models and incrementally increasing the fidelity of these models as knowledge of the design and implementation matures. Graded also denotes the incremental integration of these models towards the goal of evaluating and demonstrating the TPD concept of operations across a representative suite of simulations. Each simulator iteration provides unique additional capabilities. Altogether, this graded approach spans multiple years from initial conceptual development to human operator-in-the-loop (HOIL) and equipment-in-the-loop testing. These works represent the culmination of R&D in service of a demonstrable and effective strategy to industry. The FPOG pathway research approach is documented in detail in Westover et al., (2022).

This report documents the latest developments in thermal power dispatch (TPD) systems and technologies at INL in support of FPOG objectives. This work focuses on expanding the simulator capabilities at INL by installing a new plant-specific, full-scope training simulator in the Human Systems Simulation Laboratory (HSSL). It comprises modifying and testing a previously installed generic full-scope training simulator used in prior FPOG research. The objective was to verify that the integration of the procedures, models, and human-machine interface (HMI) developed in the last year and documented elsewhere (Hancock et al., 2023), was an effective evolution of prior FPOG works that tested individual pieces of the TPD concept. This verification was achieved by conducting an integration and verification workshop in the HSSL, conducted in partnership with GSE, Westinghouse and Sargent and Lundy (S&L).

The GSE Solutions Generic Pressurized Water Reactor (GPWR) simulator was selected because of its high fidelity, extensive validation, and accessibility to the public. It is a full-scope, glass-top, real-time simulator based on a three-loop Westinghouse PWR. Modifying the GPWR simulator to include TPD operations provides realistic responses to the existing plant systems when evaluating the performance of these designs. GSE is known as an established plant modelling vendor worldwide and assisted with design implementation. However, GSE does not possess expertise in developing new control systems for integrating NPP operations with TPD.

Thus, a cooperative research and development agreement (CRADA) was entered into with Westinghouse Electric Corporation, a vendor with deep experience and capabilities in developing high-fidelity NPP control systems. It should be noted that Westinghouse's simulator is proprietary so that their designs cannot be openly shared with stakeholders. S&L, an architecture and engineering firm, was also engaged to provide support for a graded TPD approach to low-temperature steam industrial applications (Hancock & Westover, 2022).

Together, a multidisciplinary team of scientists and engineers performed an integration and verification workshop in early August 2023 in INL's HSSL. Up until that point, previous TPD iterations had been limited to simulating the nuclear processes with assumptions regarding reception and response to thermal and electrical power by the nearby industrial hydrogen plant. In other words, TPD concept modelling previously assumed an infinite heat sink in which steam for HTSE was received and handled without issue. Ramping the hydrogen plant also changes the amount of electric power that the nuclear plant provides to the grid because the hydrogen plant requires much greater amounts of electric power compared to thermal power input.

The R&D highlighted here coupled these external simulations beyond the nuclear control room to be a more realistic replication of the relationships between the NPP and hydrogen plant. Modeling the integrated operation of the different complex systems made it possible to test communication between the models and their integrated functionality. The goals of the integration and verification workshop were:

1. Install the revised GPWR TPD model at the HSSL
2. Verify the functionality of the TPD HMI prototype
3. Integrate the updated GPWR simulator with an HTSE Matlab/Simulink model.

The workshop provided the opportunity to identify and resolve modeling gaps and glitches, as well as verify the connection of an NPP model coupled to large industrial process models that use a combination of heat and electricity. Here, we document the model integration development and the results of the workshop. This R&D lays the groundwork for a full-scope formal evaluation slated for Spring 2024, in which operator-in-the-loop integrated simulations including an NPP, a hydrogen plant, and the electric grid, will be tested with TPD scenarios.

2. WESTINGHOUSE THREE-LOOP SIMULATOR

The 3-loop pressurized water reactor (PWR) Westinghouse-based simulator represents a high-quality industry-grade control system implementation. This simulator has undergone modifications with the specific goal of incorporating a hydrogen generation plant into an NPP system, facilitated by the implementation of a new instrumentation and controls HMI.

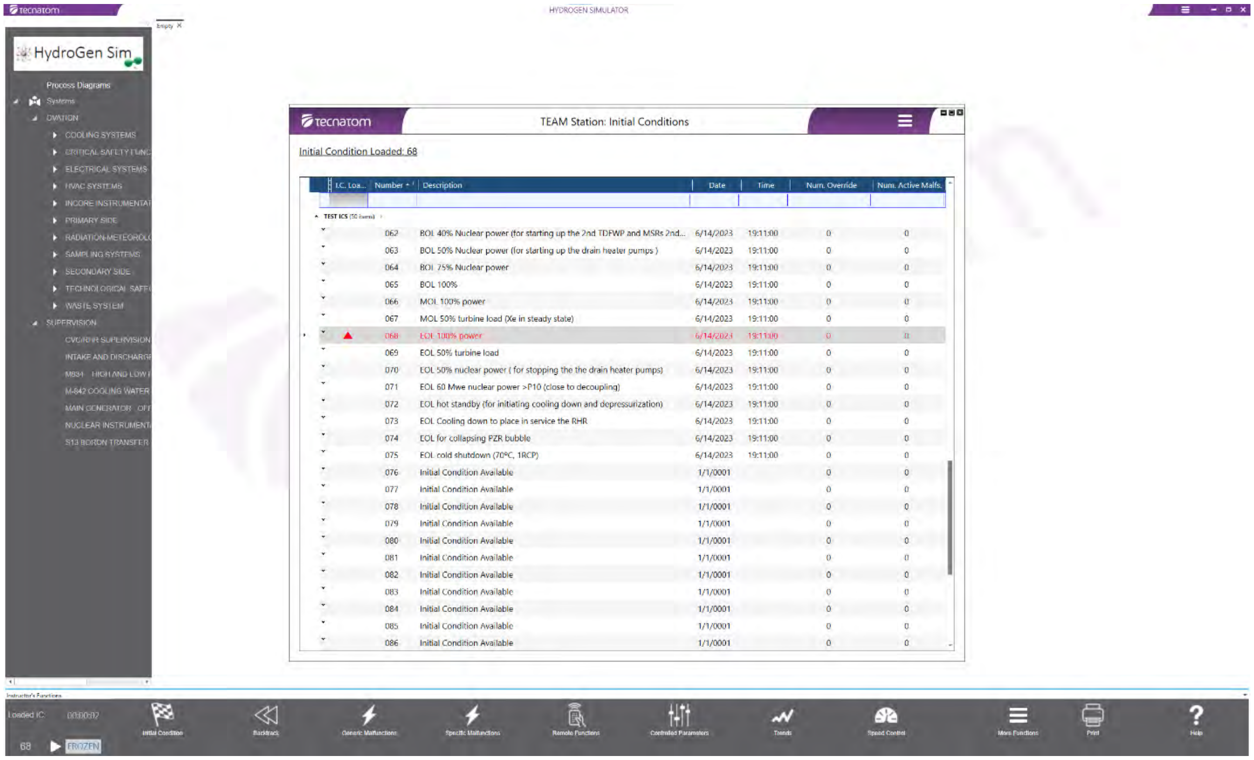
Westinghouse is an established authority in this domain with substantial experience in related non-U.S. district heating designs. As such, Westinghouse is well-positioned to provide a high-fidelity, industrial-grade control system for TPD operations. The reference plant simulator provided by Westinghouse is based on a simulator from an actual unnamed Westinghouse three-loop PWR, so the simulator is referred to as the Westinghouse three-loop simulator (W3LPWR). The W3LPWR is of the same basic Westinghouse three-loop design as the GPWR simulator and therefore serves as an ideal simulator to perform HOIL TPD evaluations.

2.1 Reference Plant

The W3LPWR simulator is a full-scope real-time ANSI/ANS 3.5 simulator that comprehensively emulates all the control room systems encompassing thermal hydraulic, electrical, instrumentation, control, and protection systems. High-fidelity simulation capabilities developed by Tecnatom have been evidenced through various thermohydraulic analyses, and projects such as Angra 1 in Brazil and Atucha 2 in Argentina (Cuadra et al., 2004; Reventos et al., 1993; Lasierra et al., 2017, R. Garcia & Ramos, 2017; Selvatici et al., 2015; Alonso et al., 2011).

Within the W3LPWR simulator, analog controllers on the panels have been replaced by high-resolution, touchscreen monitors to provide interaction with the full-scope simulator. The simulator's model depicts the main systems of the plant, encompassing the reactor, steam generator, and supporting systems, utilizing diagrams with graphical symbols and digital indicators to showcase the process variable values. Furthermore, this simulator enables plant operation in either real-time or accelerated modes, allowing direct interaction with the monitors (Lucas, 1996).

This simulator consists of three primary elements: the instructor station, bays, and Ovation overlays. The instructor station runs as a server and operates within a virtual machine on the HSSL server. It allows for actions, such as running and freezing the simulator, loading the initial plant condition, triggering malfunctions, adjusting the simulator's speed, and recording and replaying event sequences. The same software is installed on each of the bays but is configured as a client on the bay computers. Using the same software for both instructor stations and bays streamlines the need for separate software maintenance. Figure 2 demonstrates how 'SketchViewer' provides the instructor station, soft panel views, and process diagrams used for scenario configuration.



Initial Condition Loaded: 68

TEST ICS (50 items)

I.C. Loa...	Number	Description	Date	Time	Num. Override	Num. Active Malfs.
	062	BOL 40% Nuclear power (for starting up the 2nd TDFWP and MSRs 2nd...	6/14/2023	19:11:00	0	0
	063	BOL 50% Nuclear power (for starting up the drain heater pumps)	6/14/2023	19:11:00	0	0
	064	BOL 75% Nuclear power	6/14/2023	19:11:00	0	0
	065	BOL 100%	6/14/2023	19:11:00	0	0
	066	MOL 100% power	6/14/2023	19:11:00	0	0
	067	MOL 50% turbine load (Xe in steady state)	6/14/2023	19:11:00	0	0
▲	068	EOL 100% power	6/14/2023	19:11:00	0	0
	069	EOL 50% turbine load	6/14/2023	19:11:00	0	0
	070	EOL 50% nuclear power (for stopping the the drain heater pumps)	6/14/2023	19:11:00	0	0
	071	EOL 60 Mwe nuclear power >P10 (close to decoupling)	6/14/2023	19:11:00	0	0
	072	EOL hot standby (for initiating cooling down and depressurization)	6/14/2023	19:11:00	0	0
	073	EOL Cooling down to place in service the RHR	6/14/2023	19:11:00	0	0
	074	EOL for collapsing PZR bubble	6/14/2023	19:11:00	0	0
	075	EOL cold shutdown (70°C, 1RCP)	6/14/2023	19:11:00	0	0
	076	Initial Condition Available	1/1/0001		0	0
	077	Initial Condition Available	1/1/0001		0	0
	078	Initial Condition Available	1/1/0001		0	0
	079	Initial Condition Available	1/1/0001		0	0
	080	Initial Condition Available	1/1/0001		0	0
	081	Initial Condition Available	1/1/0001		0	0
	082	Initial Condition Available	1/1/0001		0	0
	083	Initial Condition Available	1/1/0001		0	0
	084	Initial Condition Available	1/1/0001		0	0
	085	Initial Condition Available	1/1/0001		0	0
	086	Initial Condition Available	1/1/0001		0	0

Loaded IC: 00:00:02

68 FROZEN

Figure 2. Example image of the instructor station monitor

When initiated from the instructor station, the simulator model is accessible to each of the bays. Each bay is configured to display a specific portion of the control panels and can then populate the plant parameters in virtual representations of the analog control panels. The graphics for these virtual control panels represent the reference plant's physical analog control boards and were developed by Tecnatom for Westinghouse using custom simulator software. Bays also support control functionality with virtual representations of the controls. Gesture schemes are provided to interact with the controls using the touch interface capability for each bay display. Figure 3 provides a visual representation of the control of analog instruments. 'SketchViewer' serves as the interface for viewing and interacting with soft panels and all operations can be performed using a touchscreen.

Figure 3. Analog instrument on the bay

Some of the systems from the reference plant use digital control systems developed in Westinghouse's Ovation platform. Tecnatom developed a custom Ovation classroom software as an overlay that can be displayed on each bay. These digital control systems provide more advanced information and control capabilities than are available in traditional analog control panels. The Ovation digital control systems provide the functionality to support distributed process control, manage data, and perform monitoring with specific system interfaces (Westinghouse, 2014). The reference plant has Ovation digital controls for the Reactor Control and Monitoring System (SDCR), Plant Process Computer (SAMO), and Turbine Control System (DEH). The acronyms purposefully do not match the system names for proprietary reasons. Due to the configuration, each instance requires a specific license; for this initial installation it was loaded on four bays only and the system will be accessed as a proof of concept. The next round of updates scheduled for early in the next fiscal year will install licenses on all bays so that it can be accessed from anywhere in the simulator. Figure 4 provides an overview of the navigation menu, encompassing plant information, operation, and control graphics. Figure 5 depicts the Ovation interface for the DEH main control panel.

