Light Water Reactor Sustainability Program

Dynamic Human-in-the-Loop Simulated Nuclear Power Plant Thermal Power Dispatch System Demonstration and Evaluation Study

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EXECUTIVE SUMMARY

The nuclear industry is facing increasing economic challenges within the wholesale electric market due to completive alternative energy sources and increasingly dynamic grid conditions. Nuclear utilities can take advantage of selling thermal energy to a nearby industrial user by adopting a thermal power dispatch capability. A critical aspect of thermal power dispatch is understanding the impacts of the operations required to shift the plant from the traditional electricity production to a hybrid electricity production and thermal power dispatch mode. An Idaho National Laboratory research team performed a human-in-the-loop study with two formerly licensed reactor operators to evaluate thermal power dispatch operations supported by the modified GSE Systems' Generic Pressurized-Water Reactor (GPWR) plant simulator.

The study aimed to demonstrate and evaluate an initial concept of operations for using a portion of the steam from a nuclear power plant for an industrial user through a thermal power dispatch coupling. Virtual representations of the analog control panels were presented on touchscreen bays configured to mimic the control room layout in the newly renovated Human Systems Simulation Laboratory. A prototype human-system interface (HSI) was developed and displayed in tandem with the virtual analog panels to support the operators executing procedurally driven evolutions and transient responses. The operators performed 15 scenarios covering normal evolutions to transition the plant from full turbine operation to joint turbine and thermal power dispatch operations, in addition to transient response scenarios induced with simulated faults. The impact of the thermal power dispatch (TPD) system on operator and plant responses was evaluated with a particular emphasis on the amount of workload and attention required to operate in tandem the thermal power dispatch and existing plant systems. An interdisciplinary team of operations experts, nuclear engineers, and human factors experts observed the operators performing the scenarios to evaluate the operations. Several different measures were collected including expert observer performance-based metrics, plant parameter logs, operator attention via eye tracking, debriefs, and self-report questionnaires.

Analysis of the collected data generated two primary results for thermal dispatch operations that are pertinent to the adoption of the capability within the nuclear industry. The manual control supported by the HSI to transition from standard operations to TPD operation imposed a considerable amount of workload on the operators due to tedious manual valve manipulations and system monitoring required to verify their intended effect. An additional operator would be required in the control room to support the daily evolution. Automatic control for the transition was deemed a requirement for plant adoption without imposing additional staffing costs. The second finding was the necessity for an automatic TPD system trip isolation function linked to a turbine and reactor trip signal. The operators completed scenarios with automatic isolation functionality and manually required actuation of the TPD system. The operator response was sufficiently slower in the manual trip condition, such that operators were unable to manually actuate key post-trip safety functions and indicate a degraded control capability that should be avoided. With an automatic trip signal, little to no impact of the TPD system was identified on the primary plant response, and therefore, the system could be readily and safely adopted. Together, these two findings represent the need to support the adoption of TPD capability into existing operations, by leveraging automation to augment any additional operator tasking required to control and monitor an additional system beyond existing operations.

Future work is planned to demonstrate and evaluate an automatic control capability with an operator in the loop study. Furthermore, alternative designs and their impacts on operations are also planned. Specifically, alternative thermal power dispatch designs with different main steam connection points and alternative condensate return connections points impact different types of operations and require evaluation.

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ACRONYMS

AOI	Areas of Interest
CV	Control Valve
DOE	Department of Energy
DSL	Delivery Steam Line
FPOG	Flexible Plant Operations and Generation
GPWR	Generic Pressurized-Water Reactor
GV	Governor Valve
HF	Human Factors
HRA	Human Reliability Analysis
HSI	Human-System Interface
HSSL	Human Systems Simulation Laboratory
HTSE	High-Temperature Steam Electrolysis
I&C	Instrumentation and Controls
INL	Idaho National Laboratory
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MW	Megawatts
MCH	Modified Cooper Harper
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
NPPs	Nuclear Power Plants
OATC	Operator at the Controls
P&ID	Piping and Instrumentation Diagram
PP	Paper procedures
PSF	Performance Shaping Factor
PWR	Pressurized-Water Reactor
RCS	Reactor Coolant System
SART	Situation Awareness Rating Technique
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SI	Safety Injection
SRO	Senior Reactor Officer
SS	Shift Supervisor
Tavg	Average Temperature

T_{mis}	Mismatch Temperature
T_{ref}	Reference Temperature
TCS	Turbine Control System
TPD	Thermal Power Dispatch
XSL	Extraction Steam Line

DYNAMIC HUMAN-IN-THE-LOOP SIMULATED NUCLEAR POWER PLANT THERMAL POWER DISPATCH SYSTEM DEMONSTRATION AND EVALUATION STUDY

1.   INTRODUCTION

The Thermal Power Dispatch (TPD) project within the Flexible Plant Operations and Generation (FPOG) pathway of the Light Water Reactor Sustainability (LWRS) program under the U.S. Department of Energy (DOE) aims to develop and demonstrate diversifying the thermal energy produced by nuclear power plants (NPPs) beyond their traditional and sole use to generate electricity. Cheap natural gas prices and the inexpensive combined-cycle gas plant operational costs are challenging the economic viability of large commercial NPPs. Additional economic pressure from an increasingly diverse and dynamic electric grid, due to wind and solar generators are forcing nuclear utilities to reevaluate their business model in order to maintain economic viability. Ensuring the continued operation of the existing nuclear fleet is intrinsically necessary for nuclear utilities to continue to exist but is also crucial to supporting the United States' goal to achieve the 100% carbon-free electricity greenhouse carbon gas reduction target set for 2035 by President Biden (Waldman, 2021). Developing and demonstrating the concept of operations informs the nuclear industry of the best practices for adopting and implementing the technology with guidance to maximize profitability, ensure safety and reduce licensing risk, and configure and operate at peak efficiency with minimal equipment degradation.

1.1   Thermal Power Dispatch Concept

The TPD concept attempts to diversify operating U.S. NPPs' revenue streams to enhance their economic competitiveness with the electrical energy producing industry. In existing NPPs, the thermal energy from fission reactions in the nuclear core is transferred to the primary coolant, which in turn transfers this heat to a secondary system through steam generation. In this secondary system, the produced steam is used to drive a turbine connected to an electrical generator and provide electrical power to the grid. A constant baseload electrical output provided by the NPP is troublesome and economically challenged due to the increasingly dynamic nature of the electrical grid and the resulting fluctuation in wholesale electricity prices. NPPs were developed to operate at a set capacity, and it is infeasible, due to a variety of reasons (International Atomic Energy Agency, 2018), to modulate operating status to accommodate shifting grid demands. The TPD concept provides a relatively simple solution in which the plant continues to operate at 100% power, but during low electrical demand, the steam is repurposed for use with an industrial user physically located near the plant. The industrial user purchases the thermal energy to support their chemical process with the initial and primary use case of a hydrogen production plant.

1.2   Thermal Power Dispatch Simulation Approach

GSE Systems' GPWR is a full-scope real-time simulator validated on an operating pressurized-water reactor (PWR) in the United States. The simulator represents the entire power plant from the reactor core to the electrical switchyard and auxiliary systems. For the present research, the underlying model for the secondary turbine system was modified to include a TPD system intended to extract and supply thermal power to an offsite industrial process facility. The intended thermal power user is a high-temperature steam electrolysis (HTSE) plant for hydrogen production.

The TPD uses a fraction of the main steam generated in the PWR to generate process steam for use in the HTSE plant. The TPD uses a three-stage heat exchanger system to preheat, boil, and superheat the process water. A simple diagram of the system is shown below (see Figure 1). Steam is extracted from the

main steam header—upstream of the high-pressure turbine and downstream of the main steam isolation valves. The main steam condensate is returned to the main condenser to combine with the main feed water at the PWR. Process water is supplied from a demineralized water source and is sent as superheated steam to the HTSE plant for use in the HTSE process.

This system operates in parallel with the turbine-generator system and is designed to use up to 15% of the main steam from the secondary PWR system. The HTSE plant uses steam generated in the TPD system and the electrical power generated in the turbine-generator system. A basic control system combined with a first pass of operating procedures were developed to allow for the parallel operation of the systems and the transition in operating state of the turbine-generator system. Together, this design aimed to maintain the reactor at or near 100% power during all operating conditions and transitions in operation. This design combined with the procedures were the basis for a human-in-the-loop study performed in the Human Systems Simulation Laboratory (HSSL) at Idaho National Laboratory (INL).
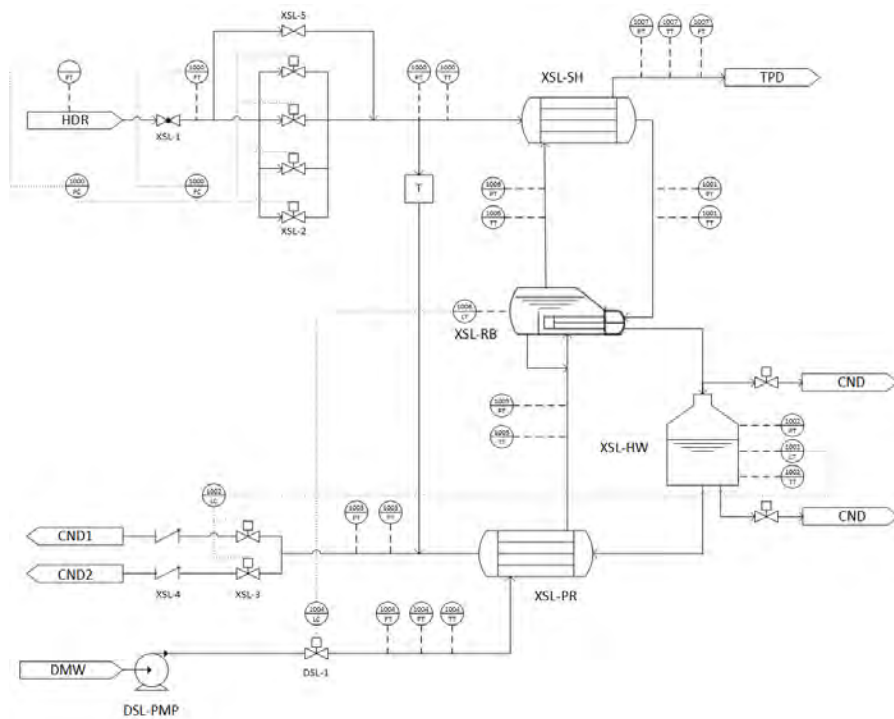
Figure 1. TPD engineering dispatch system design as modeled in the GSE Systems GPWR simulator. The diagram shown in Figure 1 depicts the essential systems of the TPD that were included in the modified version of the simulator. The diverted steam from the secondary system is maintained in the shell side of each heat exchanger, while the demineralized water for use in the HTSE process is boiled and superheated on the shell side. There are three automatic control systems used for operating this system.

The first and most important is the steam flow controller, which is used to control the flow of steam at the outlet of the main steam header to the TPD system. The system is designed to use 15% of the main steam generated in the steam generators. The steam flow rate to the TPD system is the controller set point in this controller and is controlled by a bank of control valves at the outlet of the main steam header. The HTSE production plant is intended to be split into three separate modules, each handling 5% of the thermal power from the PWR. Therefore, the TPD system must operate at varying amounts of steam flow, including 5%, 10%, and 15% of PWR main steam as well as a small amount of steam to maintain a hot standby condition in the TPD.

The remaining control system used in this model is the level controllers surrounding the reboiler used for vaporizing the demineralized process water. One level controller is used to control the level in the reboiler condensate hot well. This creates a barrier between the steam in the system and the liquid used in the preheater and dumped into the main condenser. The other level controller controls the demineralized process water flow rate by maintaining a level in the shell side of the reboiler. This liquid level also serves to drive the heat transfer in the reboiler, maintaining the tube bank covered by liquid to increase heat transfer effectiveness. Only the steam flow controller is manipulated for the transition from hot standby to TPD online. The other controllers are important for bringing the TPD system from a shutdown state to a hot standby state. Process indicators including flow rates and temperature and pressure transmitters are placed at important locations in the system. This was intended to provide information to the operators in the study and use the results of the study to determine which parameters are more important than others.

1.3   Human Factors Background and Prior Work

This study is part of a larger TPD project that spans activities across a number of different disciplines. The overall project aims to develop the necessary technologies and techniques to implement TPD in a safe and economic manner to enable industry to readily adopt the capability with minimal risk. The activities include engineering and design activities to develop the physical system and control system required to operate it safely and effectively. Risk analysis must also be performed to evaluate the impacts of the system on the existing plant. The system concept of operation must also be developed and refined. This last aspect is the focus of the human factors work performed for this year's effort to support the overall TPD project.

The TPD project is in its second year. The first year focused on developing the initial system design comprised of a thermal power extraction and delivery system to couple the nuclear power plant to an industrial user, a hydrogen production facility using HTSE. A prototype human-system interface (HSI) and the GPWR full-scope nuclear simulator, modified with a TPD system model, were developed to perform the initial system testing to evaluate the envisioned normal operations. Mock-procedures were drafted, and a remote human-in-the-loop study was performed to evaluate the concept of operations in terms of the underlying system, the HSI, and procedures. Additional details can be found elsewhere (Ulrich[a] et al. 2020; Ulrich[b] et al. 2020).

The initial year's effort used an oil loop to simulate the TPD portion of the system. The system design has since been refined. The second version of the system developed during this year's effort implemented a steam delivery system. The HSI was revised to reflect the new system design, and the mock-procedures were revised in tandem. Additionally, the ability to simulate and test operator responses to TPD-specific faults were developed and tested. Furthermore, the impacts of the TPD on operator responses to plant faults, such as steam generator tube ruptures (SGTRs), were developed and tested. A significant addition to human factors research performed during this year's activities included operator testing with a more realistic and integrated test environment and format for the scenarios. The initial year's effort relied on remote testing with operators attending via web-meeting software due to COVID-19 restrictions. This second year's effort comprised an in-person study in the HSSL located at INL. The in-person format supported representing the existing analog control boards and provided the operator participants with a much richer context to perform the TPD scenarios than was capable during the remote testing format. This report details the activities performed to develop and execute the human-in-the-loop study, the results of the study, and conclusions comprised of recommendations for TPD implementation in existing NPPs.

2.   METHOD

The in-person human-in-the-loop study was conducted with an interdisciplinary research team comprised of human factors experts, nuclear operations experts, nuclear engineers, and simulation

experts. Each discipline contributed insights into the method development to support a multi-day study aimed at evaluating the concept of operations for the TPD.

2.1   Participants

The participants were two retired male operators aged 67 and 68 years with 28 and 39 years of experience as commercial NPP operators, and 37 and 44 years of experience in commercial nuclear power, respectively. Both were native English speakers.

2.2   Observation Team

A total of 12 individuals provided observations of the scenarios at different times throughout the workshop. The team included: two PhD human factors researchers, two PhD cognitive scientists, five graduate students from human factors or nuclear engineering programs, and three individuals with prior experience in the commercial nuclear power industry. Across 15 scenarios, two to ten observers were involved in data collection for the scenarios.

2.3   Simulation Environment

The HSSL at INL is a full-scale virtual NPP control room simulation environment that allows the safe application of advanced simulation and modeling techniques for validation of new and improved HSI designs (see Figure 2). The simulator contains virtual equipment representations identical to the high fidelity and certified training simulators used in NPPs. Thus, the participants are able to view analog instrumentation and controls (I&C) on touchscreen displays that mimic the control boards of an actual NPP control room. Because the control boards are virtual, new digital HSIs (e.g., one with a TPD system) can be introduced, similar to the way NPPs would introduce plant upgrades to their operators.

Glasstop simulators contain a virtual display of the controls, levers, and buttons found in commercial NPPs. The one at the HSSL encompasses the full-scope of operations and is reconfigurable to represent different plant systems (a detailed description of the HSSL is reported elsewhere [i.e., Boring et al. 2012; Boring et al. 2013]). In Spring 2021, the glasstop underwent an upgrade that comprised a redesign of the room to remove the original control booth and replace it with an observation gallery. The observation gallery was moved to the side of the room near the entry to provide a larger and more open space to accommodate larger control rooms. Furthermore, new bays with higher 4k resolution capacitive touchscreen monitors and motorized stands were built and installed. The higher resolution bays provide greater flexibility in integrated prototypes within a virtual bay panel representation since there are more pixels and, therefore, a larger design surface to use while maintaining a clear and readable display. The motorized bays support greater flexibility in control room designs to accommodate both vertical control panels and curved control panels with aprons.

Figure 2. Upgraded HSSL at INL.

2.4 Prototype Human-System Interface

A prototype HSI was developed to support the operators performing the scenarios. This variant of the prototype was developed from the original steam- and oil-based HSI developed for the remote format testing performed during the first year of the project. Prior to the study, a user-centered iterative design process was pursued in collaboration with researchers at the University of Idaho. Specifically, a reduced-order model-based simulation representative of nuclear process control and the key systems, the Rancor Microworld, was used to test several refinements to the system (Ulrich et al. 2021). Based on the series of iterative design cycles, the prototype HSI indication and control displays can be seen below in Figure 3 and Figure 4.

Many of the interface design elements are existing elements employed in complex process control, such as spark lines, mode indicators, and dynamic iconography to denote live state changes. However, there were several key design features incorporated into the HSI that are worth noting. First, the instrument cluster approach was useful in integrating detailed process parameters into the piping and instrumentation diagram (P&ID) while minimizing clutter. Furthermore, each instrument cluster is given a unique identifier that is common across the different process variable types (i.e., flow transmitter and temperature transmitter), which aid the operators in understanding the correspondence between the different parameters and points within the system. The number scheme employed across the interface and within the clusters was developed to assist operators in understanding the flow path and to differentiate between control elements and indication elements. Indication elements use a thousand-based number scheme such that the extraction steam line (XSL) portion of the system uses numeric identifiers starting at 1001 and the delivery steam line (DSL) portion of the system uses numeric identifiers starting at 2001. The control elements use a hundred-based numbering scheme in which the primary flow path control elements begin at 101 and secondary flow paths that branch from the primary start at 111.
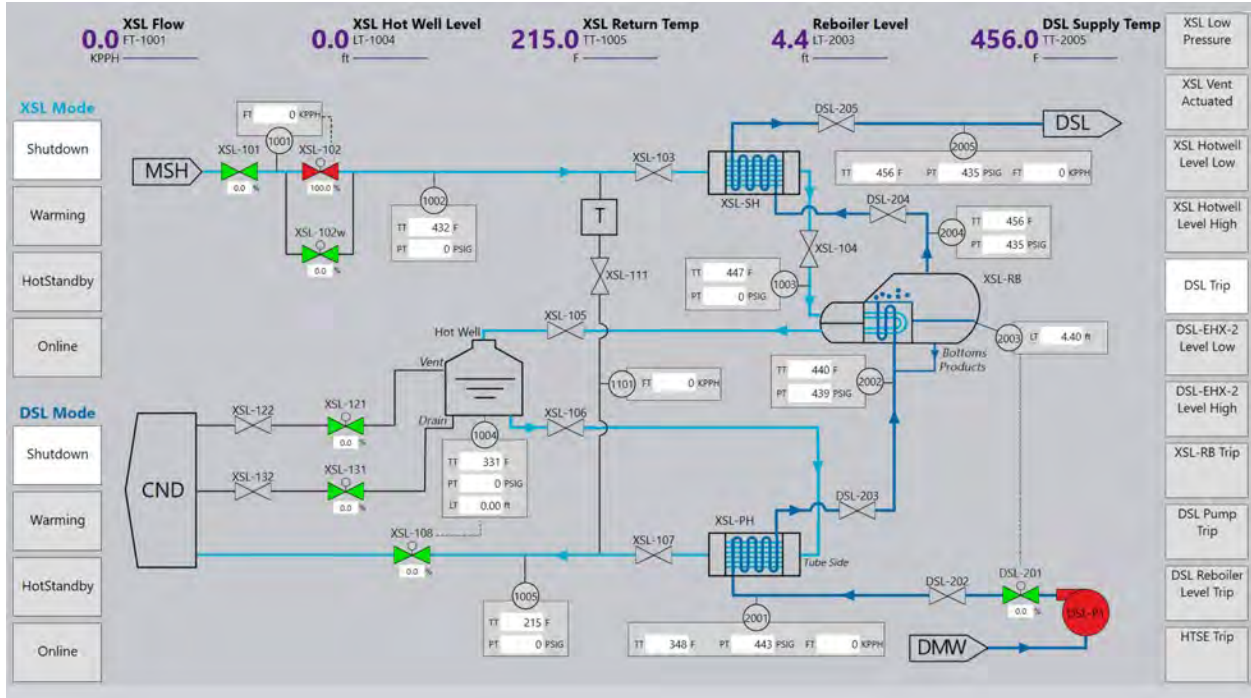
Figure 3. TPD indication display depicting the XSL and DSL P&ID diagram representations with embedded instrument clusters. System modes are positioned along the left side, and alarms are positioned along the right.

Figure 4. TPD display using a task-based display approach to provide pertinent parameters near the main flow controller (FC-1001) used for normal TPD operations.

Figure 4 shows the control display, which is quite standard. The notable design feature for the control display is the task-based indication included for the primary flow controller (FC-1001) to alleviate

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operators from redirecting their attention to the control board to verify pertinent parameters while actively manipulating the flow control valve during the normal evolutions.

2.5   Scenarios

The primary concern with the TPD centers on impacting reactivity via feedback is due to its use of steam from the main steam system. The TPD consumes steam, and it is essentially a steam leak as viewed by the existing plant systems and their configuration since they are tuned to the turbine receiving the steam at known rates for optimal efficiency.

A series of 15 scenarios were identified prior to the study that would evaluate the plant and operator responses to these known vulnerabilities associated with the TPD modification to existing plant operations. The following sections describe the rationale for each scenario's inclusion in the study in terms of four key elements: (1) the issue the scenario was intended to address; (2) the initial scenario conditions; (3) the progression of the scenario regarding key plant parameters and (4) the operators' predicted and expected responses as they use the procedures and their skill of the craft to work through the scenarios.

The 15 scenarios were put into five blocks denoting a common grouping that supported the analysis performed on the scenarios. They included normal and abnormal existing plant operations and normal and abnormal TPD operations. This schedule of scenarios was selected to provide a comprehensive test of operator performance within TPD operations benchmarked against existing plant operations (see

Table 1). For example, the first block of scenarios comprised one SGTR without the TPD system followed by three TPD variations evaluating different types of technologies to support the operators responding to the primary SGTR fault while also contending with the TPD. These scenarios included failed manual actuation, successful manual actuation, and automatic actuation. The scenarios in this block support comparing the operators' responses to an SGTR fault with variants on the implementation of the TPD, thereby identifying the most appropriate implementation of the TPD for that scenario context. The five blocks and corresponding scenarios are explained next.

Table 1. Description of scenarios and corresponding procedures.

Block	Scenario	Description	Procedure
1	1	SGTR using GPWR without the TPD in operation	AOP-16, EOP-E-0
1	2	SGTR with TPD Failed Manual Trip	AOP-16, EOP-E-0
1	3	SGTR with TPD Automatic Trip	AOP-16, EOP-E-0
1	4	SGTR with TPD Manual Trip	AOP-16, EOP-E-0
2	5	Hot Standby to Online at 5 MW/min Turbine Ramp Rate	OP-TPD-002
2	6	Hot Standby to Online at 15 MW/min Turbine Ramp Rate	OP-TPD-002
2	7	Online to Hot Standby at 10 MW/min Turbine Ramp Rate	OP-TPD-003
2	8	Online to Hot Standby at 20 MW/min Turbine Ramp Rate	OP-TPD-003
3	9	TPD Steam Line Leak	No Procedure
4	10	Load Rejection GPWR without the TPD in Operation	AOP-15
4	11	Load Rejection GPWR with the TPD in Operation	AOP-15
4	12	Load Rejection with TPD in Operation	AOP-15
4	13	Load Rejection without TPD in Operation	AOP-15
5	14	Hot Standby Failed CV (looks like main steam leak)	OP-TPD-002
5	15	Hot Standby Evolution Interrupted with Load Rejection	OP-TPD-002, AOP-15

Note. MW=Megawatts; CV=Control Valve

2.5.1   Block 1 Steam Generator Tube Rupture (Scenarios 1–4)

A total of four SGTR scenarios (referenced as Scenarios 1–4) were selected. The first was a generic SGTR selected to reacquaint the operators with the control boards and act as a baseline warm-up scenario.

See Table 2 for initial conditions for all SGTR scenarios. Three TPD-related scenarios were selected to evaluate how the TPD should be isolated following a plant transient with the tube rupture serving as the fault. The three variants included a manual isolation performed by operators, an automatic isolation linked to the turbine trip signal, and a failed manual isolation in which the operators could not manually isolate the TPD. The automatic isolation is the quickest isolation route, the manual requires more time due to the operators performing the immediate post-trip actions and then tripping the TPD, and the failed manual isolation represents an un-isolated TPD during the SGTR transient. The fourth scenario was particularly pertinent as it was selected to evaluate the impact of the TPD continuing to draw steam while the operators were actively contending with the transient, which could result in a more complicated transient and challenge the operators beyond existing operations.

Table 2. Initial conditions for the main plant operating at full power without the TPD and with the TPD in operation used for the SGTR, load rejection, TPD steam line leak, and miscellaneous fault scenarios.

Main Plant	(a) Without TPD in Operation	(b) With TPD Online
RCS $Tavg$	588.9 °F	588.8 °F
Pressurizer Pressure	2243.4 PSIG	2241.4 PSIG
Pressurizer Temp	652.2 °F	651.9 °F
Rx Power	99.6%	99.8%
RCS Pressure	2250.3 PSIG	2248.3 PSIG
Boron	795.9	795.8
Core Life	Middle of Life	Middle of Life
Rod Pos	210	210
TCS Demand	936 MW	705 MW
Thermal Power Dispatch		
XSL Flow Rate	0 KPPH	1939 KPPH
XSL Hot Well Level	0 ft	13.37 ft
XSL Return Temp	0 °F	400 °F
Reboiler Level	0 ft	3.5 ft
DSL Supply Temp	0 °F	518 °F

Note. $Tavg$ = Average Temperature; RCS = Reactor Coolant System; TCS= Turbine Control System.

2.5.2 Block 2 Normal TPD Operations (Scenarios 5–8)

The normal TPD operations scenarios were selected to evaluate two primary aspects of the TPD system. First, the scenarios built on the previous year's effort that evaluated the TPD normal operations in an isolated prototype environment. The GPWR plant was integrated with the prototype during this study to provide greater fidelity and a much richer plant variable environment. The operators were able to view and control indication on virtually represented control boards representing the plant. Second, these scenarios were intended to evaluate the speed of the hot standby to online and online to hot standby evolutions. In the current design, the operators were provided with manual controls to manipulate the XSL-102 control valve in tandem with manual turbine load adjustments to divert steam from its typical flow path to the turbine and direct a portion of the steam to the TPD. The speed, as dictated by different turbine load adjustment rates, can impose different levels of workload on the operators as they may have to accelerate their manipulations to avoid raising the average temperature (T_{avg}) and reference temperature (T_{ref}) mismatch to the point that reactivity would be impacted, and rods would begin stepping to adjust. These scenarios supported identifying the ramp rates that provided sufficient time while also maintaining the contrasting goal of a quick transfer between modes of operation necessary for the economic viability

of the TPD concept of operations. The intersection of these two goals was critical to aiding the system design as it matured. Furthermore, these scenarios were also useful in evaluating the manual control capability and assisting in determining the need for automatic control functionality to preclude the manual valve manipulations and coordinate the turbine load adjustments such that the operator sets these and monitors as opposed to monitoring with active manipulations during the evolution.

Scenarios 5 and 6 (hot standby to online) initiate with the TPD system in hot standby and OP-TPD-001 Shutdown to Hot Standby successfully completed. The transition from hot standby to online state is an important task to evaluate because it may occur frequently and can impact reactor power. The operators set a ramp rate on the turbine with a target setpoint of 705 MW and then open XSL-102 using flow controller 1001. The operators have a 1% and 10% option to increment the position of the valves with a desired valve position of 62% open achieving the 1936 KPPH flow rate for the XSL. See Table 3 for initial conditions for hot standby.

Table 3. Initial conditions for the hot standby TPD mode of operation.

Main Plant	With TPD
RCS T_{avg}	588.9 °F
Pressurizer Pressure	2242.9 PSIG
Pressurizer Temp	652.2 °F
Rx Power	98.6%
RCS Pressure	2249.8 PSIG
Boron	795.9
Core Life	Middle of Life
Rod Pos	210
TCS Demand	920 MW
Thermal Power Dispatch	
XSL Flow Rate	97 KPPH
XSL Hot Well Level	8 ft
XSL Return Temp	335 °F
Reboiler Level	3.5 ft
DSL Supply Temp	461 °F

Scenarios 7 and 8 simulated the transition from online to hot standby state, which is the reverse of the hot standby to online evolution. The evolution reduces the flow through the XSL to move from an online to hot standby state, such that the thermal power is directed back to the turbine to restore full electrical power generation. Specifically, the evolution requires operators to reduce flow through the XSL to a predetermined minimal target flow rate and, in tandem, ramp the turbine to normal flow rates and demand for electrical power generation. See Table 4 for initial conditions used for the online scenarios.

Table 4. Initial conditions for the online TPD mode of operation.

Main Plant	With TPD
RCS T$_{avg}$	588.8 °F
Pressurizer Pressure	2241.4 PSIG
Pressurizer Temp	651.9 °F
Rx Power	99.8%
RCS Pressure	2248.3 PSIG
Boron	795.8
Core Life	Middle of Life
Rod Pos	210
TCS Demand	705 MW
Thermal Power Dispatch	
XSL Flow Rate	1939 KPPH
XSL Hot Well Level	13.37 ft
XSL Return Temp	400 °F
Reboiler Level	3.5 ft
DSL Supply Temp	518 °F

Note. RCS = Reactor Coolant System

2.5.3   Block 3 TPD Steam Line Leak (Scenario 9)

This was a stand-alone exploratory scenario without procedure support. This scenario was selected to determine the impacts, symptoms, and responses for a steam line break within the TPD system. The primary indication to alert the operators to the steam leak in the TPD is the XSL low-pressure alarm. The operators were briefed that the plant was operating in a hybrid turbine and TPD online mode of operation and were instructed to monitor the boards for an impending fault. There were not informed that the fault would be specific to the TPD but were advised to monitor it as part of their overall plant monitoring. A break in the XSL downstream of the main control valve, XSL-102, was inserted. The initial conditions used for this scenario can be found in Table 4.

2.5.4   Block 4 Load Rejection (Scenarios 10–13)

The load rejection fault scenarios were selected because they involve the main steam system and changes in flow. The secondary steam system serves as the heat sink for primary system through the steam generator coupling. As a result, secondary steam flow can impact reactor power. Since the TPD is receiving steam from the main steam header, evaluating the impacts of the TPD on a load rejection transient was considered critical to ensure operators can address the transient without being unduly challenged by any additional complexity from the TPD in operation. Two of the scenarios evaluated the operators' baseline response to a load rejection without the TPD in operation and two scenarios evaluated the operators' response with the TPD online using the initial conditions (a) and (b) from Table 2 respectively.

In a typical load rejection event, the generator electrically coupled to the grid experiences a sudden and large load demand reduction. The generator no longer has any resistance to push against as it produces current. The lack of resistance allows the generator to spin freely and unencumbered by any electrical load. Since it is mechanically coupled to the turbine shaft, the turbine begins to increase its revolving speed without any torque applied from the generator. The governor valves begin to close to prevent over speeding the turbine. In turn, this decreases the steam flow through the secondary system. As

flow is reduced, the heat transfer from the primary to secondary systems is also reduced. The mismatch between T_{avg} and T_{ref} increases, and the steam dump actuation threshold is exceeded. This results in the steam dump valves opening, which increases steam flow and lowers the average temperature of the primary coolant (i.e., T_{avg}). T_{avg} is inversely related to reactivity, or reactor power, due to the moderator temperature coefficient of reactivity for light-water reactors being negative. As T_{avg} decreases, the control rod actuation threshold is exceeded, and the rods begin to step in to reduce reactivity driven by the cooler T_{avg} coolant. While the steam dumps are open, the TPD enhances the cooling effect by drawing additional steam and can result in a greater transient and potentially larger rod motion. The thresholds for the automatic systems can be seen in Table 5.

Table 5. T_{avg} and T_{ref} mismatch plant responses.

Automatically Actuated Plant Response	Threshold
Control rods step out (retract) to raise reactivity	1.5 °F
Steam dumps open	3.0 °F

To induce this block of scenarios, a load rejection was simulated by failing to close one of the governor valves to effectively induce a 25% load rejection. This represents a significant plant transient as a 10% load rejection is sufficient to induce the steam dumps to open and maintain steam flow through the secondary system to mitigate any rises in T_{avg} if left unmitigated by any operator responses. As the TPD will continue to draw steam during the transient, it mitigates some of the lead rejection impacts, but it also complicates the transient, and therefore, it is a crucial scenario to understand how operator response is impacted by the TPD system.

2.5.5 Block 5 Fault TPD Unknown Plant Event Operations (Scenarios 14–15)

Scenario 14 simulated the TPD in hot standby, and XSL-102 CV fails to open, but the valve position reads normal. This scenario was included to evaluate a more nuanced failure in the TPD that would require the operators to quickly respond and isolate the system before it adversely impacted the primary plant. Additionally, as no automatic isolation exists in the current design, it was selected to evaluate the need for an automatic isolation. The operators were required to manually respond, which imparts a time delay in the response and could be delayed sufficiently to result in adverse plant impacts. The scenario begins with the TPD in hot standby. The operators were not informed of the specific fault but were briefed that an unknown event will occur.

Scenario 15 simulated the TPD hot standby to online with added load rejection. This scenario was selected to evaluate a main plant transient during an active TPD evolution. The central issue addressed by the scenario is how operators switch their attention from the TPD evolution to the load rejection impacting the main plant. In particular, the central question was whether the operators would simply abandon their TPD procedure and leave it in its current state or isolate the system as they handle the load rejection transient. The operators begin the scenario with OP-TPD-001 completed and initiate performing the hot standby. Once they open the valve to 3% (5% stream extraction), one governor valve failed shut (a load rejection). The failure induces an alarm such that the operators must potentially abandon the TPD in favor of diagnosing the issue. The scenario is quite challenging because the operators are actively manipulating the turbine with multiple governor valves in intermediate positions, making it difficult to determine whether the governor valve had in fact failed.

2.6 Draft Procedures

The participants executed the scenarios using accompanying draft procedures (see Table 6). These were organized into five distinct blocks of procedures. Block 2 comprised normal operations TPD procedures that were revised from the past online study completed in 2020. These comprised hot standby to online (OP-TPD-002) and online to hot standby (OP-TPD-003), and their development prior to this study is reported elsewhere (Ulrich[b] et al. 2021). Once written by the INL human factors team, these draft

procedures went through several iterations including reviews by four former NPP operators to ensure their validation, and that they were worded and ordered correctly. The updates to these normal TPD operations for the current study were primarily to make sure the operating parameters were correct for the currently developed TPD model for GPWR. Because the shutdown to hot standby procedure would rarely be performed and extracts a very small amount of steam, we elected not to carry out a shutdown to hot standby scenario this year.

Last year's study did not examine any fault conditions. A rapid shutdown procedure was developed for Blocks 1, 4, and 5. A normal TPD shutdown has the operators set a TCS load target and ramp rate. As the turbine picks up load, the extraction through the TPD is reduced to the hot standby flow. With the rapid shutdown, the operators quickly close extraction flow and isolate the TPD. We also modified GPWR's OP-TPD-005 procedure for loss of component cooling water to isolate the TPD on Step 14. There was no procedure for the scenario in Block 3 (Scenario 9), because we wanted to determine how the operators would respond to a steam line break within the TPD system without procedural support. The SGTR was performed with the existing fault procedure (AOP-16, EOP-E-0).

Lastly, all procedures were subjected to a final check from two members of the research team 1 day prior to the study commencement in which minor corrections (e.g., typos) were made. The OP-TPD-002 procedure is provided as an example in Appendix A.

Table 6. Catalog of Draft Procedures

Procedures	Title	Notes
OP-TPD-001	Shutdown to Hot Standby	Not used in FY-21
OP-TPD-002	Hot Standby to Online	Revised for FY-21
OP-TPD-003	Online to Hot Standby	Revised for FY-21
OP-TPD-004	Shutdown	Revised for FY-21
OP-TPD-005	Load Change	New for FY-21
AOP-TPD-001	TPD Rapid Shutdown	New for FY-21
AOP-014(TPD)	Loss of Component Cooling Water	Revised GPWR

2.7   Measures

2.7.1   Demographics

A basic demographics form was administered that captured age, sex, and years of experience in nuclear power operations.

There were several forms of measurement, both qualitative and quantitative that converged to comprehensively capture TPD and TPD HSI performance findings, benchmarked against existing operations.

2.7.2   Scenario Administrator Log Observations

The scenario administrator took extensive observation notes via a laptop and captured debrief data pertinent to the hypotheses for each scenario. The nuclear engineer designer who built the TPD model within the GPWR simulator acted as the simulator instructor and provided comments and feedback on these observations. Additionally, the facilitator for the study, who has decades of nuclear operations experience, also provided comments and feedback on the observation notes. Lastly, the lead HSI developer also provided comments and feedback on the observation notes. Collectively the input from these individuals captures aspects of the scenarios in extensive detail and provides a descriptive narrative of the scenarios.

2.7.3   Simulator Logs

Several records of raw simulation data were collected from the simulator. These information-rich logs provide information not only on the plant behavior but also operator responses during simulation scenarios. The precise method by which these data points can be used to evaluate human performance is still being developed within human reliability analysis (HRA; Boring et al. 2017). Specifically for this study, the simulator logs served as a secondary data source to consult when an adverse plant response was identified. For example, the automatic safety system actuations are triggered at specific values, and it can be useful to identify these thresholds by examining the simulator log to determine the combination of parameters that induced the actuation. Furthermore, the logs can also serve as evidence for operator performance in terms of the deviation magnitude from optimal operating values for components. For example, if a loss of pressure in a system denotes a larger deviation from optimal, then the scenario can be examined to provide objective operator performance ratings based on the actual system response.

2.7.4   Tomlogs

An Excel template with build-in macros function was used to record different aspects of the scenarios. Aspects included operator at the controls (OATC) actions, shift supervisor (SS) actions, procedures, usability errors, and others. Observers logged the communications, actions, and usability factors observed during each scenario into their individual Tomlog. Remarks were separated into codes, procedures, and observations. Each remark was automatically timestamped as it was logged. At the end of each scenario, members of the observation team saved and uploaded their Tomlogs to a secure storage server.

All individual Tomlogs were combined to create a complete, chronological, list of records for each scenario. The time stamp was used to calculate the interval of each observation from the start of the scenario. The list was then sorted in chronological order by interval. All records in the combined Tomlogs are categorized by code, procedure, or observation and include columns that specify which observer logged the information and what aspect they were monitoring.

2.7.5   Scenario Debriefs

After each scenario was completed, each member of the observation team recorded their observations of the ensuing discussion using handwritten notes. The number of observers that made observation notes for each scenario is reported in Table 1. These data were processed by extracting relevant observations noted about the TPD system and TPD HSI and counting the number of times a relevant observation was recorded. A relevant observation was then deemed to be salient, according to the following criterion: N > 6 observers, relevant observations had to be recorded at least 3 times; 3< N≤ 6 observers, relevant observations had to be recorded at least twice; and N≤3 observers, all relevant observations were deemed salient. All relevant and salient observations are reported in the Results section.

The observation team also took part in an end-of-week debrief at the end of the workshop, during which time they recorded their observations of the overall discussion of all the scenarios using handwritten notes.

2.7.6   Survey Data

There were four questionnaires administered to the participants following each scenario. The participants completed each of these a total of 15 times.

2.7.6.1   SART - Situation Awareness Rating Technique

The SART (Taylor 2017) is a perceived situation awareness measure composed of nine dimensions using a 10-point rating scale (1=low; 10=high). The dimensions reflect the speed of change within the scenario, scenario complexity, number of factors that change during the scenario, level of alertness,

required attention, division of attention, mental workload, amount of information, and familiarity with scenario. A composite score is derived whereby a greater value denotes greater situation awareness.

2.7.6.2 Modified Cooper Harper

The modified Copper-Harper (MCH) rating scale is used to estimate perceived workload. A version was originally developed by the aircraft industry to examine the degree to which the cockpit displays supported information processing in pilots (Cummings, Myers, and Scott 2006), and it is used here to capture the level of difficulty and level of mental effort required to obtain the desirable outcomes. The measure contains a decision tree with up to three questions, depending on how far one progresses through the flowchart, and results in one single difficulty score as follows:

1. Very Easy

2. Easy

3. Adequate

4. Inconvenient

5. Tolerable

6. Difficult but Tolerable

7. Difficult

8. Highly Difficult

9. Severe Difficult

10. Impossible

2.7.6.3 National Aeronautics and Space Administration-Task Load Index

The National Aeronautics and Space Administration's task load index (NASA-TLX) (Hart and Staveland 1988) is another workload metric developed by the aviation industry and is a popular workload metric due to its simplicity and general reliability. The NASA-TLX has six dimensions on a 0–10 scale (1=low; 10=high): mental demand, physical demand, temporal demand, performance, effort, and frustration level. It contains good psychometric properties (Farmer and Brownson 2003) and has been widely used across several performance settings including nuclear power operations and requires participants to endorse ratings with the above scale and dimensions.

2.7.6.4 Performance Drivers

Both the operators and all observers completed a performance driver form which asked the individual to rate how well the operators did on certain aspects of the scenario on a scale from highly negative to highly positive. The questionnaire comprises 14 different items, including time, complexity, human-machine interface, and procedural guidance. The performance drivers were then combined into two Excel spreadsheets, one for the observers and one for the operators. Results were logged as numbers following the HRA multiplier ranking scale as shown in Table 7. Note—due to a data collection error, data from the last six items for Scenario 15 are missing.

Table 7. Ranking Scale used for performance drivers

Category	HRA Multiplier Ranking
Highly Positive	2
Positive	1
N/A	0
Negative	-1
Highly Negatives	-2

There were two questionnaires administered to the participants at the very end of the workshop. The participants completed these only once.

2.7.6.5   Glasstop Simulator Review

This 10-item questionnaire consists of six Likert rating scales and four open-ended questions regarding the efficacy, likability, and usability of the glasstop simulator itself. It also asks participants to draw comparisons to real NPP control rooms and the last iteration of the glasstop at the HSSL (if applicable). The purpose of the questionnaire is to identify key areas of improvement in the glasstop simulation hardware (Ulrich, Boring, and Lew 2014), and is not pertinent to any of the research hypotheses or testing scenarios.

2.7.6.6   Usability Questionnaire

This was a 23-item questionnaire that asked questions specific to the usability of the TPD HSI itself. Items included whether the display was easy to read, its usability and understandability, and overall function. It asks about alarms and colors and other design features of the HSI. There were nine 5-point Likert scale questions (strongly agree / agree / neither agree nor disagree / disagree / strongly disagree), and 14 binary yes/no questions. The binary questions provided an opportunity to explain any answers with written text. The purpose of the questionnaire is to identify key areas of improvement in the interface itself and is not pertinent to any of the research hypotheses or testing scenarios.

2.7.7   Eye Tracking

Eye tracking is commonly used to identify the allocation of visual attention in an operator. The location and pattern of fixations allows inferences about the focus of cognitive processing during the execution of complex tasks.

Both operators' eye movements were recorded during each scenario. Operators were fitted with head-mounted eye-tracking glasses (SensoMotoric Instruments), a battery pack, and a recording device (mobile Android phone) prior to the start of each scenario. The head-mounted glasses recorded video of the central visual field of each operator based on their position and head-orientation, and sampled gaze direction relative to the recorded video based on pupil orientation at 60 Hz. Scene video and audio was recorded at 24 Hz.

Before the onset of data collection, a short three-point calibration routine was conducted during which operators were asked to fixate on three corners of the displays. This calibration had to be repeated before each scenario due to variations in the position of the glasses and the operators sometimes wearing corrective lenses and other times not. Once calibration was successful, the system was switched into recording mode.

2.7.8 Video

Two synced video cameras were set up to capture the participants' communication and movements. The video also served as a record of the debriefs and was available to reference if clarification was needed during subsequent data analysis. No formal results were reported for the video recordings.

2.8 Procedure

2.8.1 Research Team Measures Training and Coordination

One day prior to the commencement of the study, the research team underwent training and coordination and became acquainted with the physical layout of the HSSL, their stations, and their specifics roles within the study. After the simulation environment was set up, the observation team were given training in using Tomlogs in Excel by the manager of the Human Factors and Reliability Department at INL. It was at this point that some observers were assigned specific areas of focus during testing (i.e., procedure timeline tracking, communication/procedure issues, and HSI information/interaction issues).

The research team also participated in a dry run, in which one of the scenarios was carried out with two members of the research team acting as OATC and SS. This allowed both the experienced and inexperienced members of the team the opportunity to familiarize themselves with the testing environment and practice capturing data using the measurement tools. It also afforded the research team the opportunity to ask any questions prior to the commencement of the data capture window with the operators the following day.

2.8.2 Consent

On the first day of testing soon after introductions, the participants provided written consent to participate in the study and completed the demographics form. A brief safety protocol was given, and the participants were then presented with training and familiarization of the TPD.

2.8.3 Training and Familiarization

System Overview

By way of introduction and education of the novel system, the chief nuclear engineer presented a high-level overview of the TPD concept, the economics, and how it operates with existing NPPs. Then, the nuclear engineer that designed the TPD system HSI presented an overview of the system and described the functionality. He used a slide deck with explanations and system design drawings. He pointed out key functions and system behavior and noted simulation limitations. He also walked the operators through the system using the P&ID and control display. Conventions for the interface were briefly described (the color coding of the XSL and DSL loops and the naming of these loops were discussed).

Procedure Walkthrough and Review

The participants then "walked the boards" and familiarized themselves with the HSSL layout. The goal was to orient the participants to the new upgraded HSSL and practice using the prototype HSI. Participants were able to ask questions, explore the interface, and generally become comfortable with the TPD. Allowing the participants time and practice sessions to acquaint themselves is important, so that the testing sessions examine the quality of the HSI and not learning effects, and the most useful and productive data is captured.

During the procedure review several notable findings were made. The TPD is not a safety system and the procedure for abnormal startup (which is intended to be used as a diagnostic procedure to identify leaks in the system) would never be used in the plant. The response would simply be shutting the system down and then directing an investigation team to develop a procedure to identify the leak. As this is steam

from the main steam system, it is superheated, and therefore, it poses a significant safety risk for anyone entering the area with a potential leak. This procedure was discarded and the associated scenarios, TPD heat exchanger and steam leak scenarios were abandoned in leu of other scenarios of interest.

2.8.4   Testing Scenarios 1–15

In the afternoon of the first day, the participants completed Scenarios 1–2, and a 1-hr discussion, and refinement followed, which comprised a warm-up exercise and did not include any TPD component. This was done to refamiliarize the participants with existing NPP operations and build confidence and assurance in completing scenarios under research conditions. The remaining 13 scenarios, most of which involved thermal power scenarios, were completed over the course of the next 2 days. Before each scenario began, the participants were fitted with the eye-tracking glasses before getting situated. Participants were counterbalanced across stations throughout the entire workshop (i.e., if a participant were SS for one scenario, they were OATC for the following scenario). A facilitator (one of the individuals with prior experience in the commercial nuclear power industry) provided a brief introduction of the scenario about to unfold, announced the date and time, which participant was at the controls and who was SS, and closed a clapperboard to declare the commencement of the scenario. The clapperboard also provided the date, time, role of the participant, and scenario number and was in full view of one of the video cameras, as well as the participants who were wearing eye-tracking glasses. Additionally, when the clapperboard shut, the participants were asked to orient their eyes to it, in a bid to synchronize the timestamps from the simulator, eye-tracking equipment, and video footage.

At the end of each scenario, the participants completed the SART, MCH, NASA-TLX, and performance drivers questionnaires. All members of the research team as well as the individuals with prior experience in the commercial nuclear power industry also completed the performance drivers questionnaires. Once questionnaires were completed, 15-minute scenario debriefs occurred after each scenario or pairs of scenarios. Debriefs were led by the facilitator and were collective roundtable discussions in which issues identified during the scenarios were discussed, as well as any other topics the participants or facilitator wished to discuss. Additionally, all members of the research team, the nuclear engineers, and the individuals with prior experience in the commercial nuclear power industry were given the opportunity to ask questions and raise pertinent points. The observation team collected the debrief information via handwritten notes.

2.8.5   Closing Out The Workshop

On the last day, the participants took part in a 30-minute tour of Thermal Energy Delivery System on site at INL. After all scenarios were completed, there was a 1-hr end-of-week debrief of all the scenarios, involving the participants, all members of the research team, the nuclear engineers, and the individuals with prior experience in the commercial nuclear power industry. The purpose of the end-of-week debrief was to discuss and capture high-level comments on the overall function of the TPD system and HSI that may not have been possible at the individual scenario debrief level. The extended time allocated for the end-of-week debrief allowed everyone to consider deeply all the scenarios and events over the course of the workshop and discuss at length. The observation team collected the debrief information via handwritten notes.