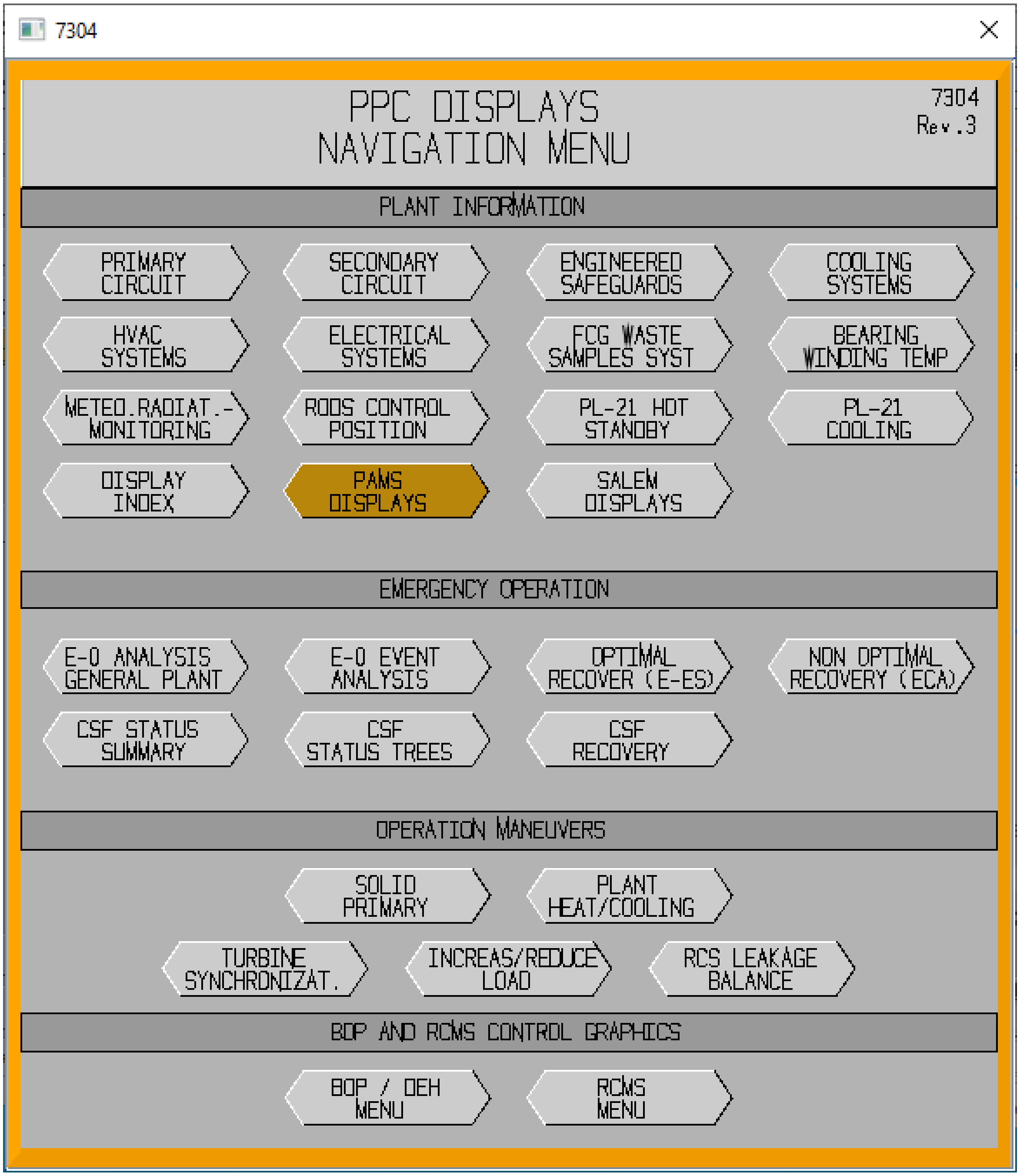


Figure 4. The navigation menu of Ovation

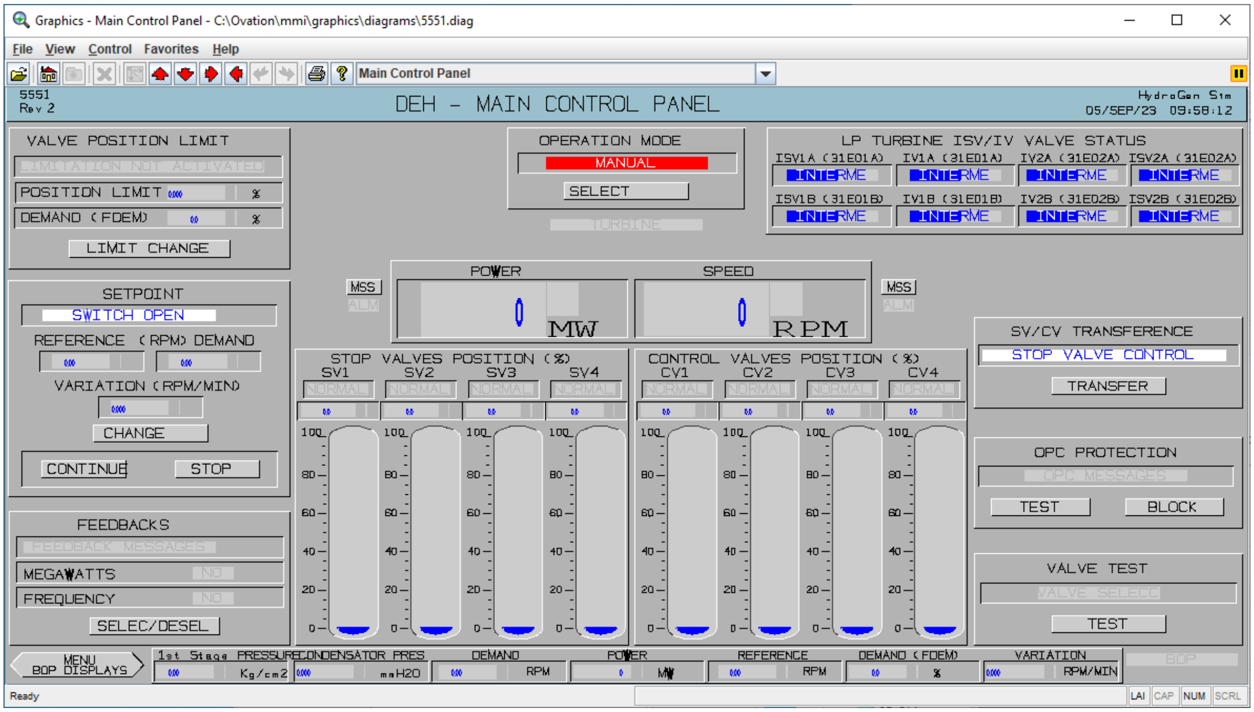


Figure 5. Ovation interface for DEH

Figure 6 shows the configuration of the simulator. This simulator is configured with multiple bays, all interconnected to an instructor station equipped with an intelligent workstation. The instructor station serves the purpose of selecting initial conditions, configuring malfunctions or transient conditions, and executing operations such as freeze and run, along with collecting parameters from the simulator. The panels provide control over all instruments in the control room. The setup of the panels consists of a back row with alarms and indications, as well as a front row containing indications and controls. The panels, labeled as P1 to P5, span horizontally across three bays each. For instance, both M1 and M2 of P1 span a total of three bays.

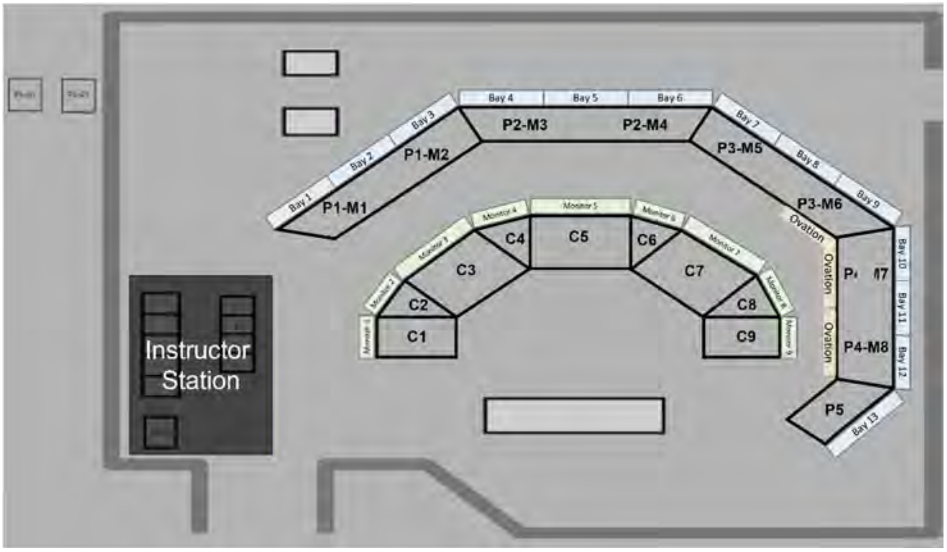


Figure 6. Layout of the simulator

2.2 Installation Workshop

A series of preliminary virtual meetings reviewed deployment options of the W3LPWR and it was deemed compatible with the HSSL three-panel bay approach to represent the virtually emulated analog control boards. One unique W3LPWR simulator characteristic is worth noting as it required additional considerations prior to the installation. The W3LPWR is a standard Westinghouse PWR design; however, the plant model itself is in a non-English language. As such, the simulator labels and procedures are also in a different language. Preliminary activities prior to the workshop evaluated the best approach for using this simulator with English-speaking operators. The most efficient method identified was translating only portions of the control boards relevant to the TPD systems; however, this resulted in a mixed language suite of displays that could lead to significant operator confusion. Furthermore, some of the procedures for the simulator needed to be translated into English. It was ultimately deemed prudent to translate as much of each control panel as possible within the project timeline. Relevant procedures were also translated, and ongoing efforts are pursing further translations. The translation approach is targeted such that the most relevant control panels have been translated to ensure at least part-task simulation can be performed to support the HOIL testing planned for the next fiscal year.

A workshop was then held to support the Westinghouse simulator installation at INL’s HSSL. One Westinghouse and two Tecnatom simulation experts joined the INL human factors and simulation team for a three-day workshop to install, configure, and then train and verify the simulator.

The installation of the simulator included installing a server instance of the TeamK software on a virtual machine hosted on the HSSL server, and client instances on each of the three-panel bay window machines. Most of the installation focused on two types of configuration activities. A large portion of the installation time was dedicated to license configuration and communication troubleshooting between the client instances on each of the bays and the server instance on the virtual machine. The graphical layout configuration also required significant time. The HSSL is a reconfigurable simulator with different dimensions than those of the native W3LPWR simulator. The graphic layout development process is described in detail in the next section.

2.2.1 Graphical Layout

This simulator has three displays vertically arranged within a single bay, Figure 7 through Figure 9 show example graphical arrangements for individual displays in a single bay. The uppermost display is equipped with an alarm indicator, as visually depicted in Figure 7. The center and bottom displays consist of a majority of switches that are operational, as illustrated in Figure 8 and Figure 9. Additionally, it is noteworthy to observe that the physical analog instruments and indicators have been replicated on the displays.