Finally, the participants ended the workshop by completing the Glasstop Simulator Review and Usability Questionnaire surveys.

3.   RESULTS

3.1   Scenario Administrator Log Observations

All the scenarios selected for study pertain the main steam system from the perspective of potential impacts the TPD may cause on the main steam system. In pressurized-water reactors, reactor power is governed in part by steam flow rates through the temperature changed feedback on reactivity. As the TPD

has the potential and by design impacts the flow rate within the main steam system, it was critical to select scenarios to examine the interactions between TPD evolutions to support normal operations as well as the impact of the TPD on transients and operators' responses to those transients as they attempt to return the plant to safe operating envelope. Each scenario block focuses on particular relationships between the TPD and the main steam system to evaluate the concept of operations for thermal power dispatch. Observations taken by the primary investigator while conferring with the lead nuclear operations expert, lead simulator developer, and lead prototype developer were recorded as the scenario administrator log. These four individuals possessed intimidate knowledge of scenarios in terms of their rationale pertaining to evaluating the TPD concept of operations, simulator response, and predicted operator response. These observations serve as a narrative for each scenario, which includes anticipated and unexpected outcomes including challenges the operators encountered while performing the scenarios. These observations are results in themselves; however, they also provide the context for interpreting the other data sources in regard to operator performance and represent a unique data set collected during the study.

3.1.1 Block 1 Steam Generator Tube Rupture (Scenarios 1–4)

The block of SGTR scenarios was included to evaluate the impacts of the TPD on the plant and operators' responses to significant fault-induced transients occurring within the main plant. The SGTR was selected as it is a significant transient relevant to the main steam system. Furthermore, it is a well-known event both from the perspective of standard operator training and human performance within the context of HRA. Therefore, the SGTR serves as a good benchmark of operator performance and can provide a good basis for comparison against the proposed TPD operations.

An SGTR fault consists of a rupture in the boundary between the primary and secondary plant systems. The primary system operators at a higher temperature and pressure than the secondary, which leads to the primary coolant leaking into the secondary system and a loss of primary reactor coolant. For each of the SGTR scenarios, a tube rupture malfunction at a rate of 500 gpm on steam generator B is inserted into the simulator. The tube rupture was sufficiently significant that it exceeded the make-up capability of the primary system and required a turbine trip. The operators should ideally initiate the reactor trip and safety injection; however, due to the severity of the leak, the automatic protection systems will engage and induce an automatic plant trip if the operator does not act swiftly. The reactor and turbine trip offline. The operators must then work through the post-trip actions to validate safety system operation, and then, they proceed to diagnose the issue. The diagnostics entails determining the loss of coolant originating from the steam generators and then identifying which steam generator was ruptured. The scenario terminated upon identifying the correct steam generator as ruptured.

Specifically, variations of the required operator response to an SGTR were evaluated to address the general issue of how operators should incorporate any responses required for the TPD in addition to the post-trip actions required as part of the SGTR scenario. Different levels of intervention were tested to provide insights as to whether a manual or automatic trip, isolation of the TPD from the main steam system, should be implemented. There were three variants of manual versus automatic trip of the TPD scenarios completed. A failed manual actuation scenario represented the worst-case scenario in which the operators attempted to trip (isolate) the TPD, but the actuation failed, and the system continued to function with the operators then forced to contend with the transient with the added complexity of the TPD. A manual actuation required the operators to manually trip the TPD as they transition to responding the main plant transient. An automatic actuation required no operator action by tripping the TPD in tandem with the turbine trip signal.

3.1.1.1 *Scenario 1 – SGTR Using GPWR without the TPD in operation*

During the first SGTR scenario without the TPD in operation, the operators entered AOP-16 following the radiation monitoring system annunciator. The crew determined the unknown leak was in excess of make-up capability, manually tripped the reactor, and manually initiated safety injection. The

operators then entered EOP-E-0, which includes assessing the appropriate actuation of the protection systems and identifying the source of the leak as a steam generator. Once the impacted steam generator was identified, the scenario terminates on Step 29. "GO TO E-3, "STEAM GENERATOR TUBE RUPTURE", Step 1. TUBE RUPTURE", Step 1." which entails isolating and mitigating the affect steam generator.

This was the first scenario of the study and the operators reported difficulty with the glasstop simulator itself. The virtual control panels were scaled to approximately 70% of their actual size of the main control room. The operators had participated in prior experiments in the HSSL using the older bays which, due to their lower resolution, were required to display the control panels at 90% of their actual size. The smaller scale proved to be challenging for the operators to discern some indication. In addition to being challenging to read, the reduced scale required the operators to reorient themselves in a new way to the spatial relationships between indication. Though reading the indication remained an issue throughout the remaining scenarios, subsequent scenarios demonstrated less difficulty in orienting as the amount of challenge reported by operators was much less if not nonexistent in subsequent scenarios.

3.1.1.2   Scenario 2 – SGTR with TPD Failed Manual Trip

A tube rupture malfunction at a rate of 500 gpm on steam generator C was inserted into the simulator. The operators entered AOP-16 following the radiation monitoring system annunciator. The crew determined the unknown leak was in excess of make-up capability and manually tripped the reactor and entered EOP-E-0. The OATC attempted to trip the XSL system using the Trip XSL button on the TPD system; however, this failed, and the TPD system continued to draw steam from the main steam system, mimicking a main steam line leak from the plants perspective. As a result, the OATC did not have sufficient time to manually initiate safety injection before it was automatically triggered by the plant due a reduction in T_{avg}. Furthermore, the unmitigated leak caused the main steam isolation valves to close, which did not happen in any other condition. Once the impacted steam generator was identified, the scenario terminates on Step 29. "GO TO E-3, "STEAM GENERATOR TUBE RUPTURE", Step 1. TUBE RUPTURE", Step 1." which entails isolating and mitigating the affect steam generator. In this manual XSL failed trip scenario, the operators were unable to activate the safety injection and plant trip preemptively due to wasted time attempting to manually trip the XSL. The effects of the XSL further complicated the leak in the steam generator, and the operators were delayed in their response. This scenario illustrated that relying on manual trip alone is inadequate in the event the operators are unable to do so. The progression of the plant systems to automatically actuate represents a more degraded state of the operators' control over the plant, and though no catastrophic failures or damage occurred as a result, the outcome is not characteristic of good operation and an automatic backup was highly suggested.

3.1.1.3   Scenario 3 – SGTR with TPD Automatic Trip (Most Like Expected or Existing Plant Behavior)

A tube rupture malfunction at a rate of 500 gpm on Steam Generator A was inserted into the simulator. The operators entered AOP-16 following the radiation monitoring system annunciator. The crew determined the unknown leak was in excess of make-up capability, manually tripped the reactor, and entered EOP-E-0, which includes assessing the appropriate actuation of the protection systems and identifying the source of the leak as a steam generator. Once the impacted steam generator was identified, the scenario terminates on Step 29. "GO TO E-3, "STEAM GENERATOR TUBE RUPTURE", Step 1. TUBE RUPTURE", Step 1." which entails isolating and mitigating the affect steam generator. The scenario played out quite similarly to a regular steam generator tube rupture scenario, which indicates minimal impact on plant operations when using an automatic XSL trip capability.

3.1.1.4   Scenario 4 – SGTR with TPD Manual Trip

A tube rupture malfunction at a rate of 500 gpm on Steam Generator B is inserted into the simulator. The operators entered AOP-16 following the radiation monitoring system annunciator. The crew

determined the unknown leak was in excess of make-up capability, manually tripped the reactor. The operators then entered EOP-E-0 and were able to initiate manual safety injection while performing immediate post-trip response actions. The OATC did successfully depress the manual Trip XSL button but was looking at the monitoring display and did not see the confirmation dialogue as a result. The valves did close as expected, but the confirmation was never confirmed and should be corrected to not actuate and inform but rather only allow the signal to trip to be sent upon confirmation. A potential fix for the missed confirmation is to provide an isolation indicator in close proximity to the "Trip XSL" button. An XSL trip annunciator would also be useful for the SS to identify the XSL has been isolated. Following the manual trip, the operators then continued through EOP-E-0 to identify the source of the leak as a steam generator. Once the impacted steam generator was identified, the scenario terminates on Step 29. "GO TO E-3, "STEAM GENERATOR TUBE RUPTURE", Step 1. TUBE RUPTURE", Step 1." which entails isolating and mitigating the affect steam generator.

3.1.2   Block 1 Steam Generator Tube Rupture Operations Scenarios Conclusions

There were three notable differences with the SGTR evolution of the plant across the four different conditions. With the auto isolation, the operators were able to engage safety injection before it was automatically triggered by the plant. With the failed manual isolation, the delay in isolation of the TPD caused T_{avg} to be significantly reduced, trending down. The reduced T_{avg} value resulted in automated SI activation (by a few seconds), precluding a manual safety injection that is the preferred operating method. Lastly, the SG level of the ruptured SG was higher after the rupture but by the end of the scenario had normalized to the level of the other SGs. The successful manual actuation of the XSL trip did allow operators to manually initiate safety injection, but a reduced T_{avg} and a reduced pressure in the pressurizer (by approximately 40 lbs. per square inch) was observed.

3.1.3   Block 2 Normal TPD Operations (Scenarios 5–8)

The normal operations scenarios were selected to examine the critical evolution envisioned to occur on a daily occurrence in which the plant transitions from a full electric to hybrid electric and TPD mode of operation. These scenarios test both aspects of the evolution including moving from hot standby to online and online to hot standby. Different speeds of the evolution were evaluated by instructing the operators to use different ramp rates for the turbine. Larger ramp rates are desirable to enable quick transitions between modes; however, larger ramp rates require faster valve manipulations of the TPD system and potentially higher operator workloads, which is a potential concern for its adoption.

3.1.3.1   *Scenario 5 – Hot Standby to Online at 5 MW/min Turbine Ramp Rate*

Due to a lack of familiarity with the system, the operators used a conservative approach comprised of exclusively using the 1% valve increment button to raise the valve position from its initial position until the desired flow was achieved. A 10% increment button was also available and noted by the operators, but they never used it during the scenario. The operators never used the 10% increment option for the valve adjustment in this scenario since they were not confident in their understanding of the response characteristics of this valve (due to a lack of familiarity and due to potential modeling issues with the valves representation in the simulation).

The scenario last approximately 70 minutes and was deemed too slow, both for the desired target for transitioning from hot standby to online within 10 minutes and because it prevents the control room from executing other activities that are necessary for an excess amount of time. The strategy used by operators entailed using the T_{avg} and T_{ref} mismatch to guide their valve manipulations. Operators used this strategy in order to avoid rods stepping, which is indicative of significant reactivity changes and should be avoided as a primary operator objective during all activities including TPD evolutions.
The deadband range in which the rods will not move (i.e., minimal reactivity change during the evolution) is a mismatch between T_{avg} and T_{ref} reported as 1.5 degrees. The simulator does not trigger rod steps until

a 2-degree difference occurs, but officially, the operators follow the 1.5 degree value. The operators never exceeded this deadband as evidenced with zero rod steps triggered at any point during the scenario. Indeed, the operators unofficially set their own mismatch limit of 0.5 degrees in which they would then open the valve another 1% increment with confidence they would not exceed the threshold to trigger rods to step. The operators adopted a slightly more aggressive manipulation approach in subsequent scenarios.

During the scenario, the OATC missed the confirmation dialogue while attempting to place the FC-1001 controller in auto. The SS did see the dialogue confirmation and prompted the OATC to acknowledge it. The dialogue was effective in preventing the OATC from taking any further control actions. Additional training and a more salient dialogue prompt could have prevented this issue, and it should be examined in future studies.

3.1.3.2   Scenario 6 – Hot Standby to Online at 15 MW/min Turbine Ramp Rate

This scenario was completed in shorter time than Scenario 5, due to the larger ramp rate which allowed the operators to achieve the evolution in less time. However, the increased ramp rate also places more time pressure and potentially workload on the operators as they now must adjust the TPD to rapidly account for turbine throttle the amount of steam it consumes at a faster rate. Even with the faster ramp rate of 15 MW/min, the evolution was deemed to slow as it engaged the control room for 54 minutes which is undesirable for an evolution that is expected to occur daily.

The operators again missed the confirmation dialogue. While manipulating the setpoint for the automatic flow control of 1936 KPPH, the OATC did not notice the confirmation dialogue, and it was not until the senior reactor officer (SRO) noticed it between 30–60 seconds later that SRO reminded the OATC to click confirm. In that time, the OATC attempted to place the controller in auto, but the confirmation successfully prevented the operator from this, or any other action on the control display, until the OATC selected confirm.

This scenario revealed two issues with the procedures for this evolution. A target flow rate required adjustment to ensure that the operators can successfully step through the procedure since the speed at which they performed the evolution resulted in a slightly lower value than requested in the procedure. operation paths available based on the design. Second, the procedure incorrectly referenced a level transmitter titled, "LT-204". However, the SS referred to the correct LT-2004 instrument since the scheme for the transmitters and controls follows a thousand numbering scheme while the valves and components themselves use a hundreds numbering scheme.

3.1.3.3   Scenario 7 – Online to Hot Standby at 10 MW/min Turbine Ramp Rate

The online to hot standby evolution is the reverse process of the online to hot standby evolutions described in Scenarios 5 and 6. This scenario entails decreasing steam flow to the TPD while ramping the turbine to its traditional full capacity (i.e., receiving all steam and thermal energy generated by the plant excluding any efficiency losses). The online to hot standby scenarios used different ramp rates with the aim of further understanding an appropriate turbine ramp rate that supports the appropriate speed for transitioning the plant from a full turbine to hybrid turbine and TPD mode of operation. The evolution itself is not symmetrical in the challenge it posed operators due to the differing impacts the evolution imparts on reactivity. The hot standby to online evolution reduces reactivity as steam is diverted towards the turbine due the steam loss feedback acting on reactivity. Conversely, the online to hot standby evolution raises reactivity as the additional steam in the system causes feedback to lower reactivity. Therefore, the operators were observed to be more cautious and reported they were more cautious, while performed the online to hot standby evolution. Despite this, the scenarios are still quite equivalent, and the timing information is still useful to inform the turbine ramp rate to achieve a quick yet smooth transition between modes of operation.

The operators were not able to finish the procedure because they moved the valve to 1% and did not want to fully close it. The issue stems from a valve model problem in which the only way to achieve the

hot standby flow target of 97 KPPH is to position the valve at 0.05%, which is not possible from the control display unless you place it in auto. Since they had not achieved the desired flow rate, they could not proceed to the auto setpoint step. A freeze was called; the operators were alerted to the issue and instructed to ramp the turbine to the target 99.8% load level and then switch the valve to automatic mode to achieve the flow rate. The solution suggested by the expert observers includes using two control loops—one for online high flow and one for standby low flow. The low-flow controller and a smaller appropriately sized valve would be used to achieve the appropriate flow at the lower flow rates. Control would be transferred to the high-flow controller for higher flow rates. With this scheme, the system could be controlled more effectively.

A key procedure change was identified and also reported by the operators concerning the prerequisite for the reactor to be below 99%. The operators deemed this unnecessary and suggested removing it from the prerequisites for the normal operation procedures.

3.1.3.4   *Scenario 8 – Online to Hot Standby at 20 MW/min Turbine Ramp Rate*

The operators were able to perform the evolution the quickest under the 20 MW/min condition, though this also placed a greater burden on the workload and attentional demands required to perform the evolution. The operators reported they were concerned that they would overshoot reactor power, so they built some head room in reactor power parameter by building up some turbine demand prior to executing the step that requires the adjustments to the TPD main control valve. The exact timing of this was unknown prior to the study and a key aspect of this scenario is understanding the speed tradeoff between a faster evolution and the critically important ability to control reactivity proactively while manipulating the main TPD control valve in tandem. This is not trivial and procedure changes to support this technique were suggested. Furthermore, the automatic capability to transfer steam between the turbine and the TPD was reiterated as a highly desirable feature to support the implementation of this system without overburdening the operators.

3.1.3.5   *Block 2 Normal TPD Operations Scenarios Conclusions*

The normal operation scenarios created an empirical basis to understand the timing in both plant response and operator behavior associated with the evolutions to change the mode of operation between full electric (turbine) and hybrid (turbine and thermal power delivery). The mode change evolution is required daily to meet the business case for adopting the capability at existing light-water reactors (Boardman et al. 2019). Therefore, establishing the operational feasibility for the evolution requires establishing the timing within the context of operator demands. The timing for each of the four normal scenarios was obtained by examining the Tomlogs for each scenario and can be seen in Table 8. The fastest ramp rate of 20 MW/min achieved a reasonable evolution time of 15 minutes during which the evolution was actively taking place; however, the overall evolution including the preparation, which includes system checks, was longer at 28 minutes in its entirety. The slowest speed for the 5 MW/min ramp rate was universally deemed unacceptable not only due to the lack of flexibility it would afford for operations but also because it engages the control room for a minimum of 54 minutes if the preparation time is not included in the timing estimate. The faster speeds are desirable; however, they are also more challenging to perform for the operators based on the observations from these administrator logs. An automatic option to perform the mode change evolution was reported by operators to alleviate many of the issues they encountered.

Table 8. Timing data for the normal evolution scenarios to transition between the full turbine and hybrid turbine and TPD mode of operation.

| Scenario | Description | Ramp Rate (MW/min) | Timing (min) | |
			Preparation	Execution
5	Hot Standby to Online	5	16	54
6	Hot Standby to Online	10	13	27
7	Online to Hot Standby	15	19	34
8	Online to Hot Standby	20	13	15

3.1.4   Block 3 TPD Steam Line Leak (Scenario 9)

Block 3 was comprised of a single scenario intended to evaluate an anticipated and pertinent failure within the TPD identified through a probabilistic risk analysis, evaluating any additional risks associated with implementing a TPD at an existing light water reactor (LWR). Since the TPD is an extension of the main steam system while it is in a hot standby or online mode of operation, a steam leak will directly impact the main plant. The online mode of operation has larger flow rates, and therefore, the scenario was initiated while the system was in an online mode of operation. The XSL low-flow alarm alerted the operators to the line leak, and they quickly isolated the TPD. The operators then monitored the main plant as the transient induced by the loss of steam dissipated. Since the TPD consumes at most 15% of the main steam flow, the leak within the TPD was quite minimal, and the transient dissipated quickly. The response by the operators was in line with expectations, and no major issues were identified as part of this fault scenario.

3.1.5   Block 4 Load Rejection (Scenarios 10–13)

3.1.5.1   Scenario 10 - Load Rejection Using the GPWR without the TPD in Operation

The scenario began with the plant at full power and without the TPD in operation. A load rejection malfunction was simulated by failing, in the closed position, one of the governor valves on the turbine which represents a 25% load rejection. The operators were quick to have AOP-015 secondary load rejection ready for completion. The operators observed the load rejection event and completed the procedure up through Step 32, which is the step to take corrective actions based on the cause of the load rejection. As this is regularly trained on scenario and did not involve the TPD, there were no critical observations or comments gathered from this scenario. The contrast between this scenario and the variant with the TPD in operation is of more interest and is discussed in the next section.

3.1.5.2   Scenario 11 - Load Rejection Using the GPWR with the TPD in operation

The scenario initiated with the GPWR in an online mode of operation and with the TPD online and consuming 15% of the total thermal reactor power. The operators were instructed to respond to the load rejection using AOP-015 secondary load rejection similarly to the basic load rejection in Scenario 10. After the failure was inserted, the SRO noticed the low-pressure alarm in the main steam system. The notable difference between the basic load rejection and this scenario with the TPD in operation was the plant's automatic response while the operators were responding to the transient. More rod stepping (control rod banks extracting to raise reactivity) was observed during the TPD online scenario. T_{avg} was also impacted during this scenario and was observed to drop 15% beyond what was observed during the basic load rejection scenario. The additional flow of steam through the TPD induced a greater reduction in T_{avg}, which in turn induced more rod insertion during this scenario. Despite this poorer plant performance, it should be noted that the impacts were overall relatively minor. Indeed, the operators reported that the relevant plant tripping parameter associated with a low-pressure signal, induced by the TPD acting as a steam dump during the transient, did not approach anywhere near the threshold level required for the trip.

3.1.5.3   Scenario 12 – Load Rejection with TPD in Operation

During the second load rejection with TPD in operation scenario, the steam dumps were noted to actuate more during this scenario than they did during the first iteration in Scenario 11. As the initiating conditions were identical in both and operator actions were quite similar and could not be attributed as the source to induce the greater actuation, a modeling issue was raised that might account for the discrepancy. As this is a newly developed and experimental model of the TPD system, and no physical system yet exists to validate against it, it was concluded that this was likely due to how model calculated Tref while the TPD is in an online mode of operation. The issue was recorded for examination and potential correction as the project goes forward.

3.1.5.4   Scenario 13 – Load Rejection without TPD in Operation

This scenario transpired identically to Scenario 10, and no additional observations were made since this was a direct replication of the original scenario basic load rejection scenario. The replication served to examine the measures for consistency and ensure they were performing properly as part of our manipulations checking.

3.1.5.5   Block 4 Fault TPD Load Rejection Operations Scenarios Conclusions

Collectively, the load rejection scenarios demonstrated the greater potential impact on Tavg. The load rejection scenarios confirmed that the TPD system does impact plant reactivity though it did not do so in a significant way that moved the plant into an unknown envelope or induced a plant trip. The operators were able to effectively respond to the transient while the TPD was in operation and effectively mitigated the load rejection without any overly problematic plant responses.

3.1.6   Block 5 Fault TPD Unknown Plant Event Operations (Scenarios 14–15)

The final block of scenarios were included as an attempt to pose the most challenging scenario in regard to the operator's ability to detect and mitigate issues. These scenarios included subtle faults with the potential to induce substantial transients on the main plant if they were to go undetected for a brief amount of time. With the inclusion of these scenarios, the research team was able to acquire confidence in the operators ability to respond to unknown events that we cannot foresee at this time or even after establishing a substantial operating history with the TPD implemented at an existing plant.

3.1.6.1   Scenario 14 – Hot Standby Failed CV (Looks Like Main Steam Leak)

This scenario initiates with the plant at full power and the TPD in a hot standby mode of operation. The main TPD valve, XSL-102 CV, and a malfunction on the XSL-102 CV, which is the main flow control valve for the TPD system, was inserted to fail the valve in an open position. The failed open valve manifests as a steam leak from the perspective of the main plant systems as it draws steam inadvertently into the TPD. Operators already undergo extensive training and are qualified to respond to main steam system leaks occurring at various points within the main plants secondary system; however, this variant of steam leak resides within the TPD and requires the operators to identify the source of the steam leak.

Within moments of the fault insertion into the simulator, the reactor coolant system (RCS) Tref alarm triggered in addition to an XSL high-flow alarm on the TPD interface. The RCS Tref alarm was immediately detected by the OATC, but they did not notice the XSL high-flow alarm as their attention was directed to diagnosing the main plant system alarm. Due to a misconfiguration of the prototype HSI, the alarm did not remain lit but was rather tied directly to the Boolean variable representing its threshold activation, and therefore, the alarm disappeared partway through the scenario before the OATC had viewed it, which was also confirmed by the eye-tracking data. The OATC picked up on the overpower event as reactivity climbed from the "steam leak" into the TPD. Additionally, in part because the operators were briefed of the initial conditions and instructed to begin the TPD hot standby to online evolution, the OATC was monitoring the TPD and noticed the flow trend increasing for the XSL portion

of the TPD. This prompted them to actuate the XSL trip button the TPD HSI control display. They failed to see the confirmation dialogue to confirm the trip action initially.

The scenario was terminated once they had isolated the TPD, and the crew began transitioning to AOP-15 secondary load rejection. The operators' response was appropriate and despite the issue with the confirmation dialogue and alarm, the operators were successfully able to mitigate undesirable flow in the TPD, isolate the system, and move to the appropriate procedures to mitigate the transient. The scenario also highlighted the need for audible alarms for the TPD system. The response by the operators was better than anticipated by the research team and demonstrated their successful ability to respond to even a challenging scenario relating to the TPD.

3.1.6.2 Scenario 15 – Hot Standby Evolution Interrupted with Load Rejection

Scenario 15 simulated the TPD hot standby to online with added load rejection. This scenario was selected to evaluate to a main plant transient during an active TPD evolution. The central issue addressed by the scenario was how operators switched their attention from the TPD evolution to the load rejection impacting the main plant. In particular, the central question was whether the operators would simply abandon their TPD procedure and leave it in its current state or isolate the system as they handle the load rejection transient. The operators did in fact abandon the TPD evolution, left it in its partially transitioned state, and began responding to the transient. This scenario was quite challenging since the governor valves were in motion by intention due to the active turbine ramp rate which moves the valve positions, they could be moving in sequential or full governor control. As a result, it was challenging to determine whether the governor valve had in fact failed or whether its position reflected that portion of the evolution as it was being closed to offset the steam flow to the TPD. Indeed, the operators reported difficulty in identifying the actual transient, but they responded to the transient appropriately by following their training and procedures.