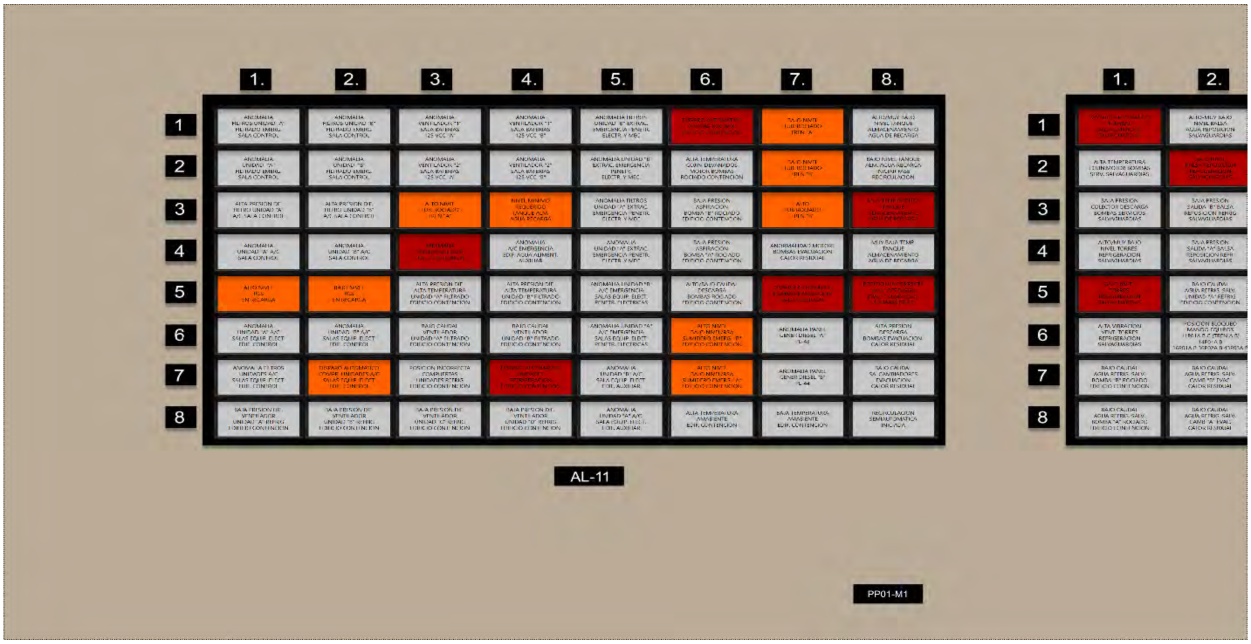


Figure 7. Configuration on the top display of a specific bay

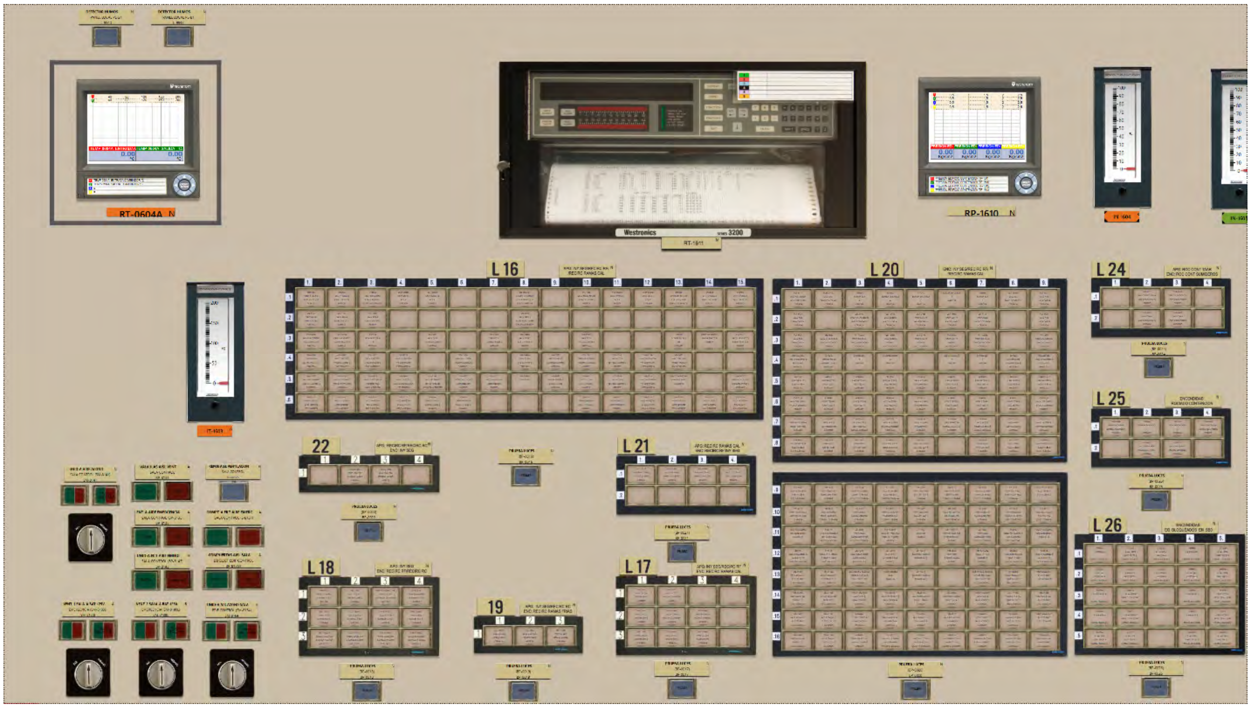


Figure 8. Configuration on the center display of the same bay featured in Figure 9.

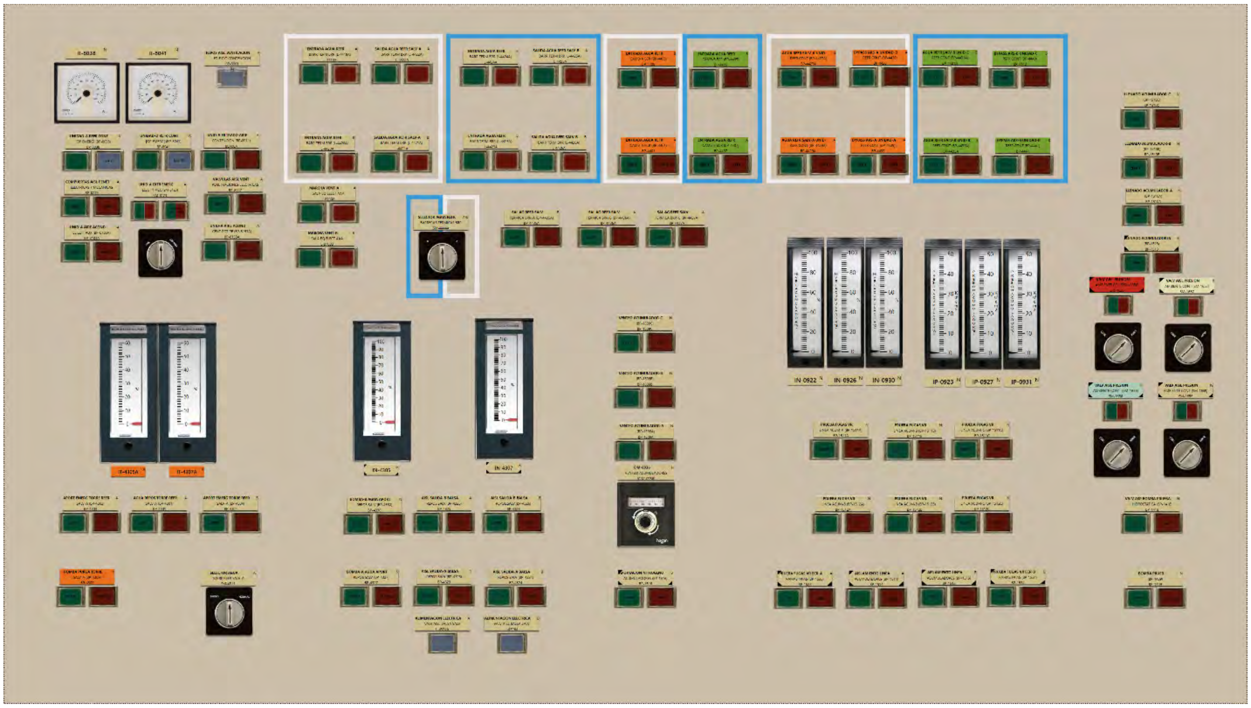


Figure 9. Configuration on the bottom display of the same bay featured in Figure 8.

2.2.2 Training and Verification

Tecnatom provided training for using the dedicated instructor workstation while remotely operating the virtual machine with the TeamK software to configure the simulator for a scenario, which includes loading an initial condition, inserting malfunctions, and logging process parameters. Verification activities were then performed to test the simulator functionality after it was installed. This evaluation encompassed the panel, console, and operating station, taking into consideration factors such as their dimensions, configurations, colors, and compositions. Moreover, it entailed an assessment of dynamic functionalities and ensured alignment with the simulator's control room environment. The assessment yielded several issues. None could be immediately resolved, and all will be addressed in the continued collaboration through the next fiscal year.

The first issue pertained to the HSSL configuration and required that adjustments be made in terms of display positioning across glass tops to prevent splits across bezels. Also, double monitor displays are needed for the front control panels, so new monitors, monitor mounts, and computers will be acquired. This front row essentially comprises chest-height panels for control, and the bays on the monitor will provide additional information and alarm panels. Furthermore, it will be essential to review operational procedures to ensure alignment and functionality.

Tecnatom will implement the HMI and Display built-in ‘TeamSketch’ and TPD models. HMI models developed based on the Westinghouse control system will be designed in ‘TeamSuite’ by Tecnatom. Procedures need to be translated and generalized to English while maintaining the procedure structure. Logging, including session recording, will require the configuration of the path to record a set of parameters to populate the dictionary.

Moreover, a method to interface and support integrated operations and potential INL HMI prototype testing is required. Since there is only a user license, a developer license is also necessary, including 'SketchViewer' and Ovation. In the short term, Tecnatom will support these changes, but a more agile approach is needed to facilitate custom testing methods so that changes can be made real-time during testing, as needed. It is important to note that these changes are limited to the interface with plant models and parameters and manipulate visuals and will not involve the underlaying thermohydraulic models. Lastly, verification scenarios will be carried out with operator support.

3. GSE SOLUTIONS GPWR SIMULATOR

The GSE Solutions GPWR simulator is a publicly available full-scope real-time ANSI/ANS 3.5 simulator. GPWR is also based on a 3-loop Westinghouse PWR plant design.

3.1 Modified Thermal Power Dispatch Model

TPD modifications were made to the simulator prior to the workshop by a GSE Solutions developer. The modifications were extensive and are documented in detail elsewhere (Ulrich, Hancock, Westover, Jurski, 2023). Briefly for context, the modifications included updating the steam extraction location at the cross under piping after the high-pressure turbine to match a design provided by S&L. Component sizes were adjusted to reflect the change to a lower 3% thermal power extraction. A second train was also added for improved process robustness. The thermodynamics of the models were evaluated to obtain comparative process values between the original TPD design and the newer S&L design. Details of the HMI targeted modifications pertinent to the workshop verification activities are described below. These modifications support displaying model variables on the TPD HMI and also support simulator configuration through the instructor station to construct scenarios with different initial states and malfunctions.

3.1.1 Initial Conditions

Simulator initial conditions were developed to support planned HOIL scenario testing. The initial conditions define the starting values of variables for both the main NPP and TPD models. The collection of initial conditions was developed to support the types of evolutions HOIL expected for TPD operations. Each initial condition used the same main plant model's initial condition with a middle-of-life core and reactor power at 100%.

Table 1. Initial conditions developed prior to the workshop in preparation for HOIL testing.

IC Number	Train A State	Train B State
191	Cold Shutdown	Cold Shutdown
192	Hot Standby	Hot Standby
193	Online	Hot Standby
194	Online	Online
195	Hot Standby	Online

3.1.2 Malfunctions

Process variables representing components within the TPD model require additional supporting variables to enable malfunction functionality to a subset of these components. These supporting variables provide configuration and dynamic manipulation functionality from the instructor station during a simulation run. Implementing malfunctions can quickly become complex with time or event-based triggering. As this effort is the initial development and testing of this system, a parsimonious approach was adopted in which each specific selected malfunction was manually activated and deactivated. The malfunctions could be binary, such as for pump trips or they could be setpoints along the operating range of the component's process parameter. For the workshop, testing of the malfunctions was limited to ensuring an appropriate process variable associated with each malfunctioning component was included in the model. Malfunctions were implemented with binary toggles and hardcoded severity values, as binary or continuous variables, in the simulator build code. Table 2 summarizes the malfunctions that were evaluated and refined in the workshop. Section 4.2.1 describes the issues and corrections identified as well as additional malfunctions that were added to the model to support the HOIL testing planned for the next fiscal year.

Table 2. Malfunctions developed in the TPD models for Trains A and B.

Number	Description	Process Variables
1a	Steam line break in turbine building	tpemf1a_vp
1b	Steam line break in turbine building	tpemf1b_vp
2	Steam line break in transport from turbine building to protected area	tpemf2_vp
3a	Steam line break in protected area	tpemf3a_vp
3b	Steam line break in protected area	tpemf3b_vp
4a	HX leaks in reboilers and drain coolers	tpemf4a_vp, tpemf4b_vp
4b	HX leaks in reboilers and drain coolers	tpemf5a_vp, tpemf5b_vp

3.1.3 Alarms

A total of 33 alarms were implemented with the TPD model (Table 3). These alarms are linked to corresponding process variables within the model; however, hierarchical logic was used to combine more complicated alarm signals from multiple combinations of process parameters. Other alarms were not implemented because the dynamics were not yet understood before the completion of the scenario walkthroughs during the workshop. Section 4.2.2 describes the outcomes of the workshop in terms of directing the approach to finalize the alarm implementation.