3.1.6.3 Block 5 Unknown TPD Fault Scenario Conclusions

The final block of scenarios was included as an attempt to pose the most challenging scenario in regard to the operator's ability to detect and mitigate issues. These scenarios included subtle faults with the potential to induce substantial transients on the main plant if they were to go undetected for a brief amount of time. With the inclusion of these scenarios the research team was able to acquire confidence in the operators' ability to respond to unknown events that we cannot foresee at this time or even after establishing a substantial operating history with the TPD implemented at an existing plant.

3.2 Simulator Logs

The simulator logs for the normal operations scenarios were examined to validate the operators' ability to maintain control of the reactor, turbine load, and TPD system while bringing it online from hot standby (Scenarios 5 and 6) and taking TPD from online to hot standby (Scenarios 7 and 8; see Figure 5). It should be noted that Scenario 5 is the first time the operators used the TPD HSI to control extraction flow. Before conducting the activity, the operators identified that the T Mismatch (T_{mis}) between T Average (T_{avg}) and the Adjusted T Reference (adj T_{ref}) would be a good parameter to control the extraction flow. When extraction flow increases, the T Reference increases, and the T Mismatch decreases. The reactor's rod control system uses T_{mis} to make rod steps when the mismatch exceeds the 1.5°F deadband. Before this block the HSI was modified to include T_{avg}, T_{ref}, and T_{mis} on the control screen of the TPD HSI.

Scenario 5 was conducted with the turbine moving at a ramp rate of 5 MW/minute as can be seen in Figure 5. Subsequent scenarios used ramp rates of 15 (Scenario 6), 10 (Scenario 7), and 20 (Scenario 8) MW/minute. As the ramp rate increases, the T_{mis} changes more rapidly, and the operators must take control actions more frequently. The slower ramp rates are potentially easier to control but were reported to be very tedious.

From this, the operators have the ability to move the extraction valve by 1% increments or 10% increments. The 1% increments are needed for low extraction flows because the flow by position curve of valves is non-linear. With Scenario 5, the operators were cautious, and only used the 1% raise control. As we can see by the plot, T Mismatch was controlled within a tight band between 0 and 0.5°F. With the other scenarios, operators were able to control the TPD without resulting in unintentional rod steps although not in as tightly as Scenario 5. The online to hot standby scenarios are potentially more difficult because not keeping up with the turbine results in the reactor, raising power where with the hot standby to online scenarios, and not keeping up with the turbine results in the reactor lowering power.
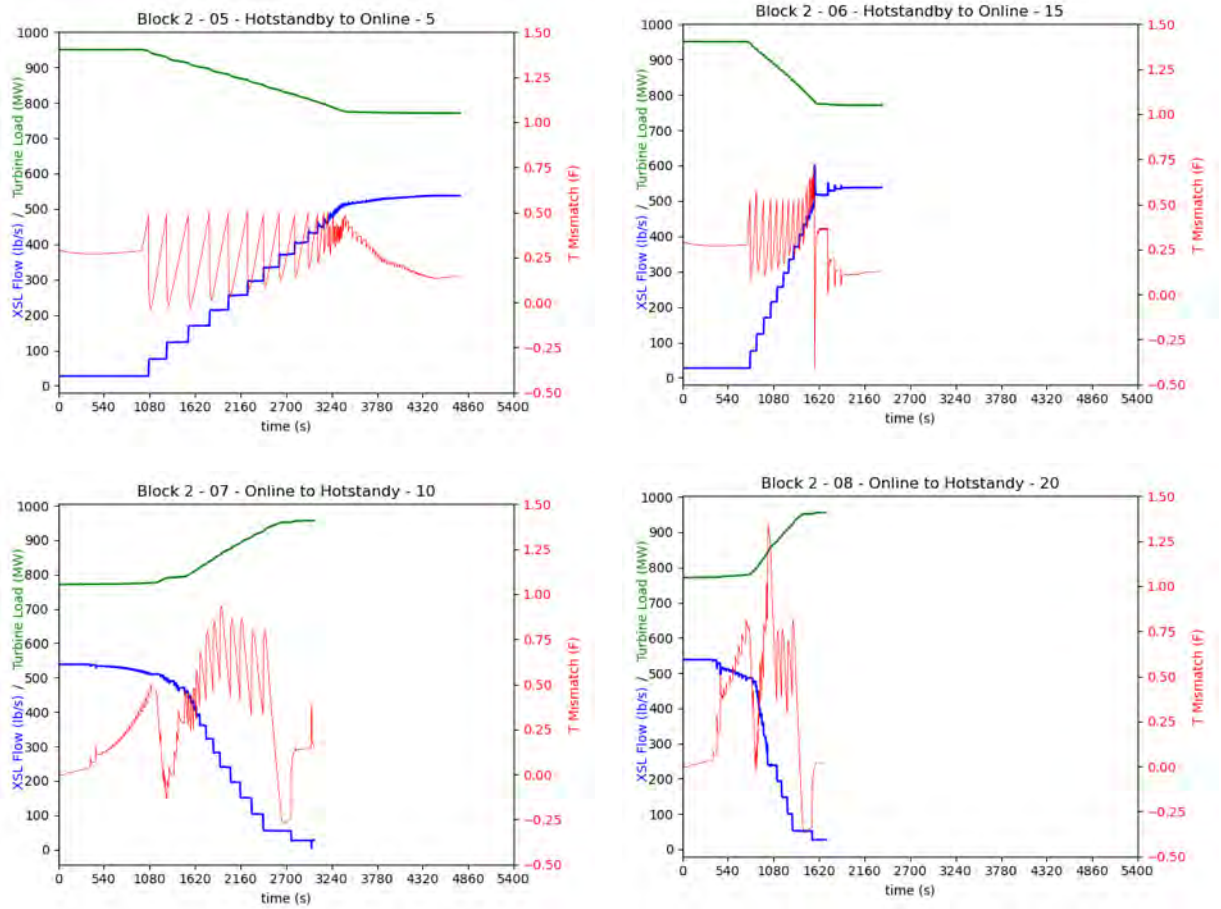
Figure 5. Block 2 normal TPD operations simulator log data.
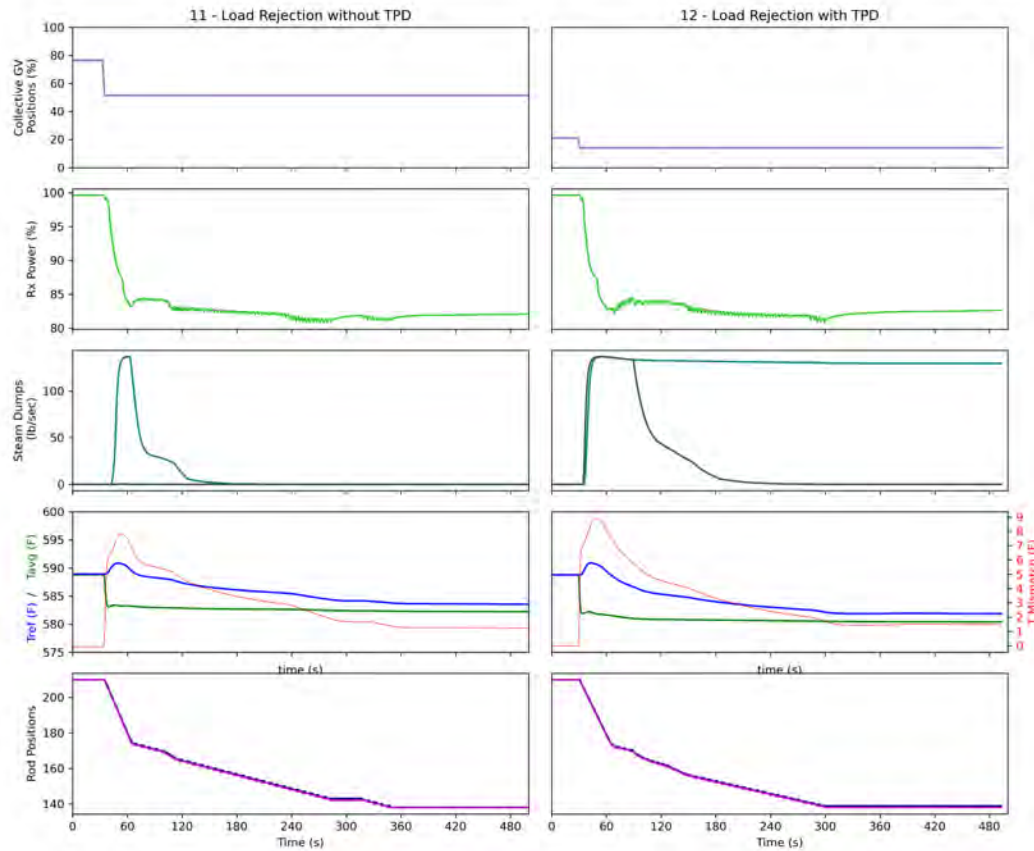
Figure 6. Load Rejection Scenarios 11 and 12 depicting the simulator log data for key parameters affected during the load rejection without the TPD in operation and with the TPD online. The longer duration of the steam dumps remaining open impacted T_{avg} and reactor power which in turn caused greater rod movement through a larger discrepancy with T_{ref} and subsequently a larger T_{mis}.

3.3   Tomlogs

The Tomlogs served two primary purposes for the study. First, they established a detailed timeline and activity log of all actions performed by the operators during the scenario runs. The Tomlogs themselves were not analyzed for content, but similar to the video recordings, they served as a record of the scenarios and provided the capability to identify the context when interpreting the results of the other data sources. Therefore, analysis of the Tomlogs was not performed as part of this effort, but rather they were used while performing the analysis of the measures and instances of their use are described in those sections. In particular, the eye tracking relied on establishing critical points of analysis by using the Tomlogs to identify pertinent time segments for eye-tracking analysis.

3.4   Scenario Debriefs

One of the critical data sources from operator-based scenario simulator studies is the debriefs performed at the end of each scenario. During these debriefs, the operators report on their experience with a particular emphasis on issues they encountered during the scenario. This section reports the findings from the debriefs. There were a total of 100 relevant and 41 salient observations made across all scenarios (seeTable 9).

Table 9. Relevant and salient observations noted by the observation team across all scenarios.

			Comment	Mentions
Block	1		Confusion over procedures	1
Scenario	1		Steam line break	1
N	4		Silencing / acknowledging alarms	3
			Too many alarms	1
			Alarms too loud / different sounds	1
			Annunciator wrong color	1
			Issues with familiarity / awareness of where controls were located	3
			Elements on screens too small	1
Block	1		Improvement from practice	2
Scenario	2		Leak misclassification	3
N	9		Issue with SG	3
			Possible issue with rad monitor	1
			Too few operators for task	1
			Recommend automatic isolation on TPD	1
			Trip XSL did not work	6
			Like / dislike automatic	4
			Stress with unfamiliarity	7
			Stress with people watching	2
			Confirmation of XSL trip is good	1
			Controls unresponsive	3
			Pay attention to pressurizer	1
			Silencing / acknowledging	2
			Confirmation requests	2
			Insufficient time / time pressure	2
			Unmitigated leak causing problems	1
Block	2		Issues with manual operations	4
Scenario	3&4		Missed confirmation dialogue	6
N	10		Simulator too slow / delayed response	5
			Manual controls desired	1
			SG leaking awareness issues	1
			Issues with SI flow	2
			Suggestions for improved confirmation dialogue (location / size etc.)	4
			Trouble finding things (due to [e.g., rescaling])	1
Block	2		Good example of task-based display	1
Scenario	5		Procedure issues	1
N	2		Conservative approach used	1
			Too long	1
			Missed confirmation dialogue	1
			Mismatch in degrees limit	1

		Comment	Mentions
Block	2	Conservative approach to ramping flow	1
Scenario	6	Mismatch	1
N	9	Plant was stable	2
		15 MW/M better [than 5 MW/M]	4
		Task-based display good	2
		Automatic ramp controls	2
		Issues with correct label	1
		Thousands for sensors / transmitters / controllers vs hundreds for valves	1
		Error in procedure	3
		Missed confirmation dialogue	1
		Evolution is too slow	1
		Ramp rate more conducive to 10% versus 1%	1
		Target flow rate needs tag name	1
Block	3	Procedure issues	2
Scenario	7	Power went greater than 100%	1
N	2	Operators did not finish procedure	1
		Valve model problem	1
Block	4	Procedure issues	3
Scenario	8	Modeling and / or human factors design very good	3
N	6	Extra operators might be needed	3
		Plant parameters must be understood before starting	2
		Tedious manual controls	1
		Controlling system well	2
		Mismatch	1
		Operators lowered the turbine prematurely	1
		Calorimetric did not bounce around as much	1
		Differences in simulator vs control room	1
Block	4	Low-pressure effects not observed	1
Scenario	9	Operators 'sat on their hands'	2
N	7	Mismatch	1
		Potential reactor trip due to the system	1
		Rods issue	2
		Too hard to read T_{ref} and T_{avg} on GPWR screen	2
		Automatic isolation of XSL	1
		Pressure trendline needed	3
		Audible alarm request	1
		Clicks on rod movement imperceptible	1
Block	4	Problem with flash rate	5
Scenario	10,11	TPD monitoring should be made easier	1
N	7	Rods stepped out—looked like a load increase	1

		Comment	Mentions
		Audible alarm request	1
		Clicks on rod movement imperceptible	1
Block	4	Steam dumps operated differently in the two scenarios	3
Scenario	12,13	Question about the physics model	1
N			
Block	5	Overpower successfully observed	4
Scenario	14	Confirmation button issue	2
N	6	Came close to a reactor trip	1
		Audible alarm request	4
		Bypass line in design request	2
		Sequential valves to be included	1
		"Check TPD" indicator request	1
		Alarms should stay lit until acknowledged	2
		Annunciator on main panel request	1
		Modify valves request	1
Block	5	Loss of load issue	2
Scenario	15	Challenging scenario	2
N	6	Simulator boards too small	2
		Limited team compared to NPP	2
		Importance of hearing clicking of rod movement	2
		Alarm on mismatch not necessary	1
		Operators did not isolate the TPD	1

Note. Items in orange are deemed salient.

3.4.1 Block 1 Steam Generator Tube Rupture (Scenarios 1–4)

The two salient issues raised in Scenario 1 (SGTR using GPWR without the TPD in operation) concerned silencing the alarms and issues of familiarity of the layout of the HSSL. Thus, despite this scenario representing one within existing operations that the operators would have performed before, these issues likely reflected the fact that the operators were out of practice using the HSI and being in the simulation environment. For Scenario 2 (SGTR with TPD failed manual trip), the mode comment again related to familiarity problems, followed closely by the observation that the Trip XSL button did not work properly (this likely dovetails with another salient comment which was that the HSI controls were unresponsive). As a result, these issues likely contributed to the salient comments that there was a leak misclassification and issues with the SG. The last salient comment from Scenario 2 was that there was both a liking and disliking for some aspects of automation used in this scenario.

Scenarios 3 (SGTR with TPD Automatic Trip) and 4 (SGTR with TPD Manual Trip) were subject to a combined debrief and similar salient issues were raised to Scenarios 1 and 2, such as issues with manual operations and the simulator having a delayed response (unresponsive). Several observers noted that one of the operators missed a confirmation dialogue button press, and suggestions were made as to how to improve the design of this step to ensure the operators could successfully complete it in future iterations.

3.4.2 Block 2 Normal TPD Operations (Scenarios 5–8)

This block reflected normal TPD operations but with varying ramp rates. For Scenarios 5 and 6 that contained the hot standby to online operations with 5 and 15 MW/min ramp rates respectively, the main salient debrief comment was that the 15 MW/min ramp rate was better than the 5 MW/min ramp rate. The 5 MW/min ramp rate was deemed too long and conservative. There were also several comments that there was an error in procedure.

Scenarios 7 and 8 contained the online to hot standby operations with 10 and 20 MW/min ramp rates respectively. Procedure issues were noted in both scenarios, and during Scenario 7, the power went >100%, and the operators were unable to complete the procedure. Other salient comments were the modeling and human factors design were very good, but that extra operators may be needed to securely complete these tasks. Note—this study made use of two former operators as participants, but this number is markedly less than the usual complement of five operators typically on shift in a commercial NPP control room.

3.4.3 Block 3 TPD Steam Line Leak (Scenario 9)

This block uniquely contained only a single scenario and produced one salient comment during the debrief, which was a pressure trendline is necessary on the HSI.

3.4.4 Block 4 Load Rejection (Scenarios 10–13)

The load rejection abnormal operations scenarios comprised two TPD scenarios and two without. In comparing across these two plant conditions, salient comments included problems with the flash rate (blink rate) on alarms, and that the steam dumps operated differently across the two plant conditions. There was also a comment raised about the underlying physics model.

3.4.5 Block 5 Fault TPD Unknown Plant Event Operations (Scenarios 14–15)

The last block comprised two scenarios reflecting unknown fault events that were not introduced to the participants. Both these scenarios generated several salient comments from the observation team. For Scenario 14 (Hot Standby Failed CV [looks like main steam leak]), the reactor came close to a trip, and the mode comment was that the overpower was successfully observed by the operators. There were several observations made about the alarms; in that, audible alarms are necessary, and they should stay lit until acknowledged. Again, there were confirmation button issues reported, likely reflecting the lag in responsiveness of the simulator. Finally, it was observed that there was a request for a bypass line in the design.

For Scenario 15 (Hot Standby evolution interrupted with load rejection), it was observed that this was a challenging scenario to carry out by the participants, and that there was a loss of load issue. The importance of hearing clicking sounds for the rod movement was also noted. Finally, differences between the simulator environment and a commercial NPP were noted in that the size of the simulator boards was smaller as well as the reduced number of operators in the team.

3.5 Survey Data

3.5.1 SART

The composite SART score by scenario (see Figure 7) revealed an interesting trend in which situation awareness is reasonable high with an interesting trend across the Block 2 normal operating scenarios. One explanation for this is the key hole effect in which the operators have a loss of situation awareness due to focusing on TPD control. As they progressed through Block 2 they became less tunneled and learned to divide attention across the plant. Appendix B provides figures for the individual dimensions of the SART index.
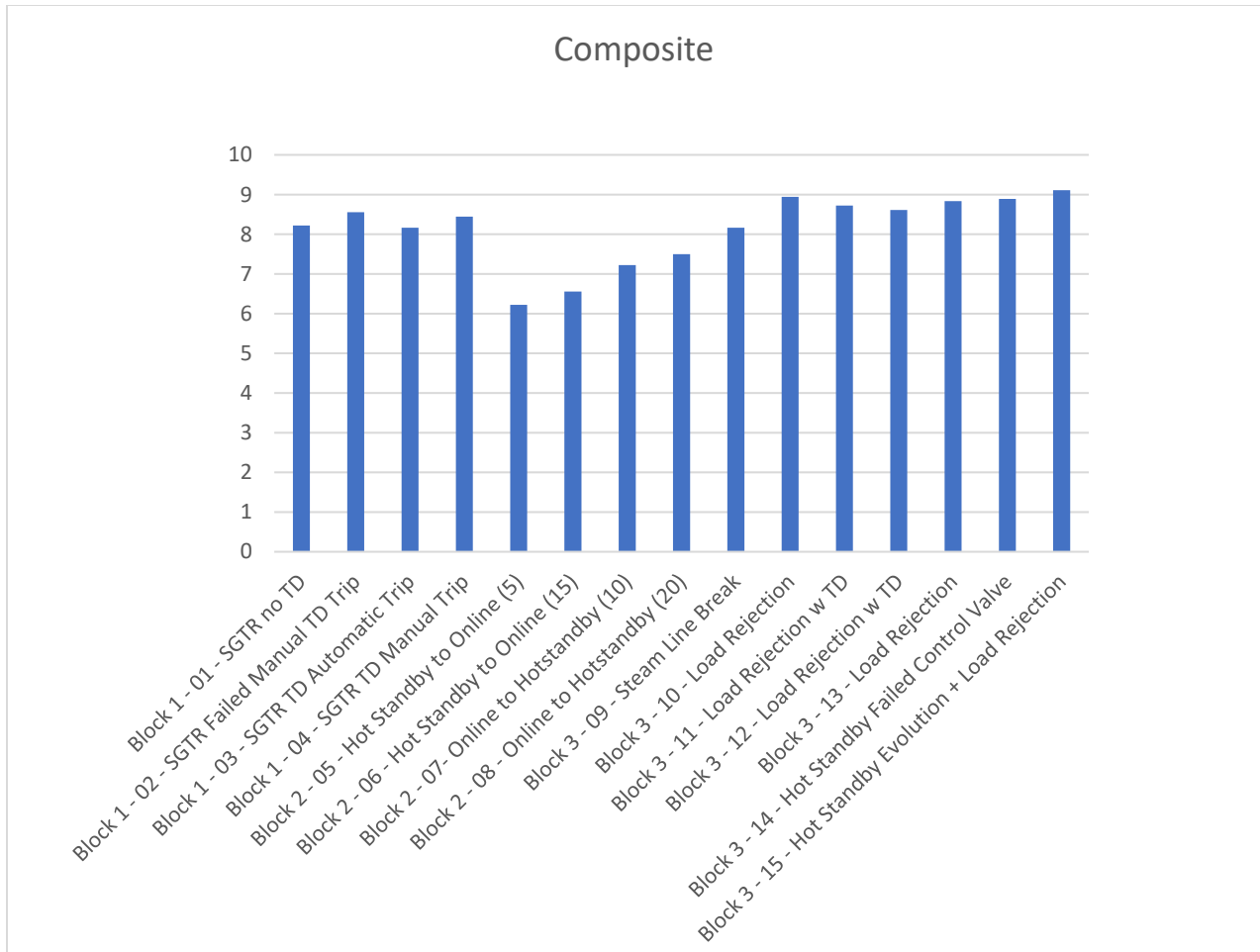
Figure 7. Composite SART scores by scenario.

3.5.2 MCH

The MCH rating scale is used to estimate perceived workload by following a flow diagram. The overall trend suggests that the operators thought the majority of the scenarios were at least "tolerable." The operators' performance driver responses suggest the 7 and 6 ratings for the first two scenarios is likely due to the small font on the glasstop simulator and not reflective of the scenarios or TPD system (Figure 8).
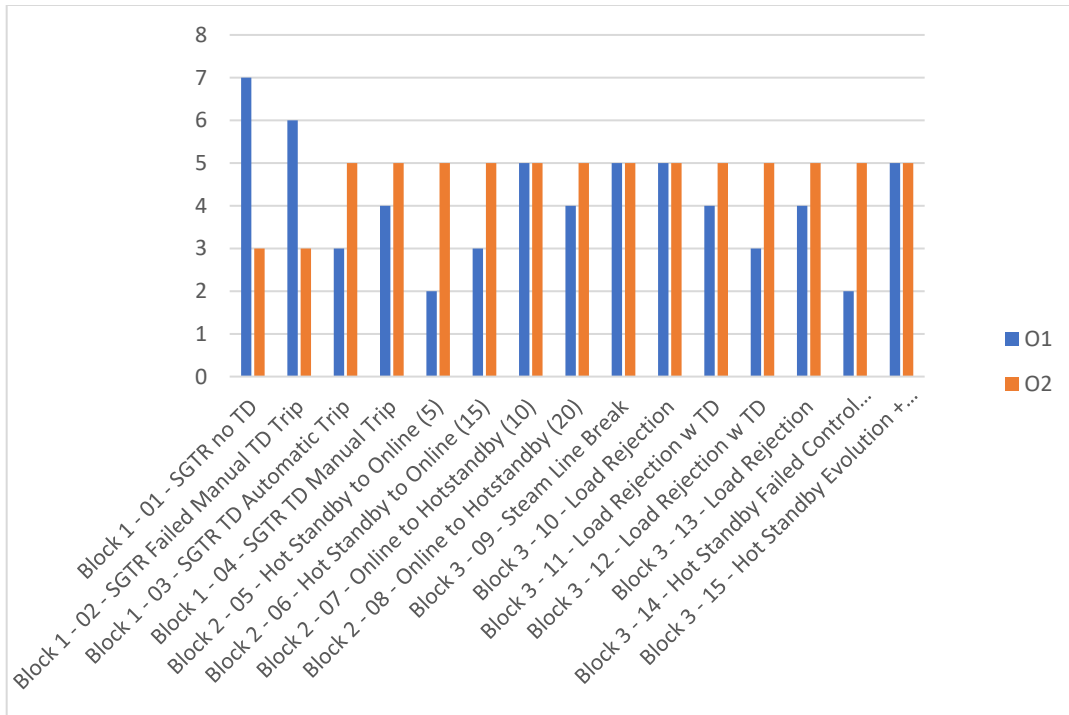
Figure 8. MCH scores by scenario. The separate bars (orange and blue) represent the two operators

3.5.3   NASA-TLX

Figure 9 depicts how the operators rated their performance by scenario. Their scores are relatively high across all of the scenarios with both operators scoring their performance as perfect for two scenarios. The ratings do indicate some variability across scenarios with lower perceived performance for the first scenario and the last scenario. With the first scenario the operators were becoming acquainted with the new HSSL layout and were having a particularly difficult time reading the labels on the control boards. With the last scenario, we surprised the operators with a fault during a normal operation.