Table 3. Thirty-three alarms for the TPD.

xslmismatch1_alarm	xslmismatch2_alarm	steam1high_alarm
steam2high_alarm	steam1low_alarm	steam2low_alarm
drain1low_alarm	drain2low_alarm	drain1high_alarm
drain2high_alarm	drain1highhigh_alarm	drain2highhigh_alarm
tpe1pmp1a_alarm	tpe1pmp1b_alarm	kettle1high_alarm
kettle2high_alarm	kettle1low_alarm	kettle2low_alarm
demin1lowlow_alarm	demin2lowlow_alarm	demin1low_alarm
demin2low_alarm	demin1high_alarm	demin2high_alarm
xsltrip_alarm	xsl1trip_alarm	xsl2trip_alarm
dsltrip_alarm	dsl1trip_alarm	dsl2trip_alarm
htsetrip_alarm	htse1trip_alarm	htse2trip_alarm

3.2 Human-Machine Interface

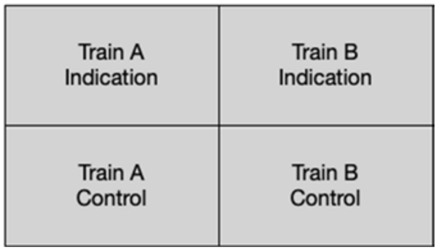
3.2.1 Human-Machine Interface Development

A revised HMI was developed based on the new S&L design. The design with two TPD trains required additional human factors considerations to include mode confusion for controlling each train and minimizing operator error while streamlining the process to ensure the 10-minute target time limit was feasible for the transition between Hot Standby and online modes. The HMI design process used a variety of design tools for development. Prototyping tools for diagramming like the online tool *Diagramsnet*, and wireframing with *Figma*, were used in the schematic design phase. Production software requiring a.NET framework was furnished by the Microsoft Visual Studio integrated development environment. The prototype HMI used for the workshop was built also using the.NET framework with a windows presentation foundation (WPF) for the graphical display.

3.2.2 System Elements

The TPD HMI provides operators with a dedicated instrument and control cluster for operating TPD components and was designed to simplify the monitoring and operation of the TPD. The types of operations include system startup, online and Hot Standby mode monitoring, Online to Hot Standby transitions, shutdown, maintenance, and incident response.

The HMI display consists of indication and control display regions for both TPD trains. The TPD primarily involves longer periods of monitoring with some infrequent control actuation during system transitions twice a day. As such, displays must be persistently visible and easy to read to assist with operator situation awareness during the primary monitoring activity (see Figure 10). The indication section contains a piping and instrumentation diagram (P&ID) for each train in the TPD system. In addition, train status indicators and alarm annunciators must be easily associated with each train and be collocated within the same display region. The control display must provide a consistent arrangement of buttons and user-editable text fields for controlling five different critical valves within the TPD system. A faceplate control template provides a common organization of the control elements in consistent arrangements across these five critical valves.



Train A Indication	Train B Indication
Train A Control	Train B Control

Figure 10. Basic four quadrant arrangement to support indication and control display regions for both TPD trains.

3.2.2.1 Whole System

Exploring different configurations between these options necessitated subsystem spatial arrangements to ensure sufficient display space for ecological continuity within the associated systems. Figure 11 shows an early multi-screen layout compared with a single-screen arrangement. Since the train controls are identical, both explorations planned for an assignable control area that aimed to eliminate duplicitous features by unifying with a train selection switch. A full-featured layout concept is shown in Figure 12.

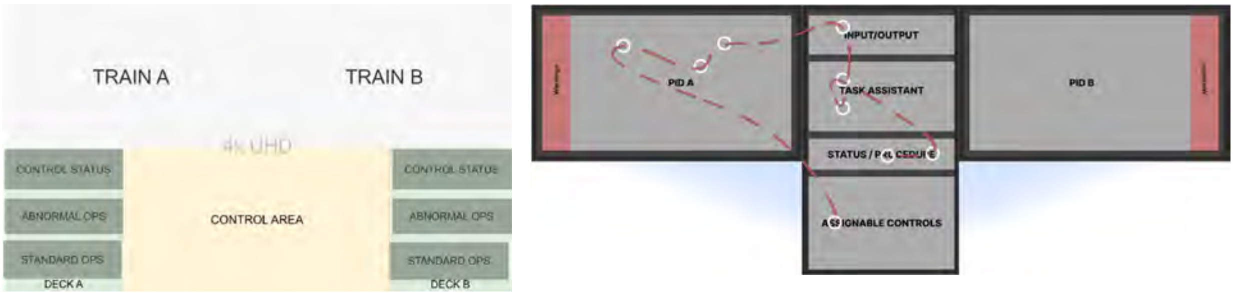


Figure 11. Single (left) and multiple dedicated Train (right) display HMI Concept Mock-ups

Figure 12. Initial single display concept, full color control layout

3.2.2.2 HMI Design Selected for Workshop Evaluation

The HMI layout was intended to be displayed on a single 4k ultra high definition (UHD) screen. The layout positions Train A and Train B P&ID display side-by-side in the top half of the screen and matching control sections in the lower half. This specification provides each P&ID and each control with a full HD screen for legible font and graphic clarity. For font legibility, the HMI uses a minimum font size of 12 pt, determined by examining the sub-tended angle of text on a 32” 16:9 4k screen at a viewing distance of 30”. This size provides character size height >15 minutes of arc as required by NUREG 0700.

3.2.2.3 Whole System

The final selected HMI layout is intended to be displayed on single 4k UHD screens. The layout positions Train A and Train B P&ID displays side-by-side in the top half of the screen, and a matching control section in the lower half. This specification provides each overview and control display the equivalent of a full HD screen sufficient for legible font and graphical clarity. [*fig final UI layout]*

For font legibility, the HMI uses a minimum font size of 12 pt. This font size minimum was determined by examining the sub-tended angle of text on a 32” 16:9 4k screen at a viewing distance of 30”. This size provides character size height >15 minutes of arc as required by NUREG 0700.

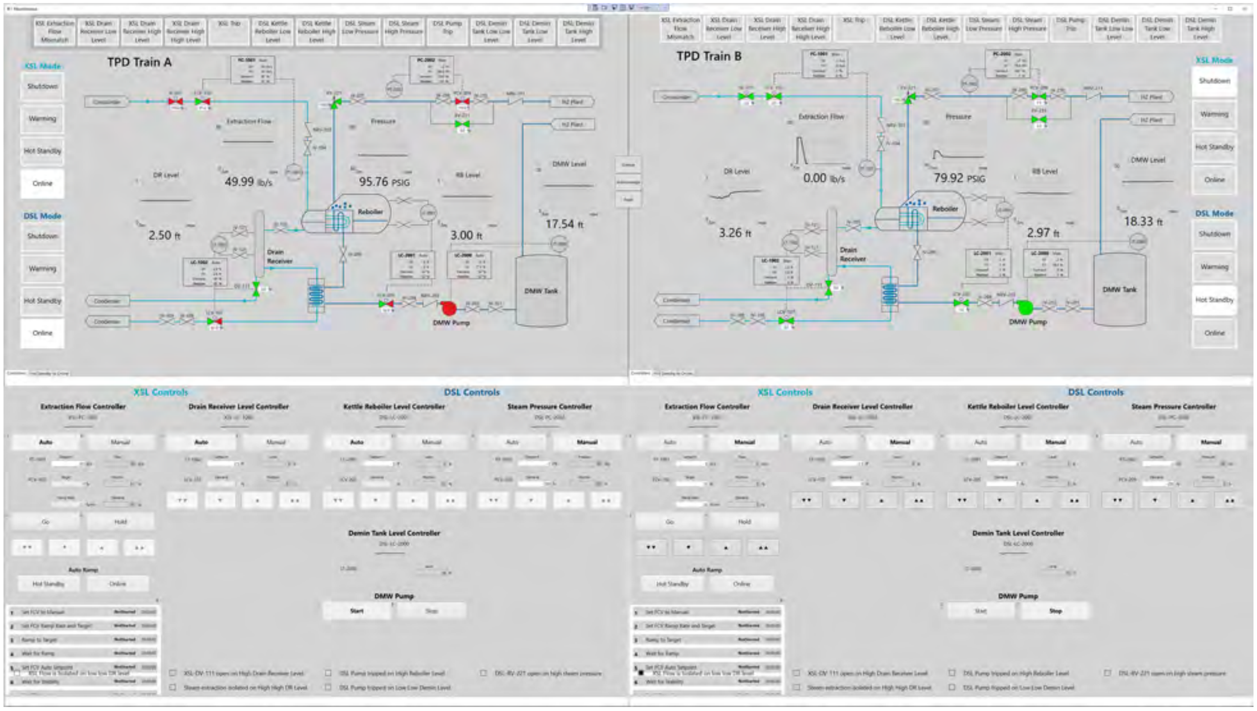


Figure 13. TPD HMI design used in the workshop.

3.2.2.4 P&ID

There is an overview display for each train as shown in figures 14 and Figure 15. Each overview display contains a dedicated P&ID for dedicated train monitoring, arranged from left to right in the top half of the screen. Each has an instantiation of the horizontal alarm annunciator bank at the top of the window, and the vertical train status indicators on the flanking external edges. Additionally, a single-operator alarm control group is situated in the center of the screen.

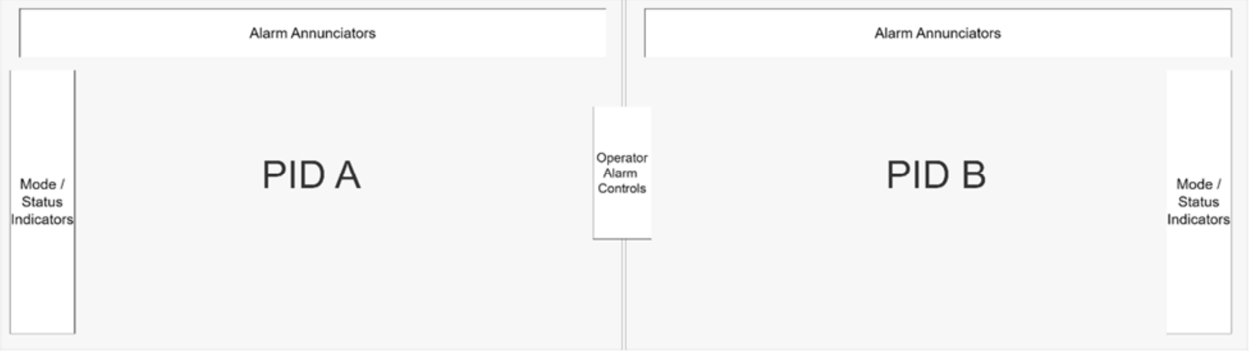


Figure 15. Mode Status, Alarm Annunciator, and common Alarm Controls locations in relation to the Indication P&ID display regions

Compared to the 2021 design (shown in Figure 16), the 2023 revision focuses on improving legibility in the overview display and refining the alarm and status sections. To reduce redundancy and save on-screen space, the key parameters formerly listed at the top of the display are integrated into the P&ID with callouts. The revised overview also has micro-trend displays with a 5-minute timebase and dedicated y-range for five process variables controlled by the controllers in the TPD system (Figure 17).

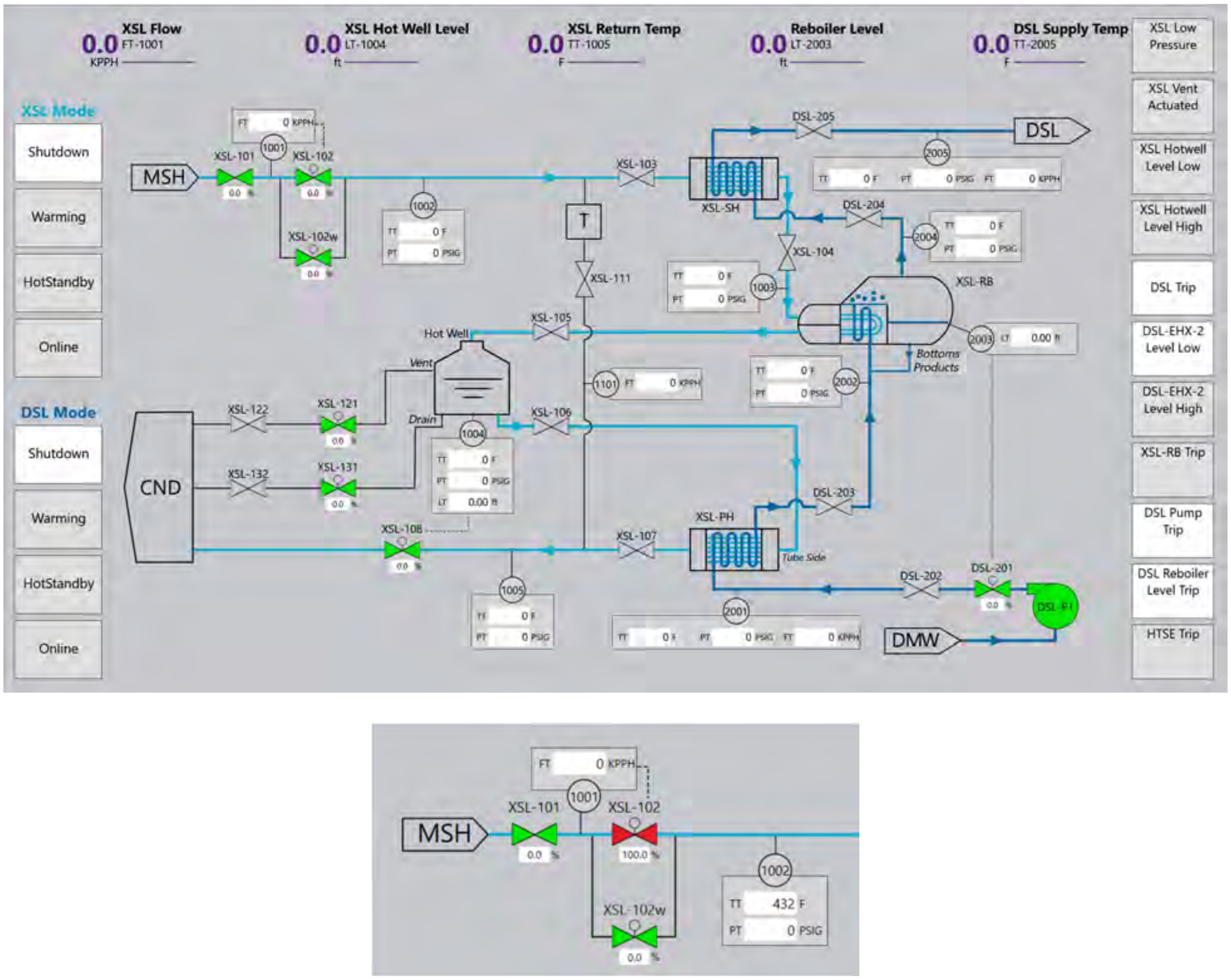


Figure 16. HMI of the original TPD system developed and tested in 2021 (top) and an expanded view of the iconography used to represent key parameters within the P&ID (bottom). These styles were carried through to the new design evaluated at the workshop.