In Figure 10, we examined how operators rated their mental demand, temporal demand, effort, and frustration level across scenarios. Of note is the observation that self-reported workload is not correlated with self-reported performance. For most of the scenarios, the operators reported near-perfect (9.5 average) or perfect (10 average) performance. However, the operators reported moderate workload for some of these scenarios (e.g., Scenario 7). This is consistent with existing literature regarding workload and primary task performance. Humans often exhibit high-primary performance as workload increases until the performance "falls off a cliff" (Kahneman 1973). From the collected data, the trend indicates that the operators in our study had no decrement of performance until their aggregated mental demand, temporal demand, effort, and frustration reached an average of 7.
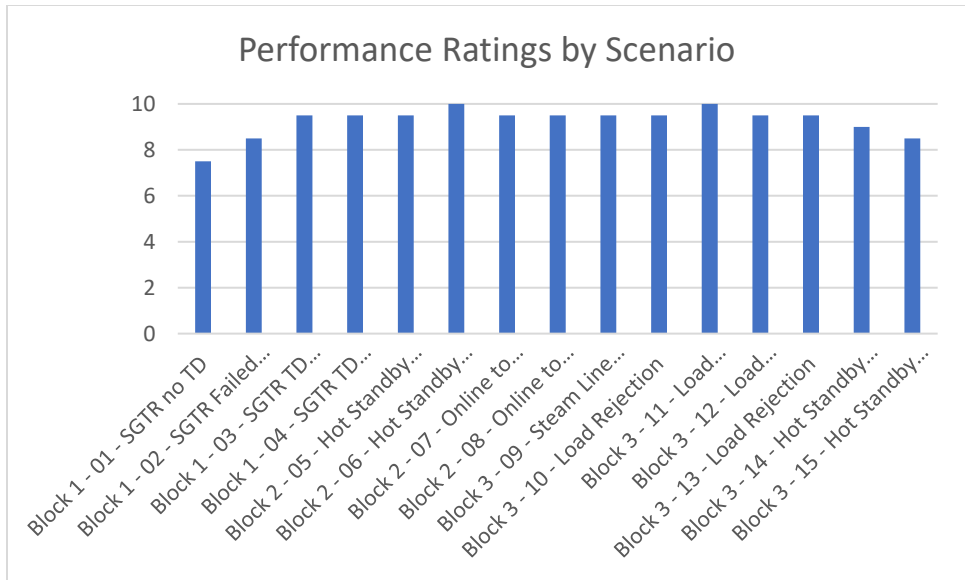
Figure 9. Operators averaged ratings of NASA-TLX performance by scenario (on a 1–10 scale). Higher scores indicate operators perceived their performance as being high.
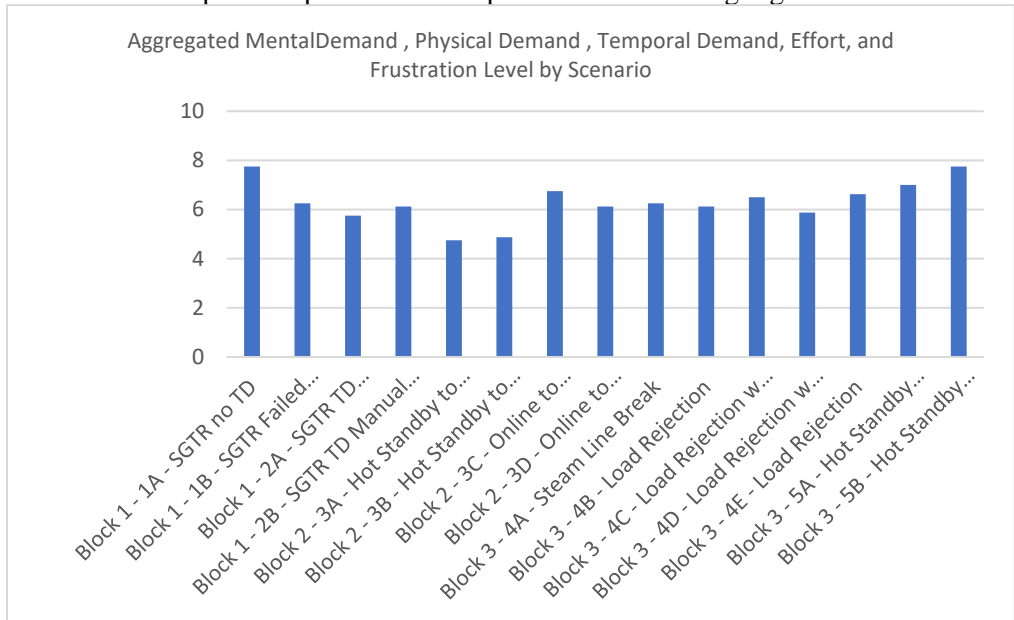
Figure 10. Operators averaged ratings of NASA-TLX mental demand, temporal demand, effort, and frustration level by scenario. Higher scores indicate operators perceived more workload.

3.5.4   Performance Drivers

Previous operator workshops have employed the performance driver questionnaire for the participants, but no workshops had used observers to rate the performance drivers of the operators. For this reason, this analysis began with examining ratings between observers (see Figure 11). From the means, we can see a large variation in the mean scores between individuals.

| 0.38 |
| 0.61 |
| 0.92 |
| 1.09 |
| 1.18 |
| 1.30 |
| 1.30 |
| 1.35 |
| 1.38 |
| 1.42 |
| 1.46 |
| 1.46 |
| 1.52 |
| 1.57 |
| 1.65 |
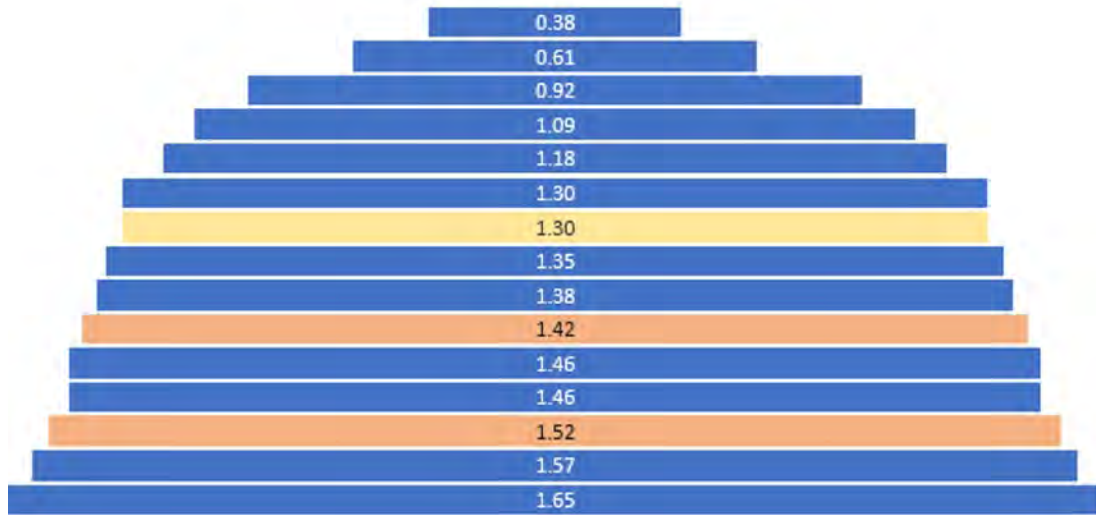
Figure 11. Mean performance drivers ratings by individuals. Operators are highlighted in orange and the mean is highlight in yellow.

To further investigate rater reliability, a correlation matrix was produced for the raters. The correlation matrix revealed that the ratings were not reliable across raters. Furthermore, the ratings were not reliable across operators or operators and raters with nuclear operations expertise (see Table 10). When the variance of ratings by measure and rater were examined, it can be observed that several raters had 0 variance across the scenarios for several measures. We also see that the variance of scores is typically low (< 1; see Table 11) suggesting that the performance driver questionnaire is not sensitive relative to the significant amount of instrument noise. Furthermore, after the study, anecdotally, the observers reported difficulty in assessing the performance drivers for people they were observing. Many of the observers were also aware of the scenarios and hypotheses and so were subject to potential demand effects. For these reasons, the performance drivers will not be further reviewed here. An extensive set of descriptive statistics is provided in Appendix C.

Table 10. Correlation matrix of interrater reliability for the performance drivers

	AA	AN	CD	CS	CA	HR	JN	KN	LE	NN	RN	SN	JS	RB
AA	1													
AN	0.33	1												
CD (Expert)	0.04	0.17	1											
CS (Expert)	-0.02	0.23	0.39	1										
CA	0.04	0.28	0.34	0.18	1									
HR	0.02	0.36	0.18	-0.01	0.23	1								
JN	0.00	0.41	0.58	0.34	0.43	0.52	1							
KN (Expert)	0.05	0.23	0.38	0.10	0.25	0.32	0.41	1						
LE	0.06	0.11	0.38	0.03	0.52	0.47	0.37	0.46	1					
NN	-0.01	0.22	0.39	0.22	0.59	0.42	0.44	0.35	0.56	1				
RN	0.28	0.31	0.52	0.23	0.27	0.29	0.44	0.40	0.33	0.49	1			
SN	-0.10	0.30	0.52	0.43	0.41	0.17	0.53	0.29	0.41	0.43	0.35	1		
JS (Operator)	-0.10	0.10	0.43	0.19	0.33	0.14	0.36	0.34	0.34	0.22	0.13	0.42	1	
RB (Operator)	0.07	0.29	0.33	0.23	0.14	0.10	0.33	0.27	0.06	0.01	0.21	0.31	0.48	1

Table 11. Variability by measure and rater for the performance drivers

Variance of Rating

Measure	AA	AN	CD	CS	CA	HR	JN	KN	LE	NN	RN	SN	JS	RB	
Adequacy of Time	0.00	0.41	0.15	0.71	0.00	0.25	0.24	0.14	1.11	0.00	0.07	0.17	0.97	0.46	0.41
Communication	0.00	0.70	0.27	0.13	0.60	0.67	0.73	0.14	0.12	0.00	0.07	0.73	0.00	0.64	0.41
Execution Complexity	0.93	0.81	1.17	1.19	0.12	0.25	0.07	1.26	1.55	0.70	0.40	0.21	0.57	1.03	0.86
Experience	1.07	0.54	0.08	0.18	0.27	0.00	0.00	0.31	0.84	0.35	0.40	0.00	1.07	0.24	0.63
Human Machine Interface	0.23	0.84	1.36	1.98	0.69	1.00	0.55	0.90	1.11	0.64	1.11	0.26	0.27	0.84	1.12
Indications of Conditions	0.93	0.24	1.06	0.68	0.21	1.00	0.55	0.76	1.21	1.10	0.57	0.67	0.30	0.64	0.92
Passive Information	0.23	0.50	0.88	1.05	1.54	0.00	0.00	1.00	0.00	0.54	0.54	0.14	0.00	0.35	0.92
Procedural Guidance	0.27	0.50	1.30	2.86	0.41	0.25	0.40	0.92	1.64	0.21	0.27	0.31	0.17	0.54	0.91
Scenario Complexity	0.90	0.92	1.36	0.71	0.12	0.25	0.43	0.23	1.64	0.69	0.27	0.27	0.17	0.92	0.83
Stress	0.00	0.24	0.61	0.42	0.69	0.00	0.69	0.90	0.78	0.00	0.35	0.17	0.00	0.46	0.78
Task Load	0.00	0.52	0.20	0.13	0.12	0.67	0.18	0.56	1.11	0.00	0.07	0.08	0.00	0.55	0.47
Team Dynamics	0.00	0.17	0.00	0.13	0.00	0.25	0.13	0.00	0.00	0.00	0.00	0.08	0.27	0.35	0.10
Time Pressure	0.00	0.50	0.08	1.21	0.27	0.33	0.07	0.59	0.70	0.00	0.31	0.17	0.67	0.52	0.75
Training	1.07	0.52	0.08	0.18	0.70	0.25	0.21	0.31	0.84	0.38	0.38	0.31	0.57	0.41	0.67
	0.53	0.69	0.90	1.11	0.75	0.46	0.41	0.66	1.06	0.72	0.70	0.28	0.82	0.80	0.80

3.5.5 Glasstop Simulator

Overall, the operators reported favorable impressions of the glasstop simulator (Table 12). They agreed the simulator performed well, and it was better compared to older versions. There were three main concerns raised about the glasstop simulator. First, the display readings were smaller than in the actual plant and were challenging to read due to the small font size from the reduced scaling of the bays. Second, the displays were delayed in responding to touch. The bays used in this study are new capacitive touch displays, and the interaction is different than what was previously supported in the HSSL simulator that relied on an infrared touch overlay. The touch overlay did not require depressing a finger on the screen but also had some delay which may account for this difference. Third, the color contrast within alarms was not defined enough.

Table 12. Glasstop simulator operator review results depicting the operators experience using the HSSL touchscreen bays to monitor and interact with the plant simulation. The mean rating is based on the operators response to a 5-point Likert scale (1=strongly agree to 5=strongly disagree).

	Likert Questions	Mean Rating	Comments
1	The glasstop simulator worked well.	1	
2	I was able to work the glasstop simulator without any problems.	3	Touch control is slow. Too small to read easily.
3	I like the glasstop simulator.	1	
4	The glasstop simulator is a useful technology platform to evaluate main control room activities.	1	
5	Performing scenarios in the glasstop simulator felt like operating the control room.	1.5	Agree that getting past the problems in Question 2 it does.
6	How do these glasstops compare to the old glasstops?*	4	Better not considering the Question 2 items.
	Open-ended Questions		Comments

	Likert Questions	Mean Rating	Comments
7	What difficulties, if any, did you have using the glasstop simulator?		Everything was 60% of full size, made it hard to find and read indications. / Slow to accept input. Indicators too small.
8	What changes would you make to the glasstop simulator to make it easier for you and other operators to perform this scenario?		See Question 7 above. The color contrast between an alarm in and one out is vague. Lit annunciators at plant show up brighter. / Bigger, display all of the control board.
9	Were any plant parameters missing or not displayed in the visible panels?		Yes. We were able to swipe panels to show hidden ones. / No.
10	Was anything missing in the room that you found necessary?		No. / RMS panel.

Note. *Likert scale for Question 6 is reverse coded such that 1=Much worse; 2=Worse; 3=Same; 4=Better; 5=Much better.

3.5.6   Usability Questionnaire

Overall, the participants favorably endorsed the usability of the TPD HSI and agreed with one another for 21/25 items. For the items in Figure 12, the participants generally agreed with the positively worded statements, and neither agreed nor disagreed for the negatively worded statements. This indicates that the participants deemed the HSI design satisfactory for the tasks that they performed. Figure 13 shows favorable responses for all the yes/no items, in that the participants deemed the HSI design better than satisfactory for the tasks that they performed.
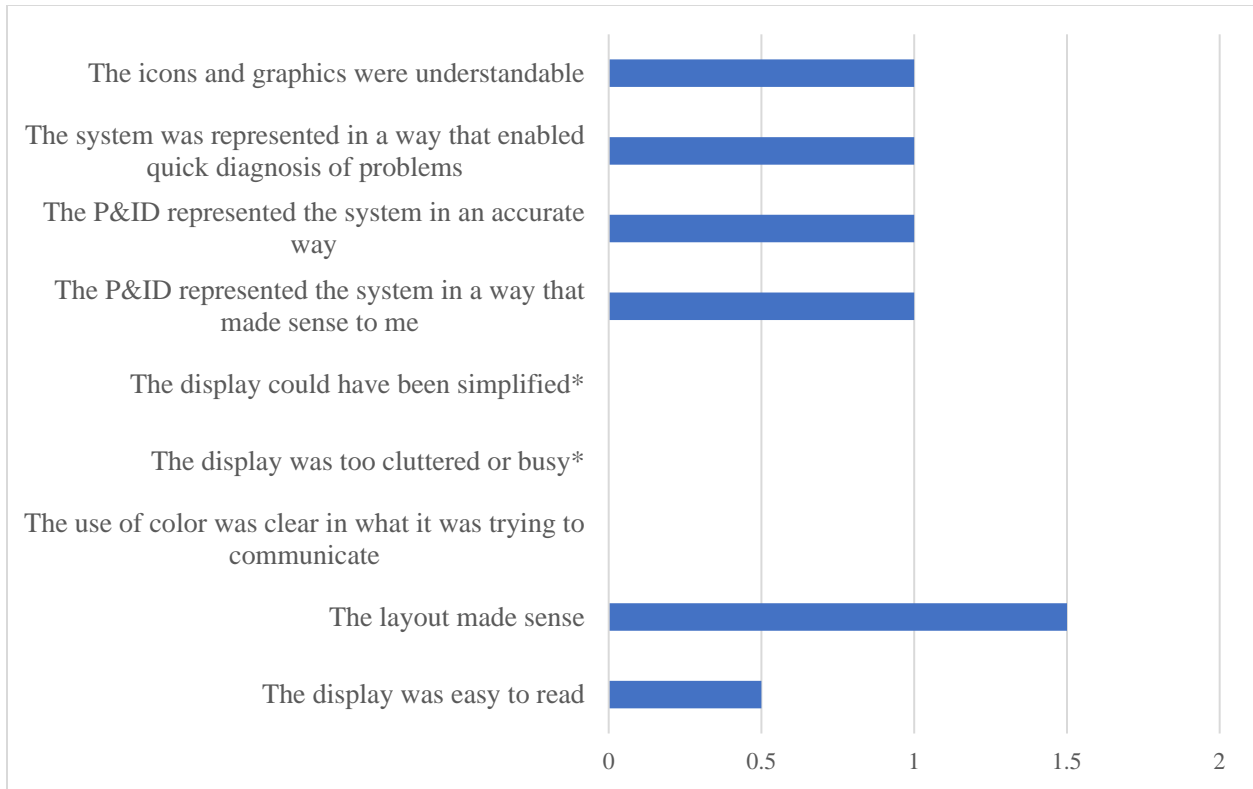
Figure 12. Average of participant responses on Likert items for usability questionnaire. Note. *A lower endorsement is desirable (i.e., disagree). Likert scale is strongly agree (2) / agree (1) / neither agree nor disagree (0) / disagree (-1) / strongly disagree (-2).
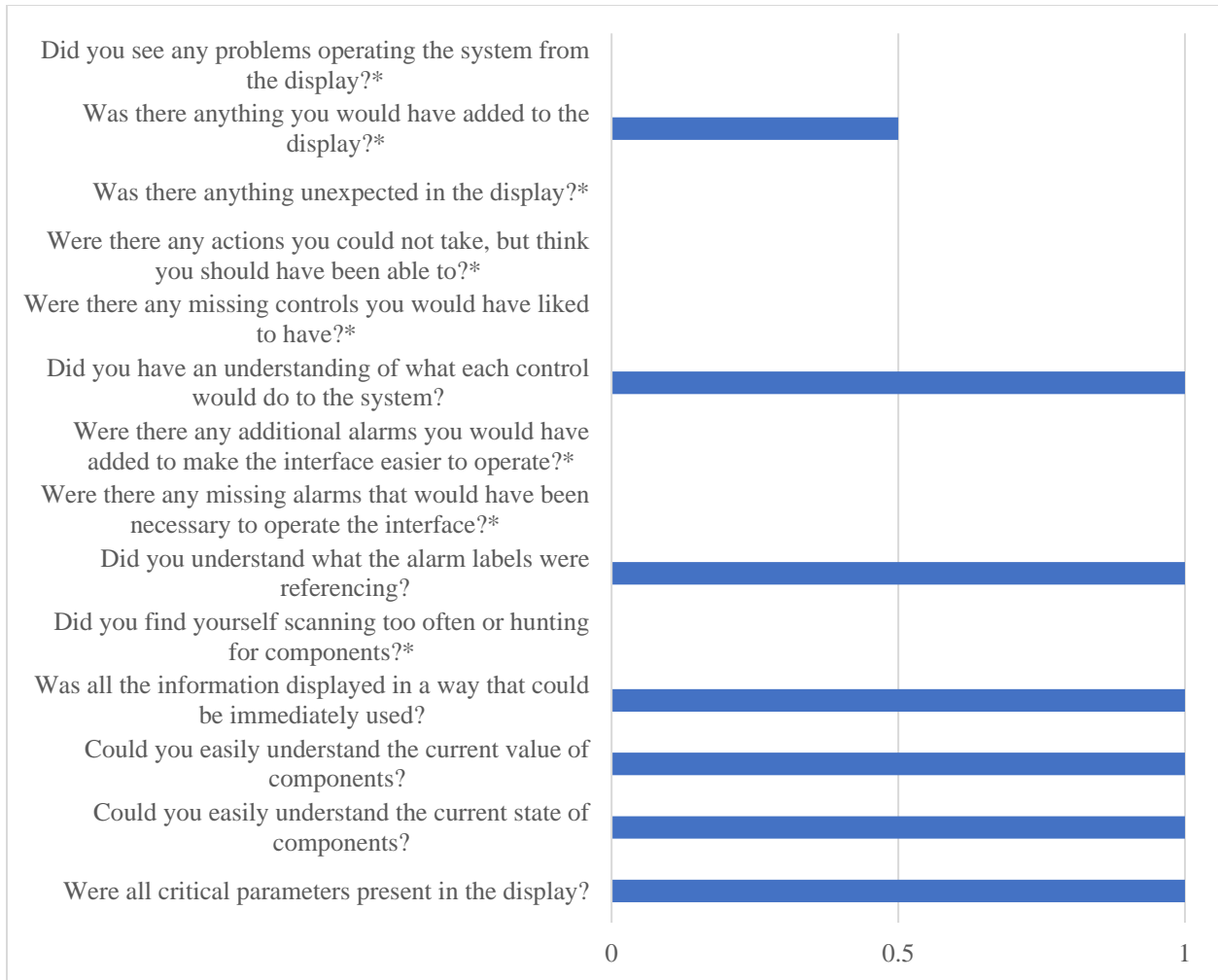
Figure 13. Average of participant responses on YES / NO items for Usability Questionnaire. Note. *A lower endorsement is desirable (i.e., no). Scale is YES (1) / NO (0).

3.6   Eye Tracking

Eye tracking was collected across all the scenarios, but it was specifically used during the analyses to address the attention demands of the TPD on the operators while performing the normal evolutions to transition between hot standby to online and online to hot standby for the TPD. The results reported here highlight the pattern of attention and attentional demands placed on the operators. Furthermore, critical observations were evaluated with eye tracking; in particular. an incident in which the OATC missed an alarm was evaluated to address the attentional demands and pattern surrounding that event.

3.6.1   Preprocessing and Analysis

A considerable amount of preprocessing is required to convert the raw eye-tracking data into usable metrics to evaluate gaze patterns in terms of where operators were looking at a given point in time, and the times spent viewing particular indicators across the bays and within the prototype HSI. The raw eye-tracking data was analyzed using the SensoMotoric Instruments BeGaze software. Since the operators were moving around in a three-dimensional environment with various depth planes at multiple angles, the gaze data was transcribed onto reference images in the software. Gaze patterns for both operators throughout a scenario were mapped onto identical reference images that depicted all of the elements of interest (displays, paper procedures (PP), and communication between operators). A composite image

was created using high-resolution images of the GPWR simulator and TPD (Figure 14). Black lines were added to illustrate the location of bezels between the displays.