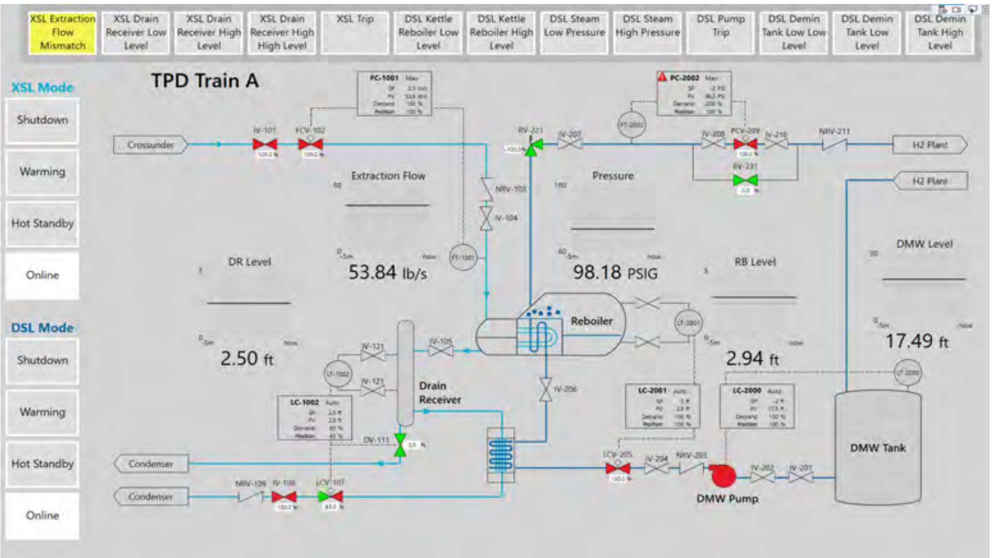


Figure 17. The current design P&ID region of the HMI depicts the same basic styles featured in the original 2021 design.

3.2.2.5 *Control Panel*

The TPD's primary function is to transfer thermal energy from the plant to an external process. The XSL and DSL systems isolate secondary steam from the superheated demineralized steam delivered offsite. Process control is primarily conducted with scheduled procedures scripted and tested for efficiency and safety, with considerations for execution time. Engineering prerogatives dictate which processes require a human-controller interaction. The control panels are in the bottom half of the screen, and each is ecologically matched to its accompanying overview above it. The control panel groups controllers for the XSL and DSL loops. The five controller faceplates and one DSL pump control are listed below:

1. Extraction Flow Controller (XSL)
2. Drain Receiver Level Controller (XSL)
3. Kettle Reboiler Level Controller (DSL)
4. Steam Pressure Controller (DSL)
5. Demin Tank Level Controller (DSL)
6. DMW Pump control (DSL)

Each controller uses the same basic faceplate template modified to accommodate additional or reduced functionality as necessary. For example, the pump controller also uses a simplified version of the faceplate. Specifically, the XSL has one main controller, XSL-FC-1001 as can be seen below in Figure 18, with additional functionality to support automatic ramping of the TPD between Hot Standby and online and vice versa. XSL-FC-1001 uses an operator-entered ramp rate and target valve percentage setpoint for the transition between Hot Standby and online TPD modes. Once a steady system state is achieved with the transition, the controller switches to an automatic flowrate setpoint mode. Interlocks specific to each controller are located along the bottom portion under their corresponding controllers.

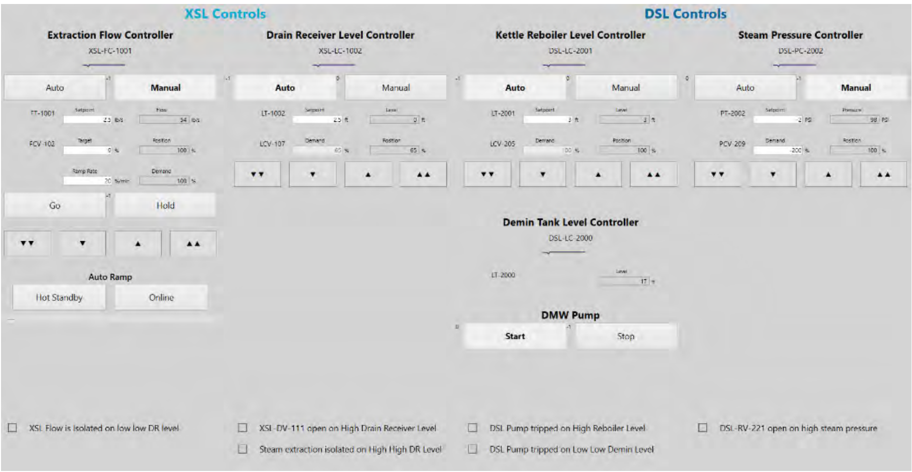


Figure 18. Control panel display evaluated in the workshop.

3.2.2.6 Faceplate Controller Displays

The controller displays (faceplates) use a standard collection of control widgets. The controller tags use an engineering-designated nomenclature that describes the loop, the type of system valve, and a numerical marker meant to place the valve in a flow sequence. There are three types of valves in the operators' control panels:

- Flow control (FC)
- Level control (LC)
- Pressure control (PC)

Components in the XSL and DSL systems are denoted numbers the 1000s and 2000s, respectively. Valve and line numbering indicates the sequential order of component placement beginning at the start of the stream flow. Before developing the final control interface in Visual Studio, faceplate styles were explored using Figma (Figure 19).

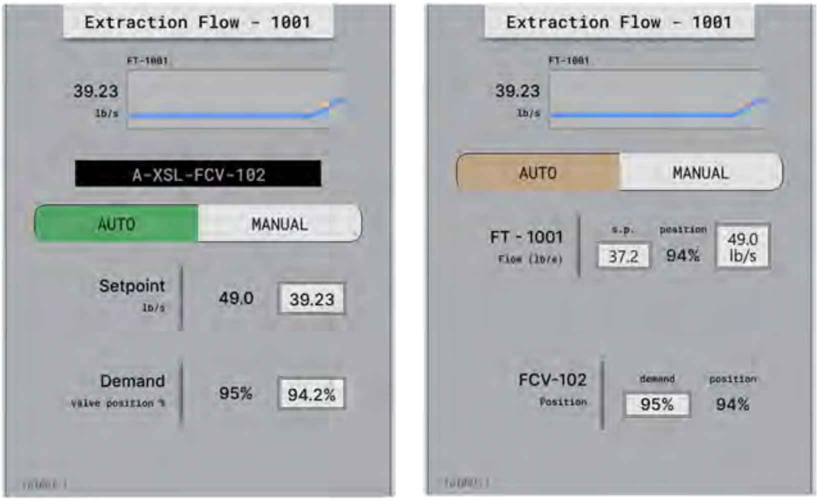
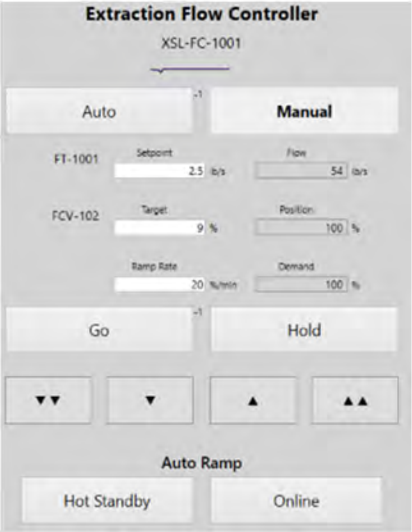


Figure 19. Conceptual faceplate designs.

After evaluating different conceptual designs, a prototype WPF was developed for the HMI. An example of a faceplate is shown in Figure 20 for controller XSL-FC-1001, which is an XLS flow-control valve and is marked as the first one in the flow stream.



Extraction Flow Controller

XSL-FC-1001

FT-1001 Setpoint 2.5 lb/s Flow 54 lb/s

FCV-102 Target 9 % Position 100 %

Ramp Rate 20 %/min Demand 100 %

Figure 20. XSL-FC-1001 example faceplate used in the WPF prototype HMI in the workshop.

3.2.2.7 Control Widget Types

The simulator control system roughly approximates a distributed control system with boolean, floating point and integer datatypes. The HMI reads these points and displays them for operators. Operator actions modify plant points. The toggle buttons like Auto and Hold invert the state of boolean points in the simulator. The text entry fields set floating point values. Up and down cursor arrow buttons provide raising and lowing actions in a press-and-hold manner. When in automatic mode, the buttons affect the setpoint, and in manual mode, the buttons affect the demand value. The buttons set a simulator point to true when pressed and set it back to false when unpressed. When the value is true the setpoint or demand moves at a constant rate. The buttons with a single arrow have a “slow” rate and the buttons with two arrows have a “fast” rate. The HMI has two classes of controllers: internal switches and [simulator] control signal controls. Internal switches may change the visible states of the HMI or toggle the availability of other controls—front-end only controls. Simulator message controls are those that send control signals to the simulator back-end.

Control signal controllers are of two main types: pushbutton and set-fields. Each push-button control connects to a specific control point in the simulator back-end, sending either a digital high or low message. Set-field controllers additionally send a parameter value from within a legally specified range.

3.2.3 Operations and Procedures Development

The initial stages of procedure development focused on two operating scenarios to transition the TPD system from Hot Standby to Online and from Online to Hot Standby. Simply put, Hot Standby to Online refers to increasing extraction steam from its Hot Standby rate of 2.5 lb/s to its online rate of 50 lb/s, while Online to Hot Standby refers to returning extraction steam flow to its standby rate of 2.5 lb/s. The TPD extraction flow controller transitions may be performed manually or automatically using the Manual Ramp or Auto Ramp feature of the extraction flow controller. When operated manually, the operator executes a series of manual control action steps to place the extraction flow controller in the desired setting. The series of target valve positions and hold times are set according to tables in the procedure. A program executes the valve positions and holds times after the operator presses a “Go” button. When the target is reached, the operator waits for two minutes for the system to stabilize before placing the controller back in Auto mode with the appropriate setpoint.

Changing the TPD extraction setpoint can also be done using an Auto Ramp feature for the flow controller, in which the controller automatically sets the correct valve target position and ramp rate, places the controller in manual, moves the valve to the target position, holds for two minutes and then places the controller in Auto with the appropriate setpoint. The combination of operating scenarios and transition modes resulted in four Operating conditions (Table 4): Hot Standby to Online (Manual transition), Hot Standby to Online (Auto Ramp transition), Online to Hot Standby (Manual transition), and Online to Hot Standby (Auto ramp transition).

Table 4. TPD operating scenarios, transition modes, and operating conditions

Operating Scenario	Transition Mode	Operating Condition
Hot Standby à Online	Manual	Hot Standby à Online (Manual transition)
	Auto Ramp	Hot Standby à Online (Auto Ramp transition)
Online à Hot Standby	Manual	Online à Hot Standby (Manual transition)
	Auto Ramp	Online à Hot Standby (Auto Ramp transition)

3.2.3.1 Procedure Development and Determination of Setpoint Values for Dual-Train Operation

Mock procedures for operating the TPD system were initially developed using dual trains (Trains A and B) operation. The dual-train operation approach ensured that both trains were operated simultaneously at every point in time but not necessarily in the same operating mode. In dual-train operation, there are three possible train statuses per time (Table 5): one train in Hot Standby and the other Online, both trains Online, and both trains in Hot Standby.

Table 5. Dual-train statuses and corresponding operating scenario options

Train Status (Dual)	**Operating Scenario Options**
1 in Hot Standby/ 1 Online	Hot Standby à Online
	Online à Hot Standby
2 in Hot Standby	Hot Standby à Online
2 Online	Online à Hot Standby

The mock procedures were adapted from those used in the GPWR static simulation with some modifications, given the reduced complexity of the TPD design. The TPD-adjusted procedure consists of four sections: prerequisites, precautions and limitations, initial conditions, and procedure. Prerequisites specify systems that must be aligned correctly before the operator can initiate the intended procedure. Three major systems were included: main steam, turbine, and condensate systems. Precautions and limitations represent the operating limits and boundaries that the operator must read and understand before executing the procedure. Initial conditions outline values and indicators confirming the TPD system is in the required starting condition for the intended procedure. The procedure section lays out, stepwise, the actions to be performed by the operator.