Underneath Bay D1 and between the two and bottom of all the other displays within each bay, we included extra symbols to capture additional fixations related to glances from one operator to the other during communication (a thinking symbol) and the reading of procedures (a file symbol). To visualize these fixations, we recoded fixations that fell into either one of these categories as fixations on these symbols.
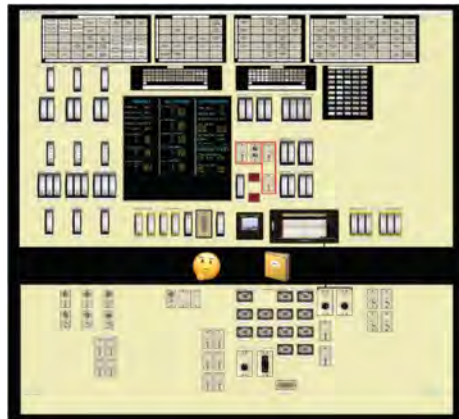
Individual Bays and their content
(from left to right)

D1 - Emergency Power
A1 - Containment, Component Cooling Water
     (CCW), Residual Heat Removal (RHR)
A2 - Chemical and Volume Control (CVC), Reactor
     Coolant System (RCS)
C1 - RCS, Rod Control
B1 - Steam Generator (SG), Feedwater (FW)
B2 - Condensor, Turbine Control
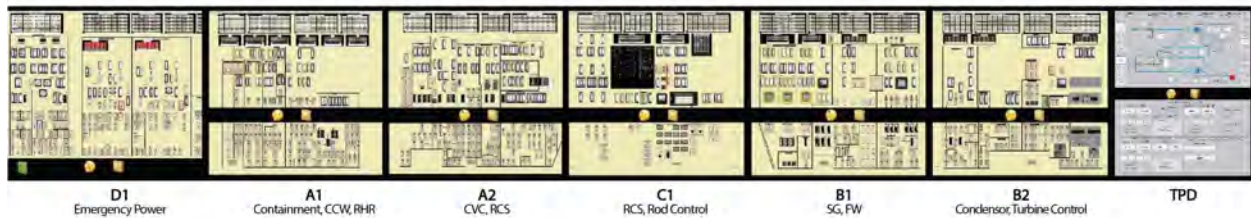
Figure 14. Composite reference image of the scenario elements as used for eye-tracking analysis. Top-Left: Blow-up of one bay including the symbols for communication (face) and PP. Bottom: Complete reference image including all GPWR bays and the TPD HSI. The label and explanation for each GPWR bay is given on the right.

We defined initial areas of interest (AOI) for future eye-tracking analysis (Figure 15). Mapping of AOI's in the different displays was based on naturally occurring groupings within the display with the main steam header area, XSL and DSL Mode indicators, and the XSL information across the top of the display being the most important to evaluate the TPD HSI. All other bays were treated as either a single (D1) or two vertically aligned areas of interest.

Figure 15. AOIs overlayed over the GPWR and TPD displays.

3.6.2   Attentional Demand

Eye-tracking data showed a clear pattern of visual gaze behavior consistent across the operators and consistent across the different normal scenarios. Due to recording malfunctions, the data for Scenario 5 were lost, but the three remaining data sets show that operators spent a large majority of their time attending to the TPD and to a lesser degree Bay B2 of the GPWR simulator at the cost of attending the remaining interface elements (see Figure 16). This is seen by the dominance of fixations in the TPD HSI region compared to the GPWR regions of the display for both operators. Scenario 8 represents the fourth scenario during which operators had to ramp up or down on the TPD side, which indicates that even after repeated exposure to similar procedures the attentional demand of manually controlling the transition led to a concerning withdrawal of attention from the rest of the simulation.
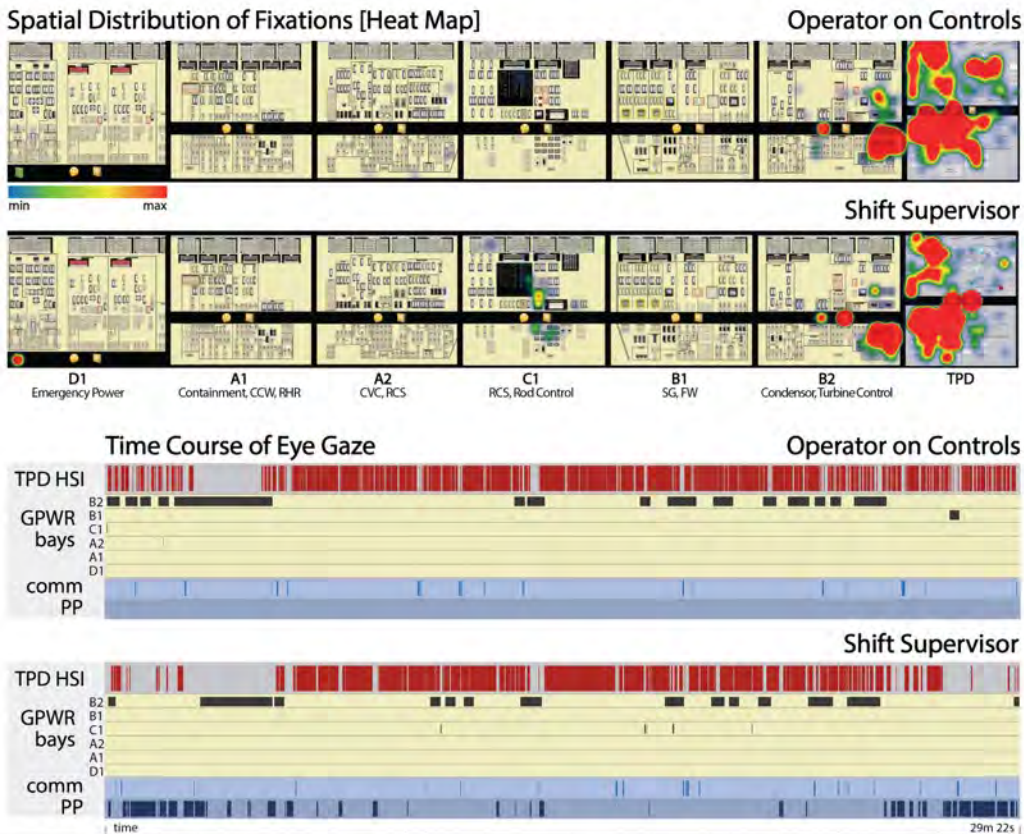
Figure 16. Eye-tracking results for Scenario 8: Online to Hot Standby at 20 MW/min ramp.In Figure 16, the two panels on the top show the distribution of fixations across all display elements for the two operators. The absence of a color overlay indicates no or a negligible number of fixations, whereas the presence of the color gradient indicates the time spent on a specific display element across a scenario (blue = minimal time, red = maximal time for a scenario). Two placeholders (a symbol for a face and a file symbol) were added for each display bay that represent fixations by an operator directed at the other operator or PP respectively (Figure 14). The two panels on the bottom in Figure 16 show the time course of fixations across the entire scenario. Each vertical red element in the top bar indicates fixations in the TPD display. Dark vertical bars in the six central beige lines indicate fixations in the GPWR display bays (D1 = left-most display, B2 = right-most display). The vertical bars in the two bottom rows indicate inter-operator communication (comm: an operator looking at the other operator) and looking at PP.

3.6.3 Missed Alarm Event

During Scenario 6 (at 2 minutes and 50 seconds), the XSL low-pressure alarm came on for approximately 15 seconds. Neither operator acknowledged the alarm and a look at their eye-tracking data clearly shows that neither operator attended to the alarm (Figure 17). The alarm was removed by the simulation administrator. This suggests that the alarms in the TPD HSI have to be made more noticeable. The addition of an auditory signal and the inclusion of an additional alert within the central display of the GPWR might alleviate this problem.
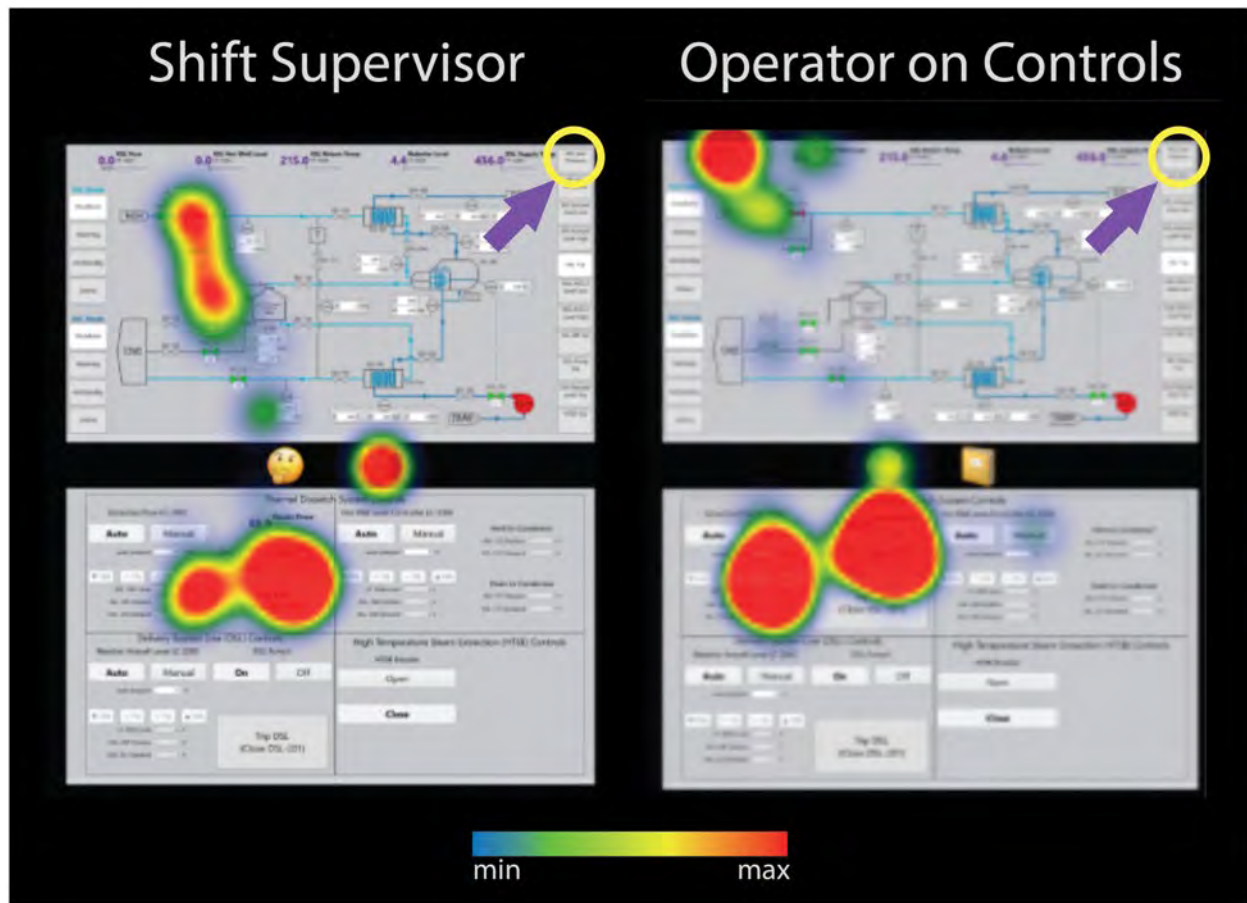
Figure 17. Gaze pattern of both operators during a 15 second interval during which the XSL low-pressure alarm (top right, highlighted by arrow) came on and turned red. Neither operator fixated on the alarm nor showed awareness of the annunciator being on.

All available eye-tracking results for Scenarios 1–15 are available in Appendix D.

3.7 Video

Video was recorded from two different cameras through the study. The video footage was collected to serve as a record that could be consulted while performing analysis with the other data sources. There are no formal video results reported here as a result.

3.8 Final Study Debrief

The final study debrief was a closing out activity to ensure that all pertinent feedback from the operators was captured, and any outstanding issues identified by the observation team could be addressed. The debrief entailed going through the main findings and issues from the scenarios, and therefore, the debrief will not be reported here, but rather it is imbued in the discussion as it closely followed the description of the major findings from the study described in the discussion.

4. DISCUSSION

The study described in this report provides a first-of-a-kind study of operator performance using a commercial reactor not only to generate electricity but also to harvest steam for other industrial purposes like hydrogen production. The study team augmented an existing commercial full-scope simulator for a PWR with TPD models and accompanying HSIs and procedures. The new capabilities were deployed in

the HSSL, and qualified operators participated in 15 scenarios to assess the ability of operators to monitor and control diversion of steam for simultaneous use of electricity and hydrogen production. The scenarios covered event sequences like SGTR and steam line breaks, normal TPD operations, load rejection scenarios requiring rapid adjustment to TPD, and miscellaneous plant faults. Over a 4-day study, including training on the thermal dispatch system, operators validated the system by running through these scenarios intended to test the impacts of the thermal dispatch system on the plant and examine how the operators manage the system within the context of existing operations.

The most important finding of the study is that reactor operators were able to complete the TPD operations successfully without compromising their primary goal of safely operating the plant. This finding indicates the viability of alternate outputs of steam beyond electricity generation from an operational context. The initial evidence from this study suggests current NPPs can maintain existing concepts of operation for control room crews while also safely supporting steam extraction.

The study further nuances this finding. Monitoring and controlling TPD does require high-attention levels by the operators, and there may be advantages to automating aspects of the TPD process. Operators did not evidence significant decrements in performance even during major plant upset conditions, as demonstrated by lack of strong empirical findings such as increased workload or performance shaping factors. Still, the need clearly remains for operators to shift attention to more primary plant operations during plant upset scenarios. The evidence from eye tracking in the final two scenarios shows the operators had to prioritize the primary plant activities over the TPD during plant upsets, essentially abandoning control of the TPD. Thus, having a TPD system that can adjust rapidly to dynamic demands would eliminate any increased operator burden through the introduction of new systems. Additionally, some tasks, particularly the Block 2 tasks related to hot standby to online and online to hot standby, proved slow and demanded considerable operator attention to manipulate ramp rates. Automated ramp rate controls are well established in systems like turbine control systems. Similar functionality would improve system and operator performance and efficiency for TPD activities.

The operators responded well to the prototype HSI. The HSI followed many of the design conventions evolved by the team in support of earlier control room modernization activities under LWRS. As such, the HSI is stylistically consistent with other digital systems familiar to the operators. Additionally, the University of Idaho engagement in refining specific elements of the general digital HSI style contributed to a system refinement that was valued by the operators. Despite positive feedback on the HSI, there remained four issues that require further work to improve the design.

- The operators on multiple occasions failed to notice the confirmation dialogue window required for key TPD functions. This resulted in unexpected delays and some confusion about system performance relative to expectations, basically because key functions were not confirmed and hence never actuated. Further work is needed to ensure the salience of confirmation dialogues, so they are not overlooked by operators. Part of this salience also includes providing greater status of operations to signify if a function is activated or not.

- The operators identified the need for additional parameters to help monitor TPD operations. This feedback is useful in establishing the most important operational parameters that need to be displayed to help operators maintain situation awareness.

- The alarms did not feature audible alarms in the digital HSI, making them easy to overlook for the operators. In general, the auditory and visual salience of alarms will be enhanced in future iterations of the HSI.

- Finally, the operators noted the possibility for greater integration with the turbine control system. Given the concurrent use of steam for both electricity generation and other industrial uses, the two functions are not truly independent. Future versions of the TPD system may consider ways to integrate turbine and thermal power dispatch into a single digital control system.

The study made use of a variety of human performance measures, building on a tradition of measures used in previous studies in the HSSL (Boring et al. 2015). The results of these measures are presented in this report, but it is beyond the scope of this report to weigh the various advantages and disadvantages of specific measures. Some measures were applied in a novel manner, such as the use of subject matter experts to rate the performance shaping factors of the operators during the scenarios. However, there ended up being low interrater reliability and low consistency to operator self-reports. On the other hand, several novel measures of eye tracking were developed for the study, which provided objective evidence of performance to support key study findings. Teasing out the utility of various human performance measures remains the subject of future follow-up work.

It should be noted that the study only employed two operators, one acting as SRO and one acting as OATC. A typical control room crew configuration features two or more reactor operators at the boards. While these operators may foremost focus on specific functions like primary side and balance-of-plant operations, they can mobilize to support operations across the control room when necessary. The challenge of maintaining both plant and TPD may therefore be obviated with additional crew members. Further research should explore the tradeoffs between different crew configurations with and without TPD automation features.

The results of this study must, of course, be considered preliminary. They represent an early prototype of a TPD system using operators who were not trained on the novel system. The system, HSI, and procedures are at a formative or early design phase, and additional maturation of the system, HSI, and procedures will be necessary to generalize the results such that they are suitable for licensing and deployment. Nonetheless, the results show promise for the prospect of TPD in legacy plants. Successful operation of an early-stage prototype under stress-test conditions bodes well for the success of actual TPD systems in the future.

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Appendix A
Example Procedure OP-TPD-002

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Appendix A
Example Procedure OP-TPD-002

Continuous Use

GPWR NUCLEAR PLANT

PLANT OPERATING MANUAL

PROCEDURE TYPE: OPERATING PROCEDURE

NUMBER: **OP-TPD-002**

TITLE: **Extraction Steam Line (XSL) and Delivery Steam Line (DSL) Operation (Hot Standby to Thermal Power Dispatch Online)**

<u>TABLE OF CONTENTS</u>

<u>Section</u>

1.0   PURPOSE

1.   This procedure provides operating instructions to transition the Thermal Power Dispatch (TPD) system from Hot Standby to Thermal Power Dispatch Online state. The TPD system consists of the following systems:

   a.   Extraction Steam Line (XSL)

   b.   Delivery Steam Line (DSL)

2.0   REFERENCES

2.1   Plant Operating Manual Procedures

1.   N/A

2.2   Technical Specifications

1.   N/A

3.0   PREREQUISITES

1.   Rod control is in AUTO.   _____

2.   Reactor power is over 95% and below 99%.

3.   Turbine load is over 95%.

4.   TPD system is in a Hot Standby:

   a.   XSL Warming Valve (XSL-102w) is closed   _____

   b.   Steam extraction flow at XSL-FT-1001 at <u>97.2</u> KPPH   _____

   c.   XSL-SH tube inlet temperature at XSL-TT-1002 is greater than 400 °F and stable or trending slowly in the upward direction. _____

   d.   XSL-SH tube inlet pressure at XSL-PT-1002 is greater than 450 PSIG and stable or trending slowly in the upward direction.   _____

   e.   XSL-RB Hot Well level at XLS-LT-1004 is between 7.5 and 8.5 ft and stable.   _____

   f.   XSL-PH tube outlet temperature at XSL-TT-1005 is greater than 300 °F and stable or trending slowly in the upward direction. _____

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g.   XSL-PH tube outlet pressure at XSL-PT-1005 is greater than
450 PSIG and stable or trending slowly in the upward direction.   _____

h.   Hot Standby Indicator on the XSL Mode display is
illuminated.   _____

5.   DSL is in Hot Standby:

a.   XSL-PH shell inlet temperature at DSL-TT-2001 is greater
than 300 °F and stable or trending slowly in the upward direction._____

b.   XSL-PH shell inlet pressure at DSL-PT-2001 is greater
than 430 PSIG and stable or trending slowly in the upward
direction.   _____

c.   XSL-SH shell outlet temperature at DSL-TT-2005 is
greater than 450 °F and stable or trending slowly in the upward
direction.   _____

d.   XSL-SH tube outlet pressure at DSL-PT-2005 is greater
than 400 PSIG and stable or trending slowly in the upward
direction.   _____

e.   DSL Hot Standby Indicator is illuminated.   _____

Thermal Power Dispatch	OP-TPD-002
	REV. 8
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4.0   PRECAUTIONS AND LIMITATIONS

    1.   Extraction Steam Power Line (XSL)

        a.   Maximum of 15% is currently planned for total steam power dispatch when operating the nuclear plant at full power.

        b.   Increasing the amount of steam diverted through the XSL will cause reactor power to increase.

        c.   Increasing the amount of steam diverted through the XSL will decrease flow of steam to the feedwater heaters from the turbine system and can cause the temperature of water entering the steam generator to decrease.

    2.   Delivery Steam Line (DSL)

        a.   N/A.

5.0 PROCEDURE

NOTE : General flow of the startup process for the TPD is the following:

- Heat XSL (OP-TPD-001)

- Heat DSL (OP-TPD-001)

- Engage and maintain steam supply to the steam user (which is assumed to be a hydrogen production plant for 15% thermal power dispatch as in this procedure or for a synthetic fuels production plant, which could require up to 50% thermal power dispatch in a future procedure)

BEGIN HOT STANDBY TO ONLINE EVOLUTION

NOTE: Manual control is desired for TPD evolutions using the XSL-102 flow control valve. After stable flow rates have been achieved, XSL-102 can be placed in automatic flow control mode.

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1. **DETERMINE** target thermal power dispatch (TPD) flow rates

    a. XSL Flow Rate 1,936 KPPH. _____

    b. DSL Flow Rate 1,725 KPPH. _____

2. **DETERMINE** target TCS demand and ramp rate for thermal power extraction pressurization

    a. TCS Demand 705 MW _____

    b. TCS Ramp Rate 15 MW/min _____

3. **VERIFY** XSL-RB DSL-LC-2003 is in auto mode and setpoint is 3.5 ft. _____

4. **VERIFY** DSL-LT-203 is between 3.2 ft and 3.8 ft. _____

5. **VERIFY** XSL Hot Well XSL-LC-1004 is in auto mode and setpoint is 8.0 ft. _____

6.   **VERIFY** XSL Hot Well Level XSL-LT-1004 is between
7.5 ft and 8.5 ft.   _____

7.   **DIRECT** Steam user to prepare to receive thermal and electrical
energy delivery.   _____

8.   **CLOSE** Steam user Electric Bus Breaker.   _____

9.   **RECORD** the time that Steam user Electric Bus is closed.