The GSE Solutions Automatic Scenario Tester (ASC) was used to identify setpoints for the TPD operating scenarios. The functions that allow operators to control the TPD according to the procedure were programmed into the TPD system (Hancock et al., 2023). The procedures for different operating scenarios were named thus: OP-TPD-002 represents the procedure for Hot Standby to Online (Manual and Auto Ramp Transitions); OP-TPD-003 represents the procedure for Online to Hot Standby (Manual and Auto Ramp Transitions).

3.2.3.2 Determination of Setpoint Values for Single-Train Operation

The TPD system has the possibility of operating with a single-train or both trains. When not shutdown, the trains are designed to run at either their standby rate of 2.5 lb/s or their online rate of 50 lb/s, but not intended to run steadily at flows in-between these two values. Single-train operation implies one train in Hot Standby/Online and the other train Shutdown. Single-train operation increased the total number of train statuses from 3 to 5 (Table 6). Due to this new development, the need to test single-train operations to determine corresponding setpoint values became pertinent. The two TPD operating scenarios were tested using single-train operation, and values at which system stability was attained were identified. Then, the initial mock procedures were updated using setpoint values for essential system parameters identified in the single-train operation. A comparison of setpoint values in the dual-train and single-train operations shows some degrees of variation (Table 7).

Table 6. Dual/single-train status and corresponding operating scenario options

Train Status	Train Combination (Dual/Single)	Operating Scenario Options
1 in Hot Standby/ 1 Online	Dual	Hot StandbyàOnline
		OnlineàHot Standby
1 in Hot Standby	Dual	Hot StandbyàOnline
2 Online	Dual	OnlineàHot Standby
1 Hot Standby/ 1 Shutdown	Single	Hot StandbyàOnline
1 Online/1 Shutdown	Single	OnlineàHot Standby

Table 7. Setpoint comparison between dual- and single-train operations

Operating Scenario	Train Status	Train Comb.	Turbine Power	Target Valve Position
Hot StandbyàOnline	1 in Hot Standby/ 1 Shutdown	Single	TBD	55%
	1 in Hot Standby/ 1 Online	Dual	951MW	69%
	2 in Hot Standby	Dual	962MW	61%
OnlineàHot Standby	1 in Hot Standby/ 1 Shutdown	Single	TBD	7%

	1 in Hot Standby/ 1 Online	Dual	951MW	10%
	2 Online	Dual	941MW	9%

4. Integration and Verification Workshop

The simulator integration workshop was conducted in early August 2023 over the course of one week in INL’s HSSL with key personnel. This included the nuclear engineer from GSE Solutions that implemented the revised TPD model for GPWR, the HMI prototyping team from University of Idaho, and personnel with operations experience with pressurized water reactors.

Preparation activities for the workshop consisted of drafting procedures, implementing the HMI, and developing and testing the simulator model. The workshop provided time and expertise to conduct the final activities to bring the operations, HMI and simulator together into a functional state.

The workshop format consisted of short iterative cycles to review the status of integration tasks and identify items that still needed attention. Outstanding items were addressed as quickly as possible. However, items that could not be immediately resolved were noted for post-workshop activities. The iterative cycle concluded with an operational walkthrough with all available workshop participants.

4.1 Synopsis of Activities

The first day of the workshop (Monday) consisted of installing the HMI in the HSSL, connecting it to the GPWR simulator, and sorting out simulator points so that the HMI would correctly display the TPD state. Operational efforts included identifying a schema for alarm color coding (white, yellow, red) and categorizing the alarms.

On the morning of the second day (Tuesday), the team focused on implementing the Auto Ramp functionality for transitioning between Hot Standby to Online and from Online to Hot Standby. This included implementing the HMI control panel and controller logic in the GPWR TPD model.

Tuesday operations and HMI activities implemented an auditory annunciator to the TPD alarm panel and an alarm control panel for silencing, acknowledging, and resetting the alarms. Modifications were made to the simulator model to support the resetting of alarms. The team also attempted to implement synchronized flashing alarms, but the task was more challenging than expected and was not completed until after the workshop.

On Wednesday morning the GPWR was integrated with the Simulink HTSE model through GSE’s SimAPI 1.0 WebAPI and a Python Tornado bridge application between GPWR and Simulink. The remainder of Wednesday was used to write the Python client functions for the SimAPI, create a Simulink TCP socket client, creating a Python Tornado server, and identify the parameters to pass from GPWR and the HTSE model.

Wednesday afternoon’s activities consisted primarily of verification and validation of the TPD controls and HMI. These efforts included determining the mode of the XSL and DSL systems, creating new initial conditions for the factorial combinations of having the TPD trains in their various modes of operation, and operator walkthrough to transition the TPD from Online to Hot Standby and from Hot Standby to Online while operating the extraction flow controller in manual and in Auto Ramp/Manual.

4.2 GPWR TPD Model

4.2.1 Malfunctions

During the workshop, the selected malfunctions were evaluated in abnormal scenario walkthroughs. Corrections were made to the malfunctions for MF1, MF2, and MF3. In each case, the admittance value was increased to support greater leaks. After walking through the scenarios for each of these malfunctions, additional functionality for the alarms and trip conditions were identified. In all three cases, each train should respond with an XSL and DSL trip. More specifically, these malfunctions manifest with the reactor power holding constant during a component failure. The Turbine Control System interprets opening of the turbine valve controller as increased incoming steam flow, which would eventually lead to a condenser caused turbine trip due to a low hotwell level in the TPD system. It is unknown how long this would take since the full span of the scenario could span hours and is better suited for basic simulation without the HOIL aspects. Evidence of this occurring should be proceduralized through checking for a flow mismatch alarm on the train and a decrease in generator power output as identified by the scenario walkthroughs.

All malfunctions were added in the same hardcoded manner as the original seven to rapidly allow the team to evaluate their impacts. These malfunctions will be further refined using supporting variables to make them functional and configurable from the instructor station during the next fiscal year.

Table 8. Malfunctions developed for the TPD models for Trains A and B during the workshop. These malfunctions complement the original seven developed before the workshop.

Number	Description	Process Parameter Variables
MF5	Pump trip due to electrical disturbance or other	mftpe1pmp1a, mftpe1pmp1b
MF6	Pump speed change	dslpmp1ansp, dslpmp1bnsp
MF7	HTSE loss of pressure	htefpr
MF8	Kettle reboiler level control valve malfunction	mfdsllcva, mfdsllcvb
MF9	Spurious HTSE trip	htse_a
MF10	Tank level change due to valve failure (open or closed)	Identified, but not implemented

4.2.2 Alarms

By the end of the workshop, most of the alarms were implemented with limits that trip them, but some higher-level alarms such as the XSL, DSL, HTSE trip alarms still require additional development for full functionality. In some cases, there are cascading alarms that are more complicated, such as a reactor or turbine trip which will cause the XSL to trip resulting in XSL trip alarm. This in turn causes XSL1 and XSL2 trip alarms. The same is true for DSL and HTSE alarms which trip due to a reactor trip signal as well. The functionality for an alarm reset button (tpd_alarm_reset Boolean) to reset all alarms to false was implemented during the workshop. Continued development next fiscal year will finalize the alarm implementation.

4.2.3 Control System Modifications

4.2.3.1 Auto Ramp/Manual Ramp Functionality

The auto ramp function automatically sets the ramp rate and the target valve position as well as switches the flow controller to manual and then back to automatic once the setpoint has been reached and approximately 2-minutes elapse for the flow to stabilize. The manual ramp allows the operator to select the ramp rate and target valve position and initiate the ramping function. Changing the flow controller status and setpoint is the operator's responsibility in this case. A hold button is included that can pause the process for both ramping functions. The auto ramp can be canceled by depressing the button which will reset the program. Otherwise, the button does not depress until the program is completed and the target has been reached.

The option for an error hold feature is included in each of the ramping functions to simulate the condition in which ramping should not occur or should automatically be placed on hold. This can be further explored with HOIL testing. The mechanisms to trigger this hold include alarms or controller value mismatch.

4.3 Non-Nuclear Model Integration

A large emphasis on the integrated simulation approach focuses on the NPP simulation due to its safety-critical nature. Prior efforts assumed nominal responses from the electric grid and hydrogen plant. For example, any changes in generation were assumed to be met by other generators while the hydrogen plant was considered an infinite heat sink that could receive any dispatch thermal power from the NPP. As the NPP and TPD modelling has matured, the interactions between the electric grid and hydrogen plant can be evaluated by integrating these models with the TPD simulator for a wholistic simulation within the HSSL. This provides the opportunity to evaluate TPD impacts on the NPP while providing electric grid support functions. The hydrogen plant is thermally coupled to the grid, but there are configurations in which it is coupled through the electric grid to the NPP as well as a direct electrical connection behind the meter. Lastly, the coordination between these three entities must be developed and this provides the platform to evaluate these interactions for both normal and abnormal conditions. Prior to the workshop, an initial application programming interface (API) was developed to couple an electric grid model to Rancor2.0, a reduced-order model of an NPP that is significantly simpler than a full-scope simulator and therefore is well suited for conceptual development. The API was tested during the Superlab 2.0 demonstration in collaboration with the National Renewable Energy Laboratory (NREL). The Superlab 2.0 demonstration integrated co-simulations of various traditional and renewable generators and hydrogen technologies in a geographically distributed grid simulation. The HSSL provided a small grid model and the Rancor2.0 model as two of the co-simulations connected to the larger regional grid simulation. Two-way communication protocols were developed to support the models with HSSL and the models model communication between the three simulation elements through the development of application programming interfaces (API) during the integration workshop.

4.3.1 Real-Time Digital Simulator (RTDS) Electric Grid Model

Real-time simulations are performed using RTDS software to validate the performance of the proposed droop-based controller. Simulation results demonstrate that PWRs coupled with large-capacity hydrogen production systems can provide contingency reserves to the power grid.

The IEEE 39-bus system, which is based on the renowned New England 10 generator power system is used to perform real-time simulations, as shown in Figure 21. This test system has been widely used to address small-signal stability in conventional power systems and fits the purposes of the current study. The system is modified by adding a hydrogen plant with a capacity of 500 MW to bus 39 (coupled to the 1,000 MW PWR generator G1). The generator G2 is considered to be a renewable energy solar power generator or other intermittent power source. The generator G1 is controlled with constant field voltage and constant mechanical torque over short time scales to emulate a nuclear power station. For these simulations, the curtailment of the hydrogen plant and inertia response are the only mechanisms that act to maintain grid functions. (There is no primary or secondary frequency control.)

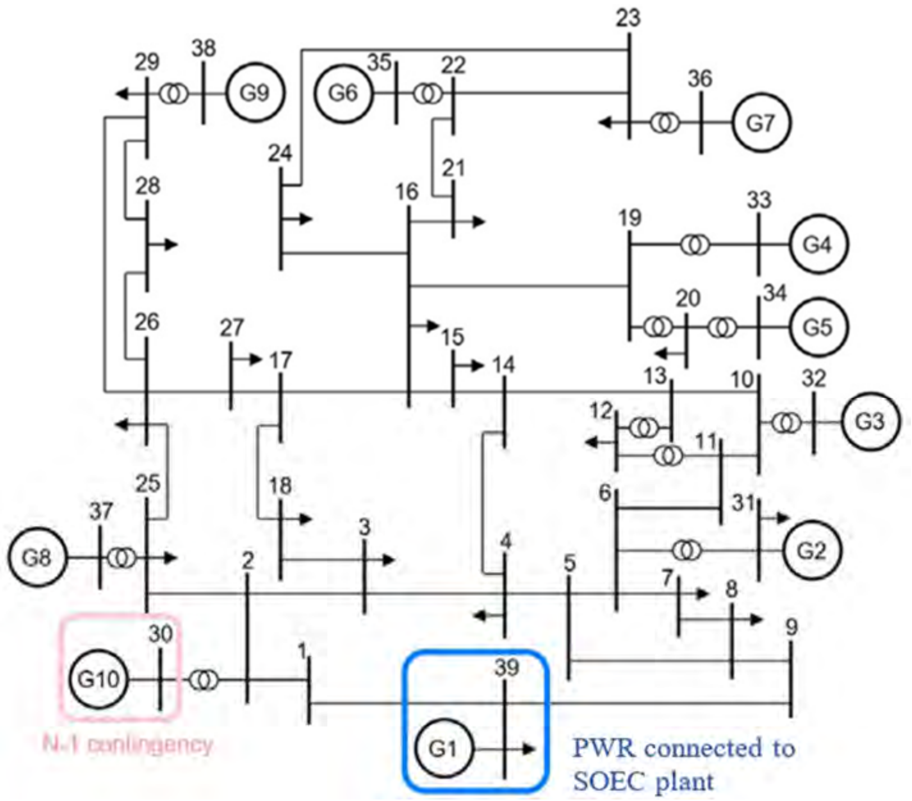


Figure 21. The IEEE 39-bus New England system.