                    Time _____   CLOSED   _____

10. **PLACE** XSL-FC-1001 in manual mode (for valve XSL-102).   _____

11. **PREPARE** TCS for load change by performing the following

     a.   **SET** TCS target demand   _____

     b.   **SET** TCS ramp rate   _____

12. **VERIFY** Steam user plant is ready for transition from Hot Standby
to Thermal Power Dispatch Online.   _____

13. **PLACE** TCS in GO.   _____

14. **SLOWLY RAISE** XSL-FC-1001 (valve XSL-102) as turbine load
decreases until target flow rate is achieved.   _____

15. **SET** XSL-FC-1001 setpoint to target flow rate and **PLACE**
XSL-FC-1001 (valve XSL-102) in auto mode.   _____

16. **MONITOR** until the following conditions are met:

     a.   XSL extraction flow XSL-FT-1001 stabilizes.   _____

     b.   XSL-SH tube inlet temperature XSL-TT-1002 stabilizes.   _____

     c.   XSL-SH tube inlet pressure XSL-PT-1002 stabilizes.   _____

     d.   XSL-PH tube outlet pressure XSL-PT-1005 stabilizes.   _____

     e.   XSL-PH shell outlet pressure DSL-PT-2002 stabilizes.   _____

     f.   XSL Online Indicator is illuminated.   _____

     g.   DSL Online Indicator is illuminated.   _____

17. **ADJUST** turbine load until desired reactor power is achieved.   _____

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Appendix B
SART Measures by Scenario

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Appendix B
SART Measures by Scenario
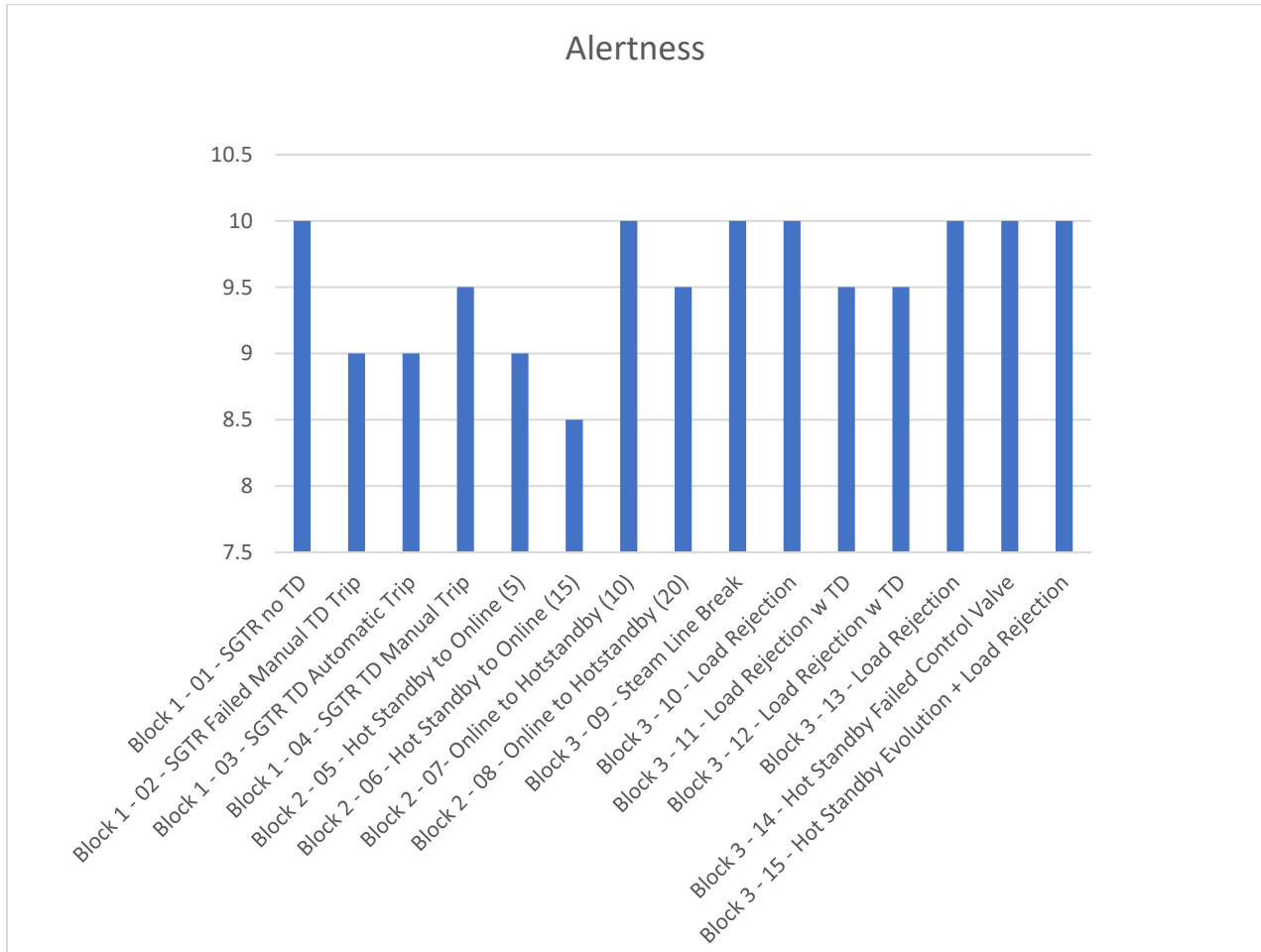
Figure B-1. Alertness SART scores by scenario.
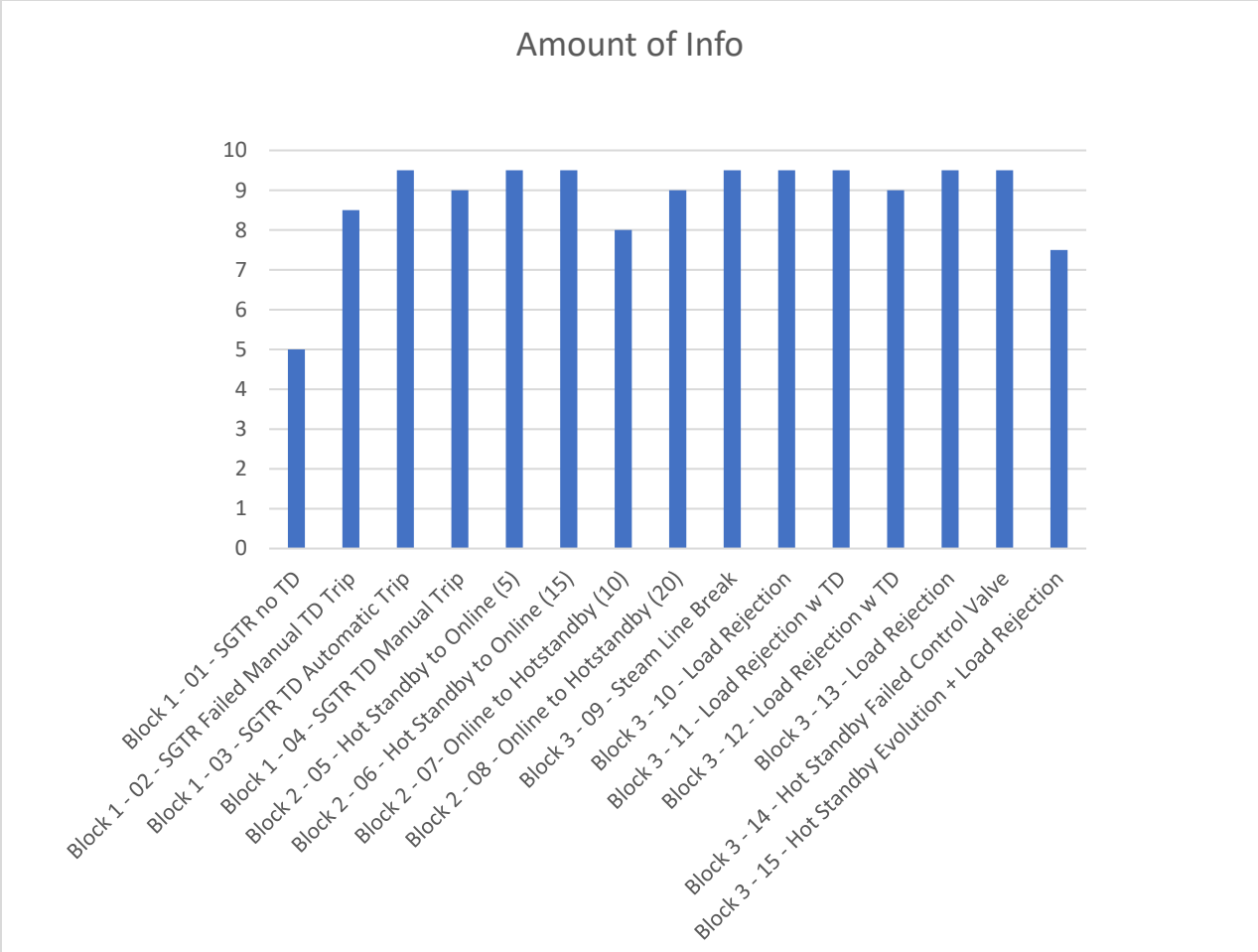
Figure B-2. Amount of Info SART scores by scenario.
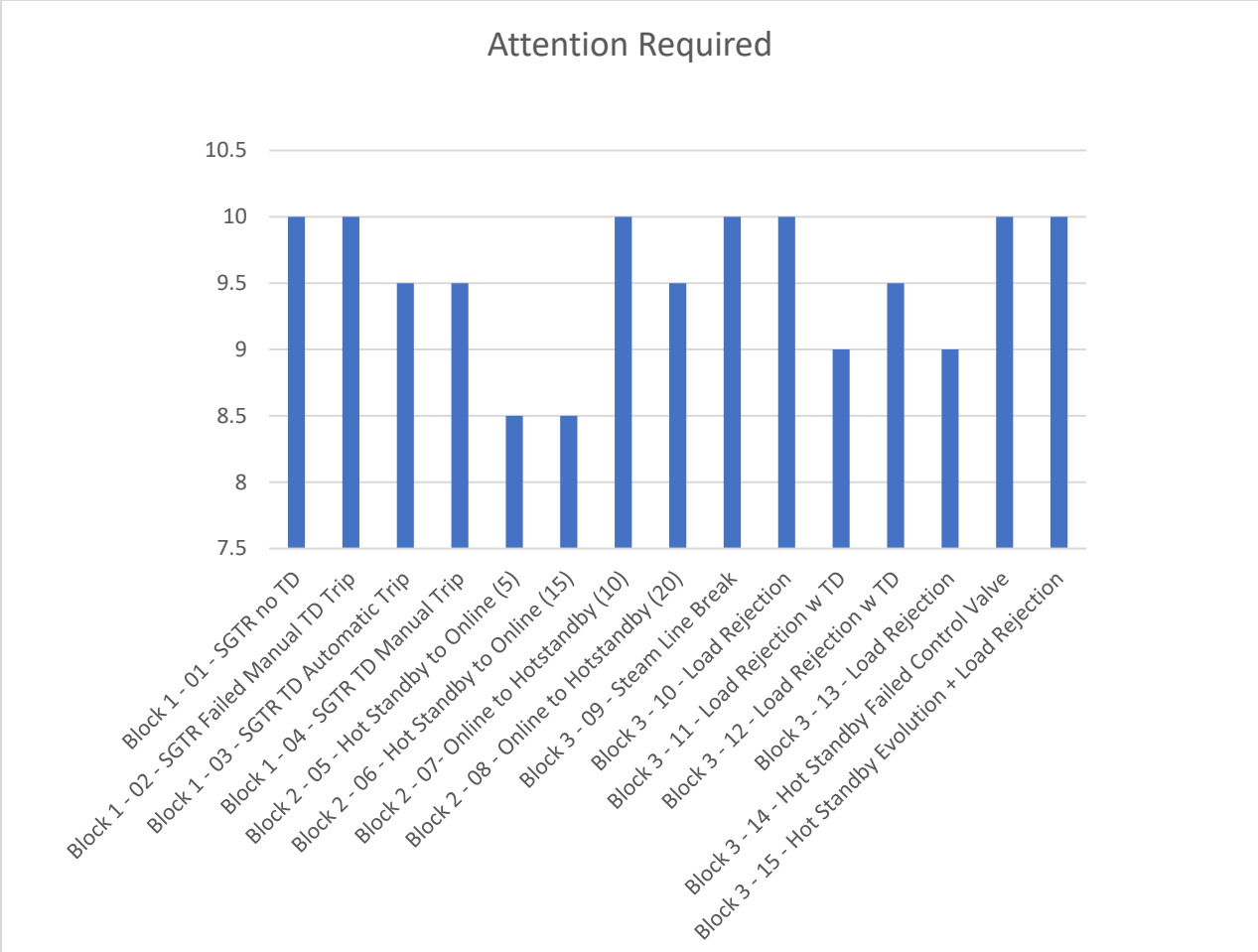
Figure B-3. Attention Required SART scores by scenario.
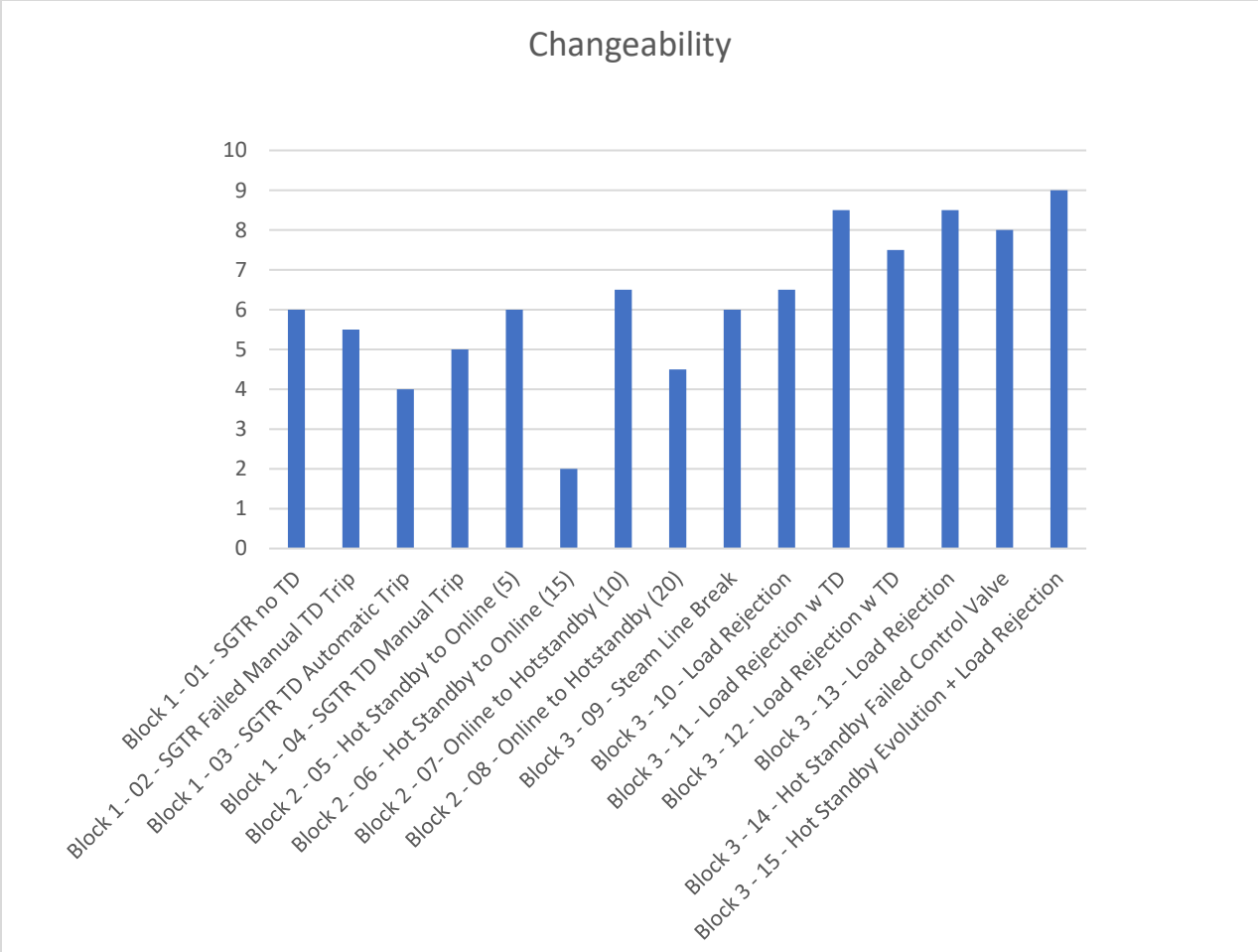
Figure B-4. Changeability SART scores by scenario.
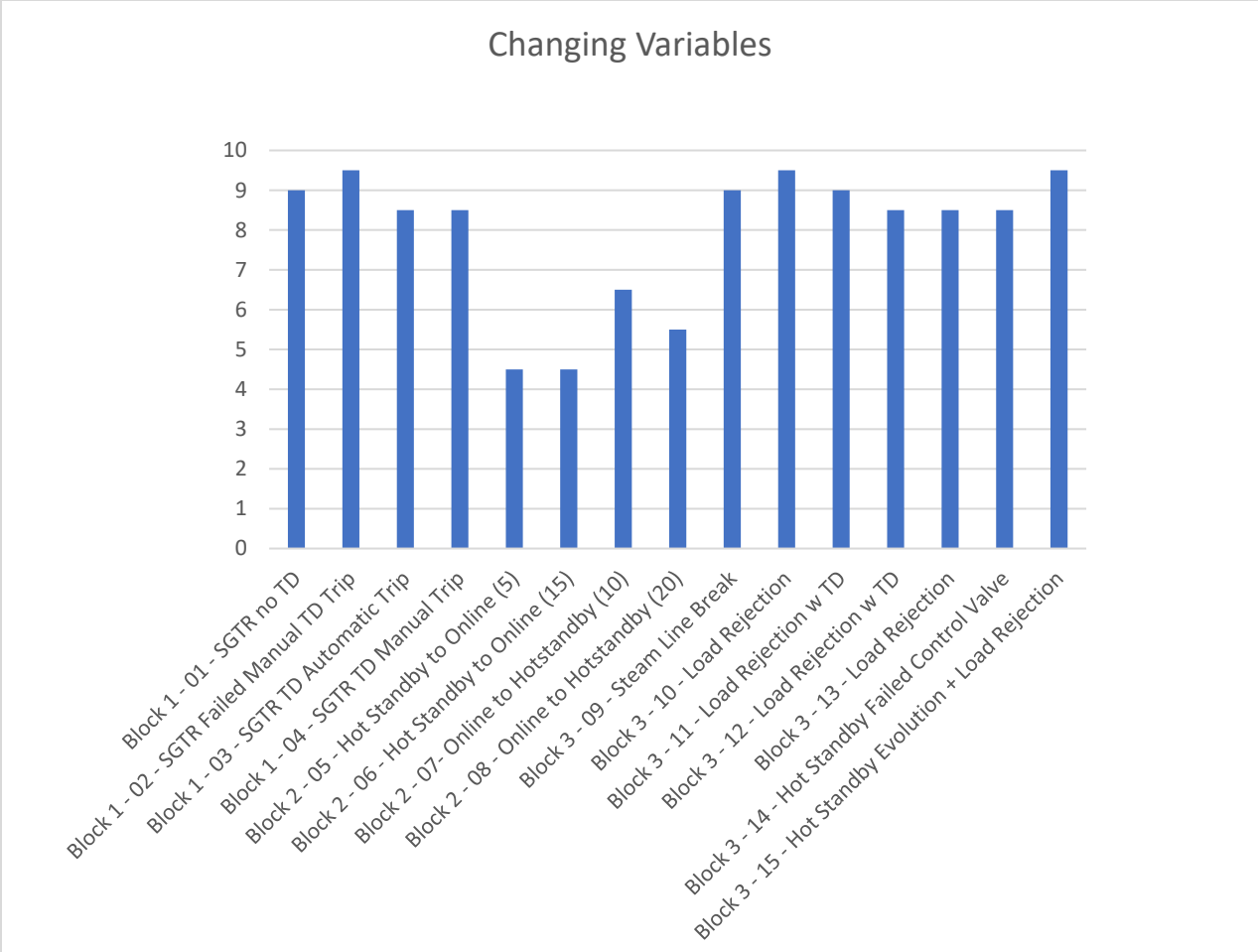
Figure B-5. Changing Variables SART scores by scenario.
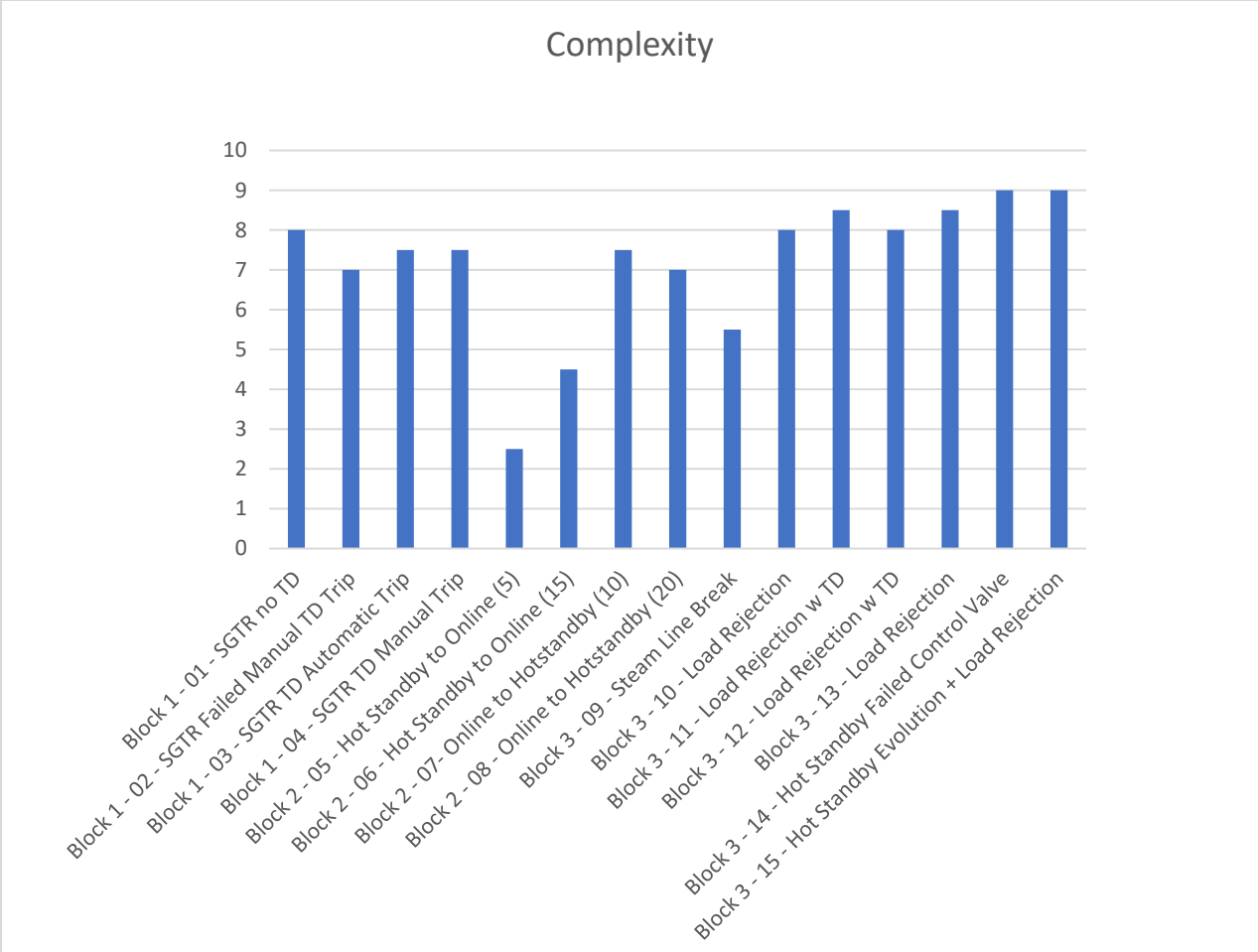
Figure B-6. Complexity SART scores by scenario.
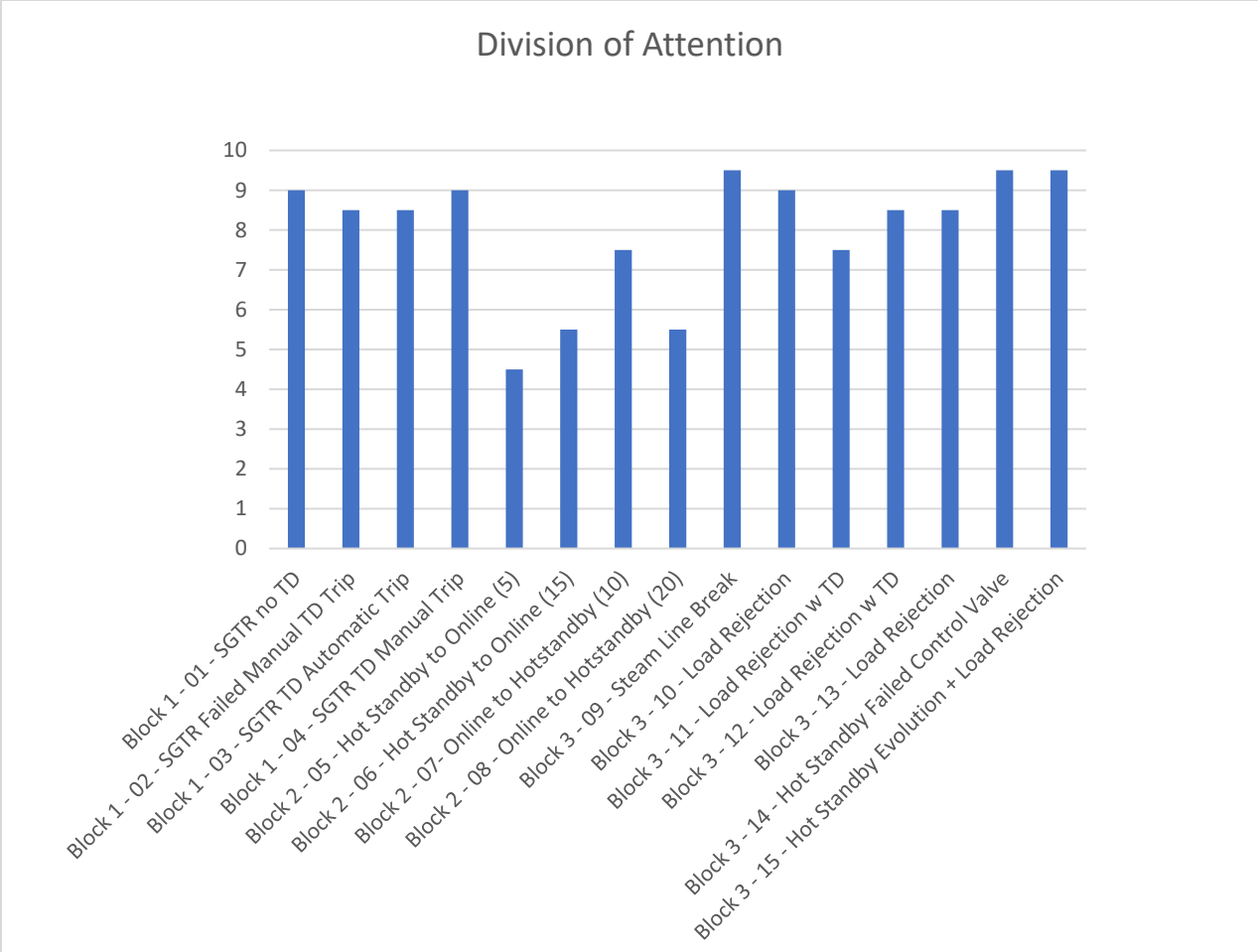
Figure B-7. Division of Attention SART scores by scenario.
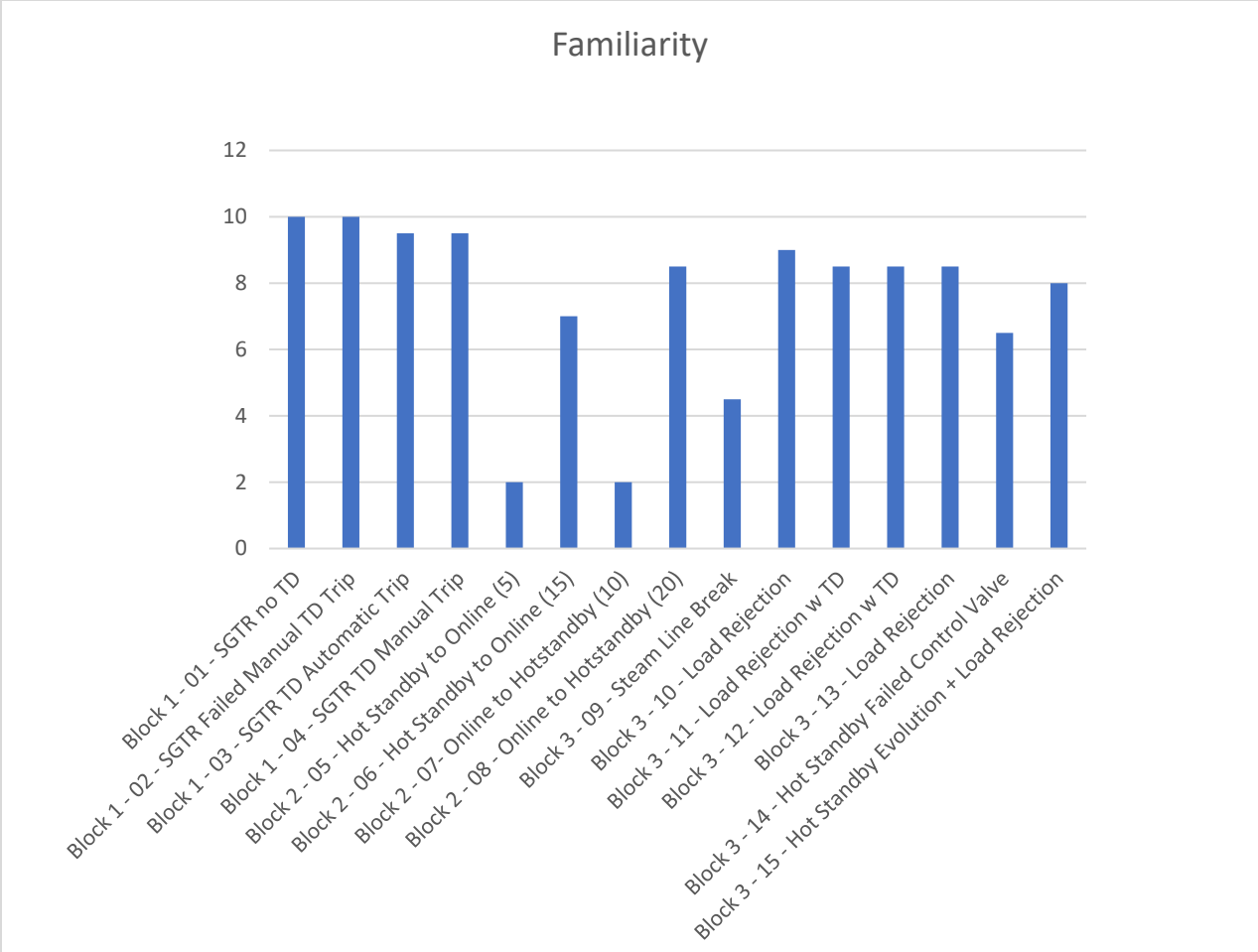
Figure B-8. Familiarity SART scores by scenario.
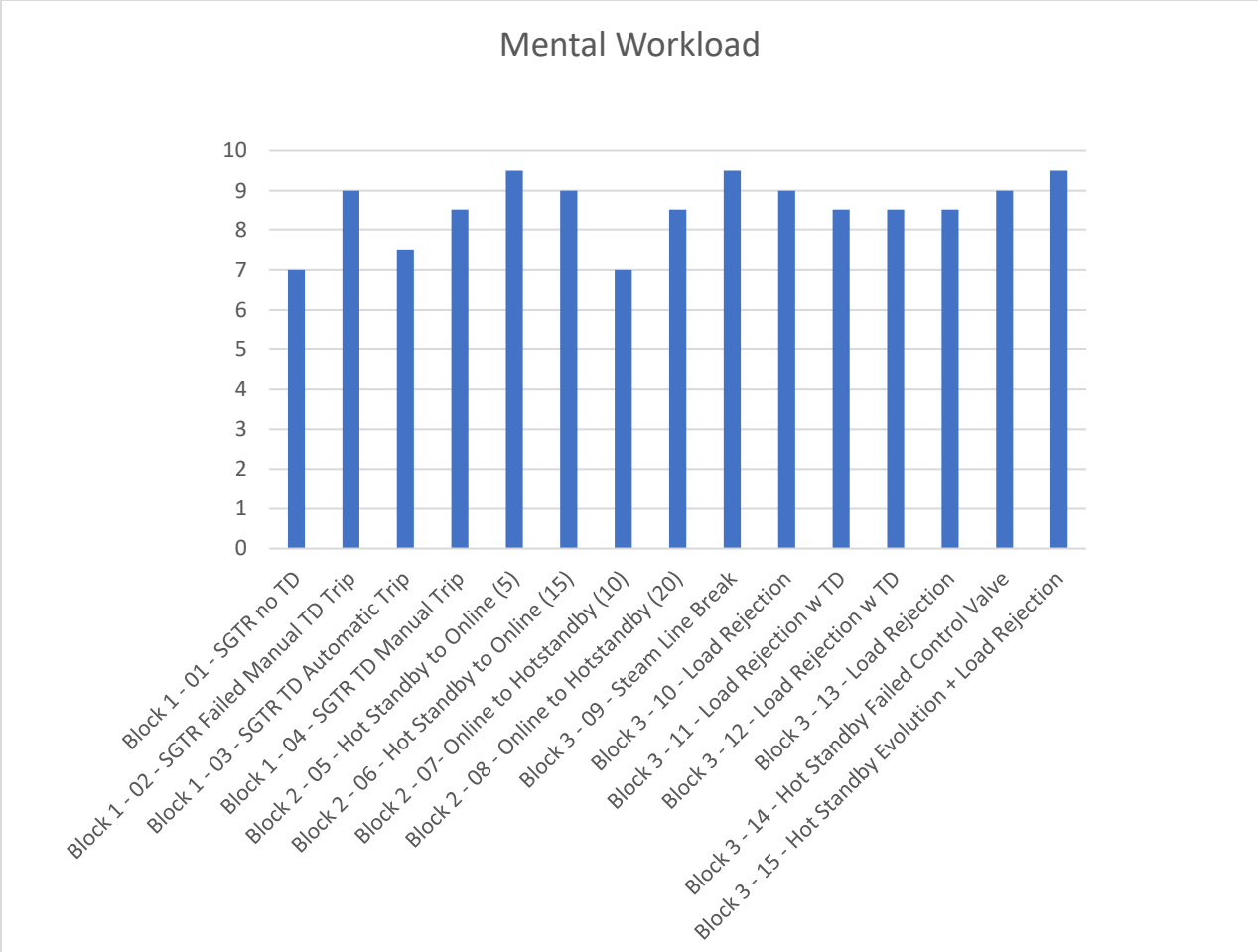
Figure B-9. Mental Workload SART scores by scenario.