4.3.2 High-Temperature Steam Electrolysis Model

The HTSE system model includes several major process systems which are (1) Hydrogen/steam system**,** Air sweep-gas system, HTSE stack system, and AC/DC conversion system. The overall HTSE plant design is shown in Figure 22.

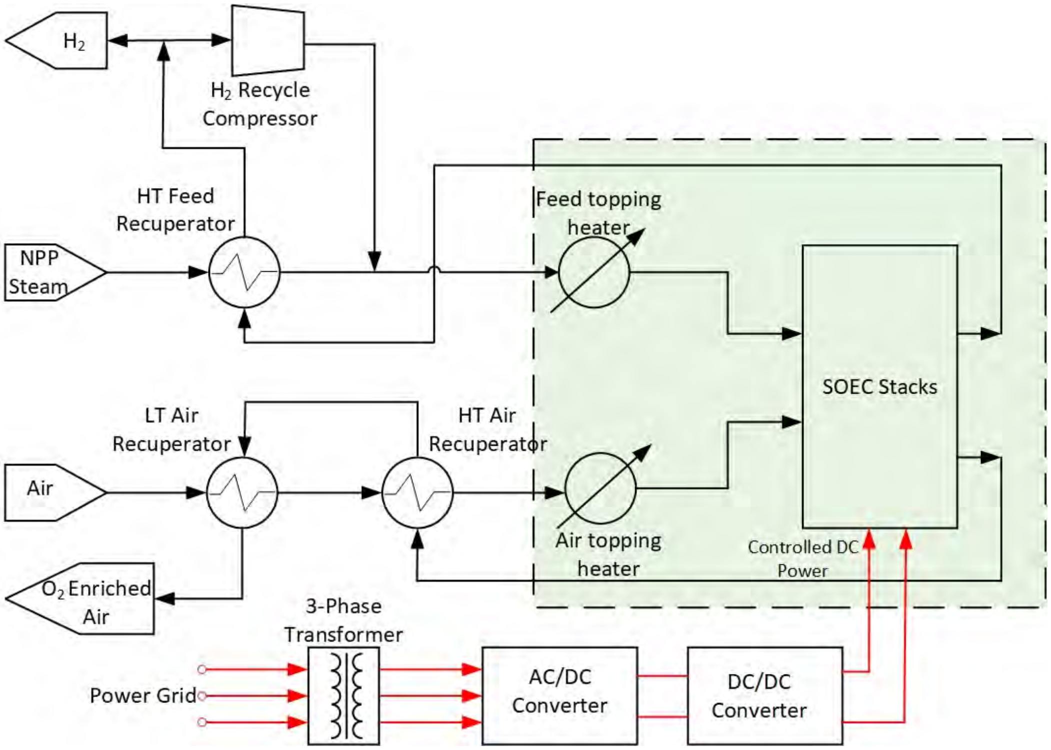


Figure 22. HTSE Plant Design

4.3.2.1 Hydrogen/steam system

The steam to be used for the HTSE comes from the steam thermal diversion from the NPP. The HSSL NPP has two streams for steam diversion, with each stream coming from a separate TPD train. The two steam streams are combined into one stream that is sent to the hydrogen plant. A fraction of the product hydrogen is recycled back to the stack inlet gas stream to maintain a reducing condition in the solid oxide electrolysis cell (SOEC) stacks, which is important for system durability. The high-temperature recuperators are used to extract the heat from the H_2/H_2O product outlet while simultaneously heating the H_2/H_2O mixture enroute to the SOEC stacks. If needed, feed topping heaters are used to increase the temperature of the H_2/H_2O mixture enroute to the SOEC stacks to approximately 750°C and 5 bar.

4.3.2.2 Air sweep-gas system

During HTSE process operation, pure oxygen is generated on the anode side of the SOEC stacks. Because the stacks operate at elevated temperatures (700–800°C), oxidation of the materials of construction is an operational issue if the oxygen concentration is not reduced. An air sweep-gas stream is used to dilute and evacuate high-concentration oxygen from the HTSE system. The sweep-gas system delivers the air sweep-gas stream to the SOEC stacks at the specified operating temperature and pressure to minimize any thermal or pressure gradients between the anode and cathode sides of each cell, which reduces mechanical stresses on the cells. The enriched-oxygen air sweep-gas stream is released to the atmosphere following expansion through a pressure-recovery turbine to capture the energy in the stream. Because the flow rate of the sweep-gas outlet stream is greater than the flow rate of the sweep-gas inlet stream (due to the addition of oxygen in the stack), the net-power requirements of the sweep-gas compressor/expander are negligible in comparison with other HTSE-system power demands.

4.3.2.3 HTSE stack system

The SOEC model includes fluid dynamics, electrical dynamics, and thermal dynamics, as shown in Figure 23. The electrical dynamics submodule outputs the dynamic behavior of cell voltage based on the cell’s electrochemical double-layer phenomenon. The fluid dynamics submodule outputs the dynamic behavior of the average partial pressure conditions of the reaction based on the pressure inertia due to finite flowrates, and inlet/outlet flow rate conditions of the stack based on the feed factors. The thermal dynamics submodule outputs the dynamic behavior of the average stack temperature and the inlet stream temperature based on the SOEC thermal dynamics and preheater thermal dynamic, respectively.

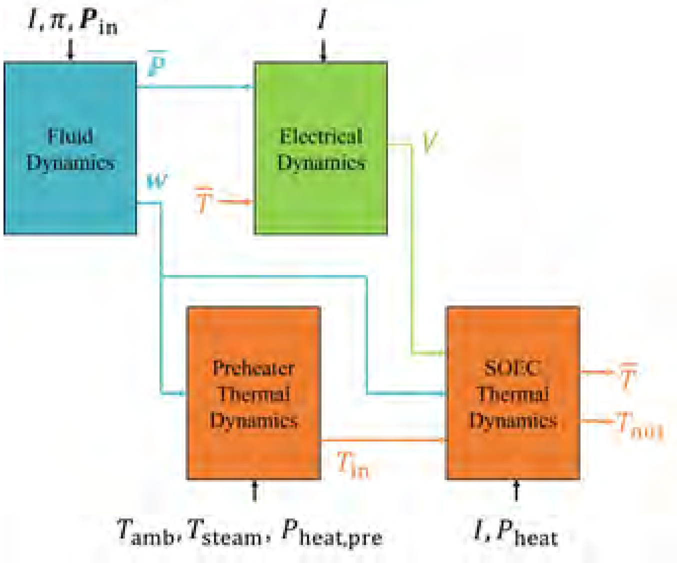


Figure 23. SOEC Dynamic Model Blocks

4.3.2.4 AC/DC Conversion System

The HTSE plant requires both AC and DC power. Within the HTSE plant, the AC loads, such as compressors, pumps and heaters, are powered by the AC supply from the grid. The SOEC stacks require a DC power. The first stage of the AC-to-DC conversion is done using an AC/DC rectifier. The DC output of the rectifier is connected to a DC-DC converter. This allows for flexible and easy control of the DC power supplied to the SOEC stacks.

4.4 Application Programming Interface

4.4.1 RTDS Electric Grid to Rancor 2.0 Communication

INL and the University of Idaho jointly developed Rancor, a reduced order model (ROM) NPP simulator (Ulrich et al., 2017). Rancor2.0 is a quasi-steady state ROM with single point neutronics for reactivity and a two-phase secondary system with a three-stage turbine and feed water heaters.

The model can also communicate with external applications through a flat-file API, a Python/Tornado based web API, and a socket-based RTDS client. This demonstration synchronously linked the Rancor ROM plant simulator to a micro-grid simulation with renewable generation and battery storage through ESnet’s OSCARS service.

The flexibility of the Rancor simulator is due to its implementation in the Python programming language, which has made it easy to develop an RTDS client and API, as well as a web API. A simple text user interface has also been created, providing a real-time interface for the simulator that makes it more accessible and user-friendly. For these reasons, the initial communication protocol was developed using this simpler simulation before scaling these principles to a full-scope simulator, such as GSE Solutions GPWR.

4.4.2 GPWR API

GPWR uses a protocol called S3Serv to provide communication between the JADE applications and the simulator model running in SimExec. In 2014 when we needed to implement a prototype Turbine Control System (TCS) HMI for GPWR we created a.NET Framework library called giiNET. giiNET was a wrapper for GSE's C++ s3dll64 library that implemented a client for S3Serv. giiNET was a.NET C++ Common Language Runtime (CLR) application that provided a.NET giiNET Client.

This approach has worked reliably for several years, although it is now reaching its end of life. Microsoft is moving away from.NET Framework to.NET. The giiNET wrapper is implemented as a C++/CLR application and cannot be migrated to.NET, so we were forced to stay with.NET Framework 4.8 for our HMI. Microsoft has indefinite support for.NET Framework 4.8 at this time, but the latest functionality of.NET (such as C# 7.0) is not available.

If not carefully implemented within a.NET application the syncing of variables using giiNET would result in blocking the UI thread, which could make it slow to respond. The research team has developed techniques to mitigate this issue, but the solutions require threading, or careful use of multiple dispatcher timer loops. Another notable shortcoming of giiNET for WPF is ensuring all the dependencies are installed and can be found by the application. Over time, this debugging process has become increasingly difficult as Microsoft moved away from.NET Framework and other libraries that were once native to Windows. Just in the last year, over 100 hours have been spent troubleshooting and debugging dependency issues. The dependencies include not only.NET Framework, but C++ redistributables for s3dll. For this workshop, creating a reliable installation required installing Visual Studio 2022 C#, C++/CLR and installing GPWR 6.0, which includes Microsoft Visual C++ redistributables. giiNET also had to be compiled from source code and properly linked.

A prior 2018 and 2019 CRADA with GSE supported the development of a computer-based procedure engine with an accompanying task-based display (GAIYO/TEJUN). In this prior project, the research team used an alpha version of GSE's WebAPI for GPWR to provide two-way communication between ReactJS and GPWR. Due to the increasing complications of using giiNET (due to Microsoft's progression away from.NET Framework) we obtained a release version of SimAPI, GSE's WebAPI, and restructured the backend of the WPF prototype to use SimAPI.

4.4.3 GSE SimAPI 1.0

SimAPI 1.0 is a CLI executable that acts as a bridge between GSE SimExec and HTTP clients. SimAPI provides a restful interface for connecting to GPWR, creating a list of variables, retrieving the values from a list id, retrieving a variable from a point, setting the values of the points in a list, and setting a value from its point name.

In C# a SimAPIClient class was created that uses `System.Net.Http.HttpClient`. This client is relatively simple and provides asynchronous methods to communicate with GPWR, as shown in Figure 24.

```
6 references
public class SimApiClient
{
    private readonly HttpClient client = new HttpClient();
    private const string apiBaseUrl = "http://localhost:3002";

    public string connectionId;
    public string listId;
    public string executiveName;

    1 reference
    public async Task<string> ConnectToApiAsync(string host = "localhost", int port = 9000, string user = "user", string udsname = "load", bool verbose = false)...

    1 reference
    public async Task<int> AttachExecAsync(string executiveName = "rtexall", bool verbose = false)...

    0 references
    public async Task<int> DisconnectAsync(bool verbose = false)...

    1 reference
    public async Task<string> RegisterListAsync(string[] variablesList, bool verbose = false)...

    1 reference
    public async Task<string[]> GetValueAsync(bool verbose = false)...

    3 references
    public async Task<int> SetValAsync(string variableName, string value, bool verbose = true)...
}
```

Figure 24. NET SimAPIClient with asynchronous API calls

Utilizing SimAPI for communication solves the following issues for current and future HMI prototyping:

- Does not require maintaining giiNET dll to support new versions of SimExec s3dll,
- Eliminates hassles with installing giiNET dependencies,
- Allows use beyond.NET Framework 4.8,
- Enables asyncronous implementation for higher performance and can be run on UI thread without blocking,
- Reduces programmatic complexity, and eliminates need for UI callbacks in some instances.

No significant drawbacks or performance limitations of using SimAPI 1.0 have been identified so far.

4.4.4 GSE SimAPI and WPF Clients

As previously noted, SimAPI is a console application that acts as a bridge between SimExec (using S3Serv) and HTTP clients. SimAPI exposes a local port for HTTP requests. Essentially, each computer running an HMI application can run an instance of SimAPI.

4.4.5 HTSE Simulink to gPWR Communication

A two-way communication protocol between the HTSE Simulink model and GPWR was developed during the workshop. The communication is to support integrated modeling of the TPD system and HTSE plant. The integrated model will allow the HTSE model to receive steam from TPD system and produce hydrogen. The HTSE model also models electrical use for hydrogen generation. The communication scheme is depicted in Figure 25. GSE's SimAPI provides communication with GPWR. A Python Tornado server functions as a TCP/IP server for Simulink socket client. Tornado is a Python web server and web application framework intended for non-blocking I/O connections with high performance. Tornado has a built-in HTTP Sever that makes developing microservice simple. The communication proceeds as follows:

1. Simulink Socket clients make request to the Python Tornado server
2. Python Tornado Server accepts requests and unpacks two single precision floating point values representing stored H_2 and HTSE power

3. Python Tornado Server application gets steamflow, temperature, pressure, and thermal power delivery from GPWR through the request to SimAPI bridge
4. Python Tornado Server sets stored H_2 and HTSE power points in GPWR through SimAPI request
5. Python Tornado Server sends GPWR values to SimAPI

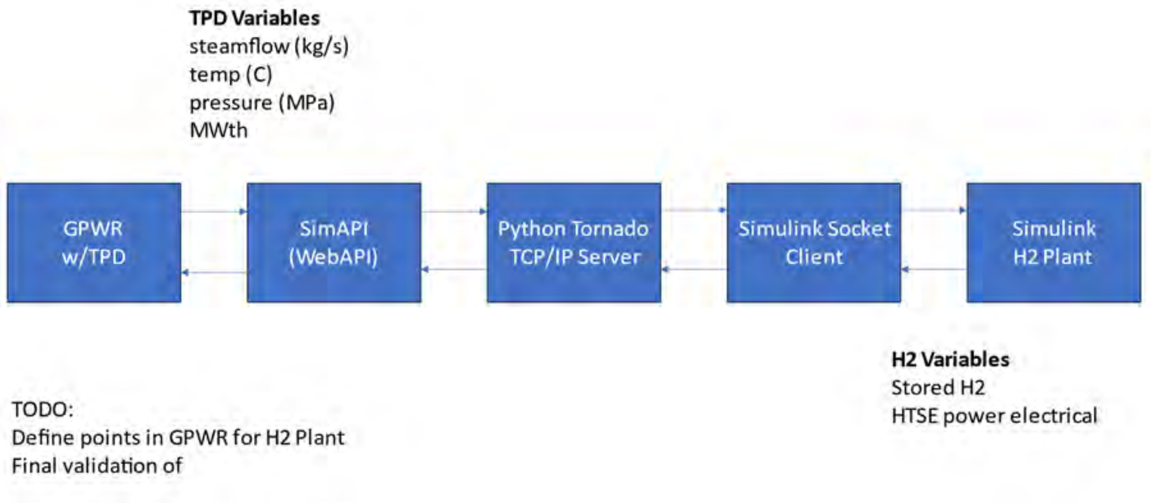


Figure 25. Two-way communication scheme between GPWR and the Simulink HTSE Plant

The dynamic HTSE plant model was developed in MATLAB/Simulink. To set up the model for connection with the HSSL NPP plant, 2023a MATLAB/Simulink was installed on the virtual machine (VM). The Instrument Control Toolbox in Simulink contains the TCP/IP client that sends and receives blocks,which allows the Simulink model to send and receive data from a TCP/IP server. The IP address of the remote server and the port to which the server will listen to the client is specified on TCP/IP client blocks. The source (HSSL) data type is specified, and the byte order was defined as part of the inputs in the TCP/IP client send and receive blocks. The data to be sent to and received from the HSSL NPP model are multiplexed and demultiplexed accordingly.

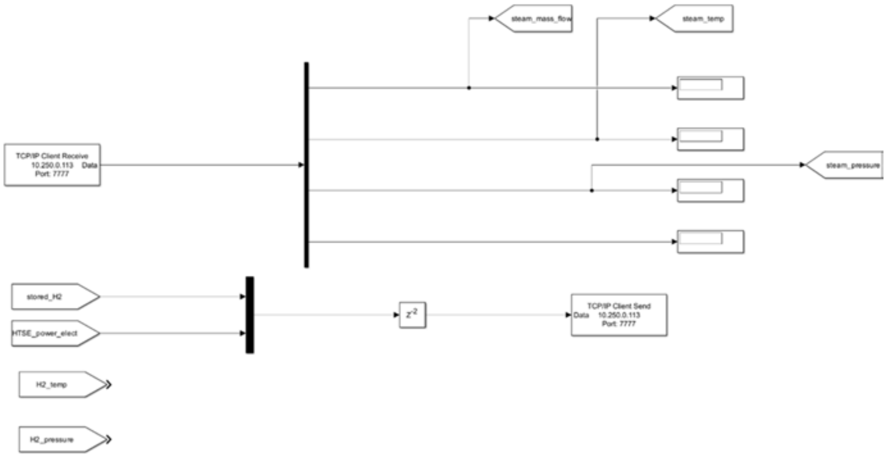


Figure 26. Block diagram of the Simulink socket client

4.5 Human-in-the-loop Scenario Testing

After initial configuration and trouble shooting was performed as part of the integration process, a series of verification testing and issue resolution iterations were performed to walk through HMI indication and controller functionality. Within each test cycle, as issues were identified, code fixes were implemented immediately during the test or after the test was complete if the issue was found to apply to broad functionality common to many HMI or simulation elements. The workshop team collectively participated in these walkthroughs. However, one team member's feedback was emphasized since this individual had nuclear operating experience and could uniquely provide operational insights. At the end of the verification and issue resolution cycle phase of the workshop, with the bulk of the integration issues resolved, this team member acted as an operator in a scenario walkthrough of the Hot Standby to Online procedure. The acting operator had extensive nuclear operating experience through serving as a qualified Engineering Officer of the Watch and Engineering Duty Officer aboard a naval vessel and participated in the ship's initial criticality and power range steam testing programs. The extensive and noncommercial nuclear process control expertise provided invaluable feedback on this novel system and its potential operation. This single walkthrough served as the final verification of the simulator and HMI integration and with operability and verbiage of the procedures.

4.5.1 Subject Matter Expert Procedure Review

The procedures were provided to the subject matter expert for review prior to the workshop for feedback. At the time of the review, the procedures only contained prerequisites and procedure sections. This expert review revised the procedures to follow the DOE Standard 1029-92, *Writer's Guide for Technical Procedures.* For example, one revision included changing the prerequisites terminology to initial conditions to maintain compliance with the standard.

More detailed revisions were also made, including refactoring the step structure. This included combining and refactoring two steps and changing some terminology to be consistent with operations. In particular, one step that called for the operator to "monitor for two minutes" was removed since the operator should always be monitoring as a basic element of the operation. If an operation would cause abnormal conditions that would warrant telling the operator to monitor the panel; it is typically done so with some sort of warning or caution statement. The two-minute "monitoring" task was replaced by providing a target setpoint range for the associated component, i.e., stabilized flow rate, implied by the two-minute instruction such that it has no monitoring action, but rather is a condition to proceed and check off the procedure step as complete.

4.5.2 Scenario Walkthrough

To begin operations, the reactor was placed in normal plant conditions at 99.5% power with both trains in the TPD system in online. GPWR provided the simulation of the nuclear reactor and JADE was utilized to emulate the panels in the control room. The following sections describe normal and abnormal scenario walkthroughs to illustrate the type of functionality tested and the types of issues identified and recorded for future resolution.

4.5.2.1 Normal Operations

The operator verified initial conditions prior to performing any operation and in doing so revealed the small discrepancies between the numbers provided in the initial conditions and what was displayed on the screen, i.e., Turbine Generator output was 950 MW vs. 951 MW. The differences were noted, and the operator completed verifying the initial conditions.

All operations performed by the operator were performed on Train A, however, both trains were confirmed to operate with the HMI.

The Flow control valve (XSL-FC-1001) was placed manually, allowing the valve position to be entered as a percent open. Opening the valve this way minimizes wear on the valve since it would rapidly and constantly reposition to achieve the specified mass flow rate. Since the mass flow rate is partially dependent on the differences in system pressures, the valve position would reposition constantly while bringing the system online. Instead, a valve position is specified with a two-minute wait period to allow the system to stabilize.

After the wait period, the plant should be relatively stable and the flow control valve is placed back in auto with a setpoint of 2.5 lb/s to maintain the system in Hot Standby.

Following a short debrief in which the simulation continued to run to allow the system to reach a steady state, the operator began the procedure to transition the TPD system from Hot Standby to Online. The procedure itself is almost identical to transitioning the system from Online to Hot Standby with inverse setpoints.

The operator then repeated the transition from Online to Hot Standby and Hot Standby to Online with the Auto Ramp function. The auto ramp function performs the same procedure described above in a preprogrammed manner.

At the time of the workshop, a formal procedure for the auto ramp function had not been developed, so the operator was told how to initiate the auto ramp function and allowed to take actions that were deemed necessary. The procedure was written afterward with feedback from the operator. After the completion of operations, the operator suggested that during future operations, a note should be added by operators in the manual operation procedure stating that the operation was performed in Auto Ramp and each step was properly taken.

4.5.2.2 Abnormal Operations

A pipe shear was built into the simulation and was used to verify there was sufficient instrumentation to identify and diagnose the abnormal situation. The abnormal operation was quickly identified by the operator and was properly diagnosed shortly thereafter as a pipe shear.

The operator correctly identified the leak and leak location utilizing the instrumentation on the HMI in conjunction with Reactor Power and Turbine Generator Output. He identified the onset of the casualty from the flow indications and immediately checked to verify the TPD system inlet valves were opening and outlet valves closing to maintain the specified setpoint in the system. He next verified reactor power and calorimetric power had remained constant. A rise from 99.4% to 99.7% power that corresponded with a rise in Turbine Generator output followed by a drop was noted by the operator. The entire leak identification process required approximately 90 seconds from the onset of the leak to the identification of the leak location.

For this situation, the operator believed there was sufficient instrumentation to understand the plant conditions. However, more scenarios will need to be developed and tested to verify sufficient instrumentation is present to diagnose a variety of plant conditions.

5. CONCLUSIONS

The goal of the work described in this report is to support the U.S. commercial nuclear industry to take advantage of a TPD capability. Through the FPOG pathway of the LWRS program, INL is supporting industry by developing the technologies, methods, and guidance required to implement TPD for a variety of use cases. The methods and guidance are intended to alleviate industry economic and safety concerns that may impede their consideration and adoption of the TPD technology. Implementing a TPD system represents a substantial capital investment. Furthermore, the additional regulatory scrutiny is still uncertain and can vary based on the magnitude of steam extracted. The 3% extraction of this design is anticipated to not exceed the threshold criteria that would result in a license amendment, but there are potential use cases that may. Future work on new designs evaluating larger magnitudes of steam extraction ranging from 30-100% will be performed to evaluate the differential implications of the TPD on the existing plant systems. Even if these more extreme implementations are not pursued, it is still valuable to evaluate these higher extraction magnitudes since this characterizes the plant impacts and can be used to contrast the smaller magnitude extraction designs. Continued development is required to modify the existing simulation capability to support these larger extraction designs. In addition to alternative TPD designs, integrating NPP TPD simulations with other related simulations is critical to comprehensively evaluate the interdependencies with the electric grid and other nuclear power users, such as hydrogen plants.

The first portion of this report describes extensive development activities performed during the current fiscal year to advance the suite of simulations to represent TPD operations more realistically within two separate NPP simulators. The GSE GPWR simulator was modified with the new TPD design and conceptual automatic control system to support auto ramping the TPD through transitions between Hot Standby and online modes. This is important to ensure the operation can be performed safely within a 10-minute transition target. A second three-loop PWR simulator was also installed from Westinghouse, referred to as the W3LPWR and was configured within the HSSL. The installation of the W3LPWR simulator supports an activity in FY2024 to install a TPD simulator with an industrial-grade automatic control system. Together, these simulators provide the means to evaluate *and* share the results of those evaluations publicly to encourage industry adoption and drive additional research by other groups. The GSE Solutions GPWR simulator is commercially available, while the W3LPWR simulator is proprietary but provides additional validation with a more sophisticated control system.

The second portion of this report describes verification activities performed to finalize the integration of the simulators and test the functionality through scenario walkthroughs. During the integration phase of the workshop, the research team tested functionality and corrected issues as they arose. Once sufficient functionality was achieved with scenario-stopping bugs, the second phase began in which planned scenario walkthroughs were performed to evaluate the procedures, HMI, and simulation collectively. The development continues into the next fiscal year to address any remaining issues in preparation for a formal HOIL study in the spring of 2024. This study will employ formal validation metrics, such as eye tracking, expert observers, logging, and substantial post-study analysis to compile evidence of the operations. Assuming that unexpected outcomes that may arise are manageable, the results should support the safety case and demonstrate the feasibility of TPD for hydrogen production while also maintaining existing and potentially expanding electric grid support by NPPs. The set of scenarios to be employed in the future demonstration is still under development; however, they will include a PWR with a TPD system coupled to a hydrogen plant and electric grid. Initiating events will be tested to evaluate their impacts on the integrated system. For example, one of the envisioned electrical grid-initiated event scenarios requires the NPP to act as a nonspinning reserve capacity by raising generation while curtailing thermal dispatch to the hydrogen plant. This integrated testing approach supports the ability to evaluate the coordination between the NPP, electric grid, and hydrogen plant to ensure the operations meet the existing U.S. commercial nuclear high safety standards.

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