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**Appendix C
Performance Drivers Data**

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Appendix C
Performance Drivers Data
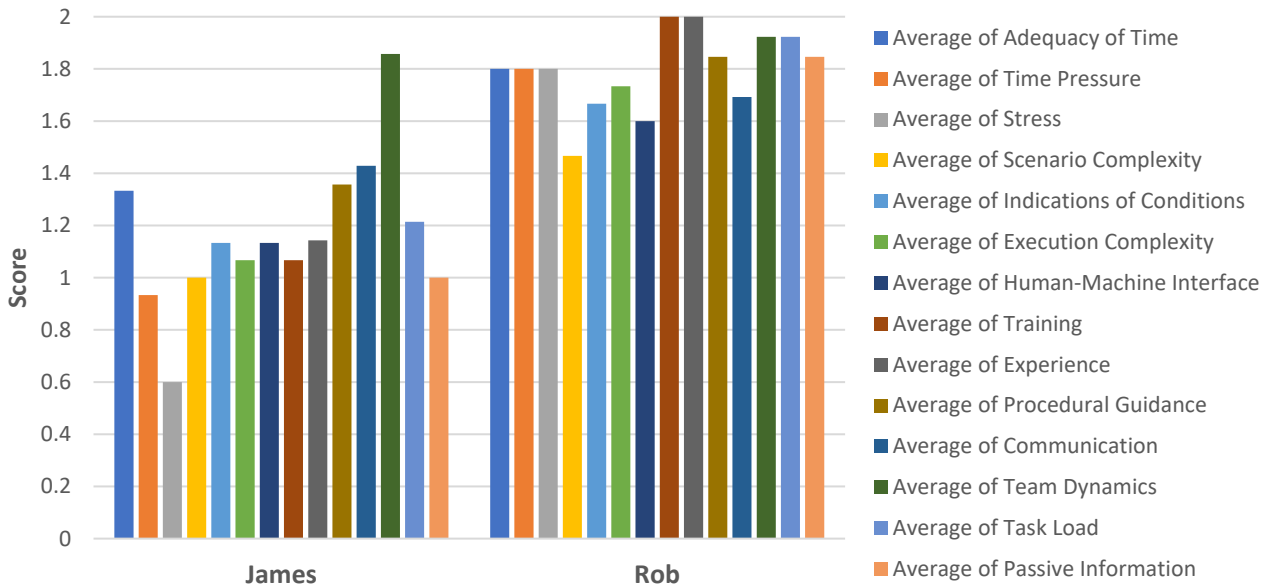
Figure C-1. Comparison of operators' answers to each other.
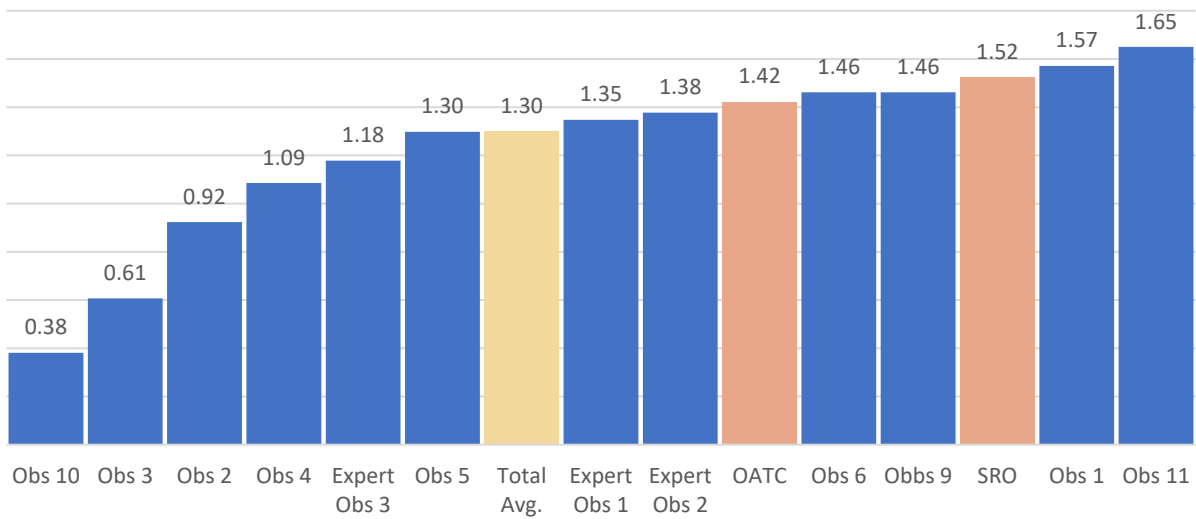
Figure C-2. Average performance driver score for the operators, expert observers with operations experience, and the research team observers.
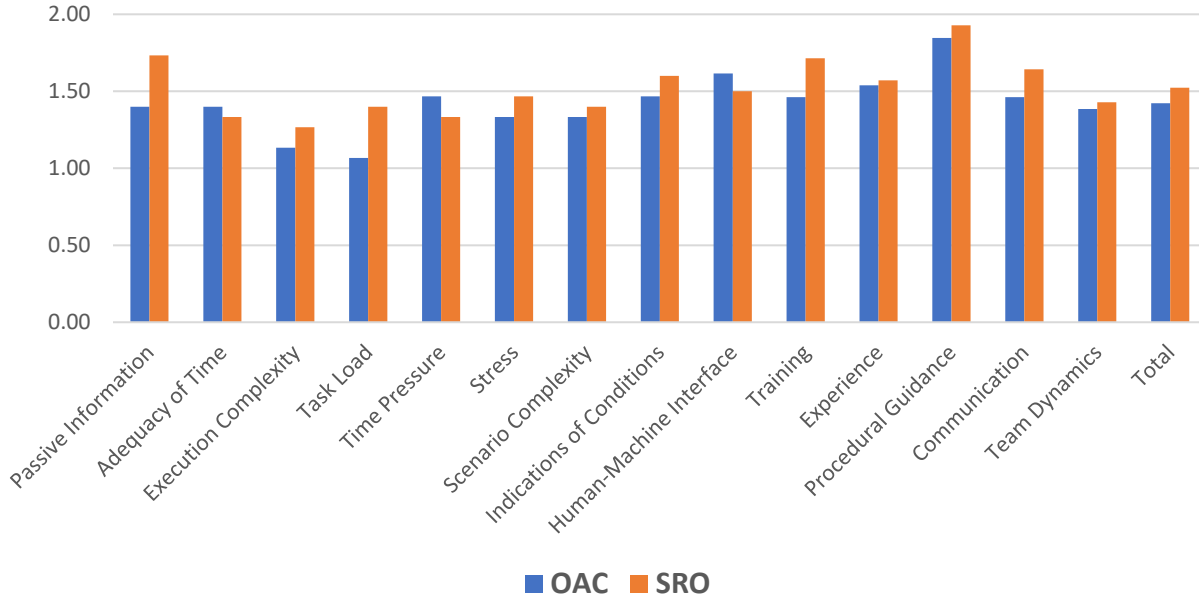
Figure C-3. Individual performance driver scores averaged across all scenarios of the study by operator role as SRO and OATC.
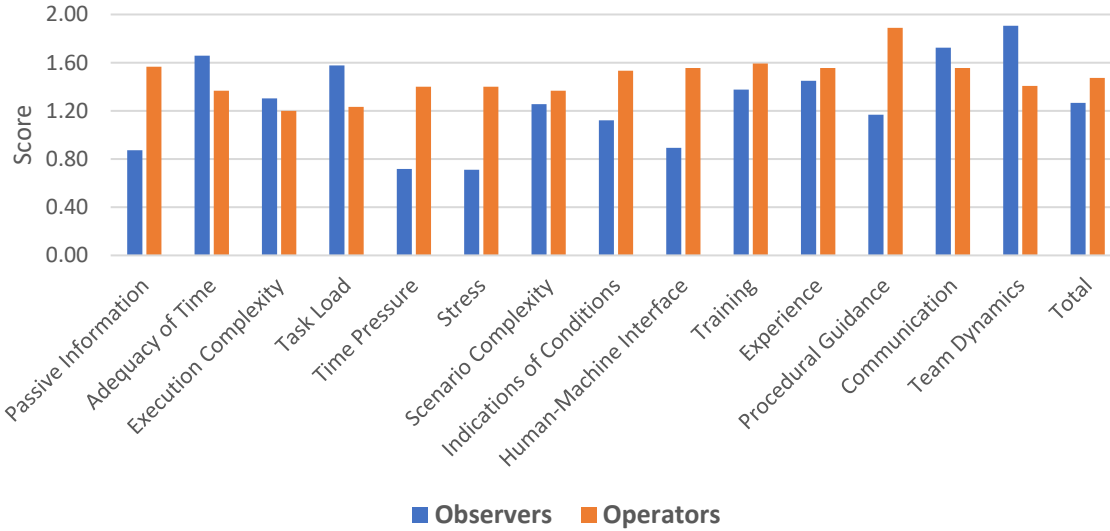
Figure C-4. Comparison of observers' and operators' scores of each scenario.

As shown in Scenario 3 (see Figure C-5 below), SGTR with automatic TPD actuation, scored the best among the two operators. Among observers, Scenario 4E, the second run of load rejection without the TPD system, finished highest. Table C-1 provides the numerical values for these scores.
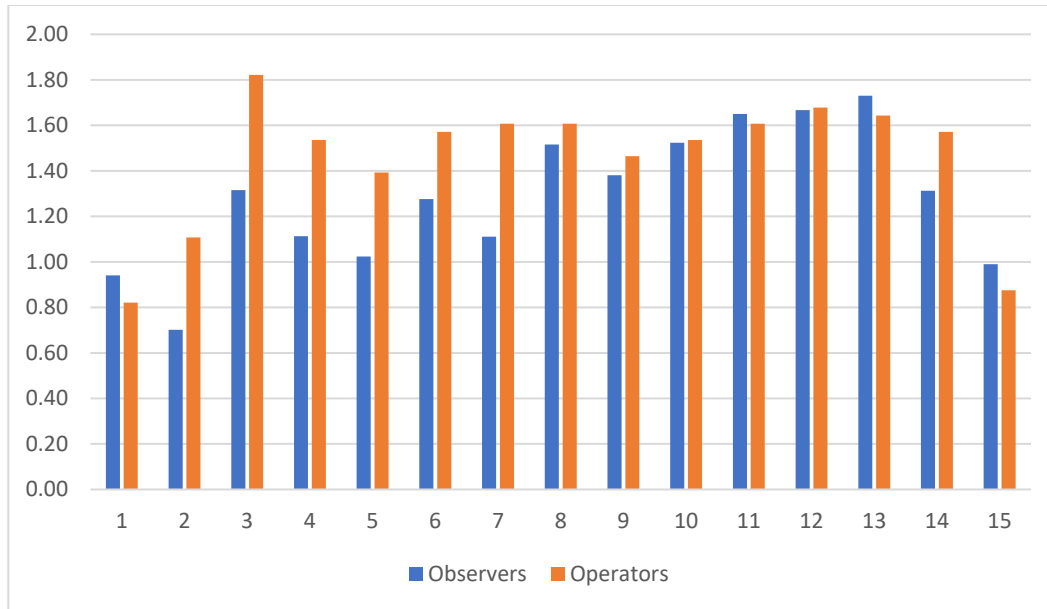
Figure C-5. A comparison of the average performance driver score for each scenario collapsed across all observers and the two operators.

Table C-1. Mean PerfRatings by Scenario. Note. HSB – hot standby.

Scenario	Category	Description	Observers	Operators
1	SGTR	No TPD	0.94	0.82
2	SGTR	Failed TPD Actuation	0.70	1.11
3	SGTR	Automatic TPD Actuation	1.32	1.82
4	SGTR	Manual TPD Actuation	1.11	1.5
5	Normal TPD	HSB -> Online 5 MW/min	1.02	1.40
6	Normal TPD	HSB -> Online 15 MW/min	1.28	1.57
7	Normal TPD	Online -> HSB 10 MW/min	1.11	1.61
8	Normal TPD	Online -> HSB 20 MW/min	1.52	1.61
9	TPD Steam Link Leak	TPD Steam Line Break	1.38	1.46
10	Load Rejection	GPWR without TPD	1.52	1.54
11	Load Rejection	GPWR with TPD	1.65	1.61
12	Load Rejection	With TPD	1.67	1.68
13	Load Rejection	Without TPD	1.73	1.64
14	Fault TPD Unknown	Failed Open CV Valve	1.31	1.57
15	Fault TPD Unknown	Hot Standby Evolution	0.99	0.88
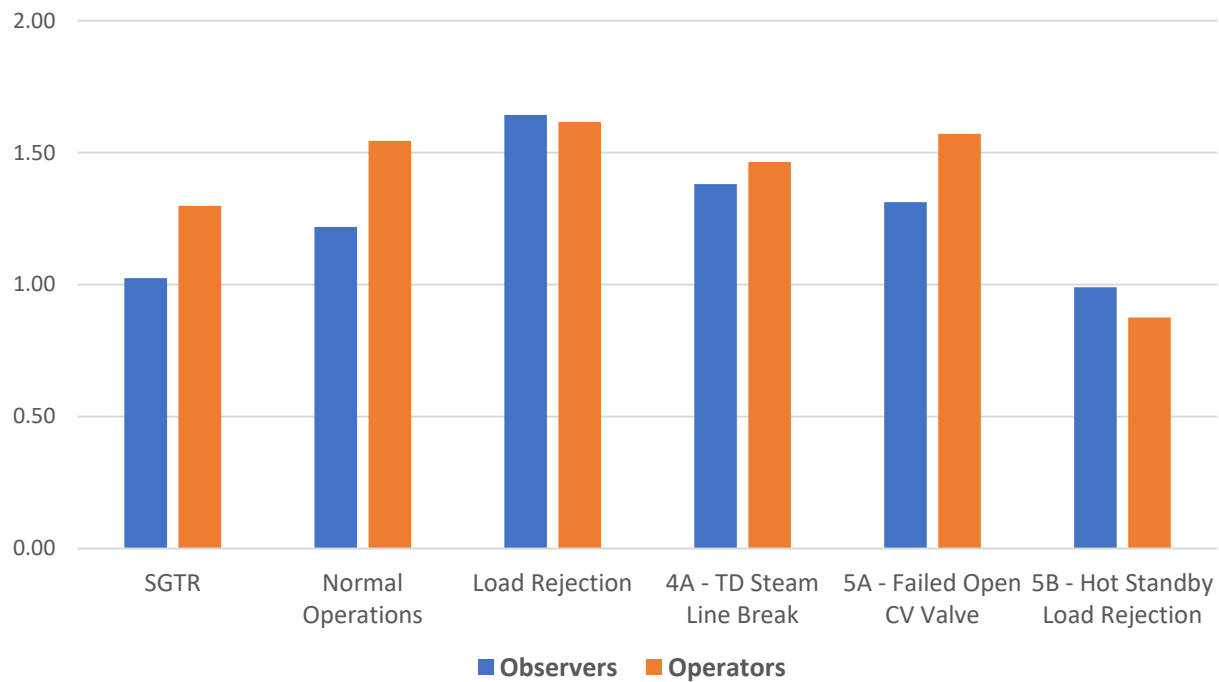
Figure C-6. Comparison of different types of scenarios.
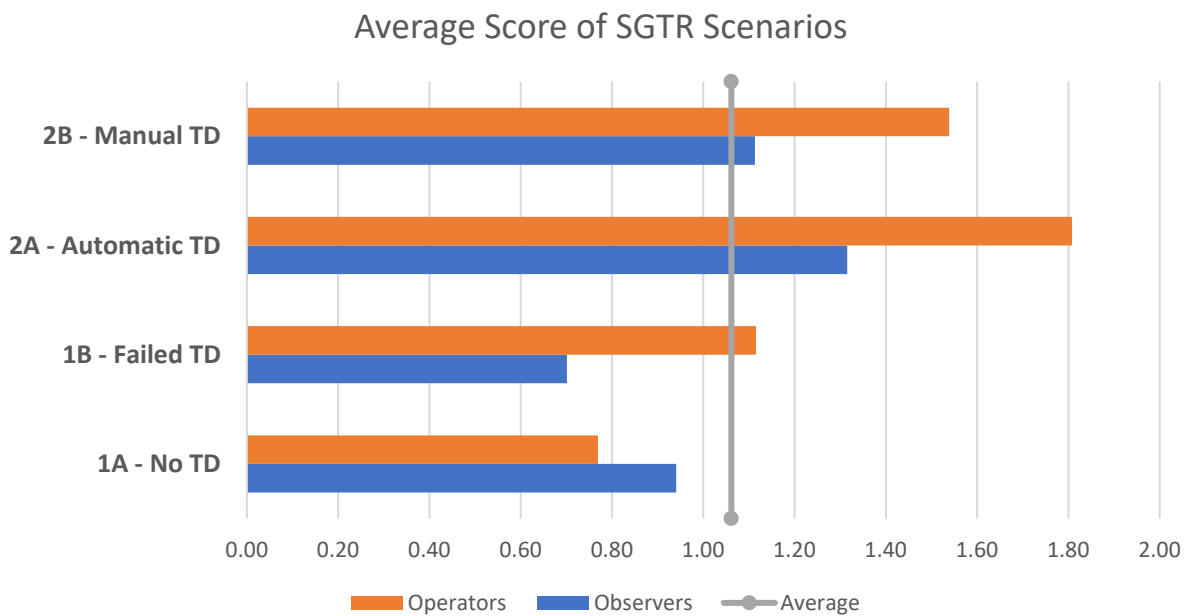
Figure C-7. Comparison of SGTR scenarios.

Average Scores of Normal Operation Scenarios
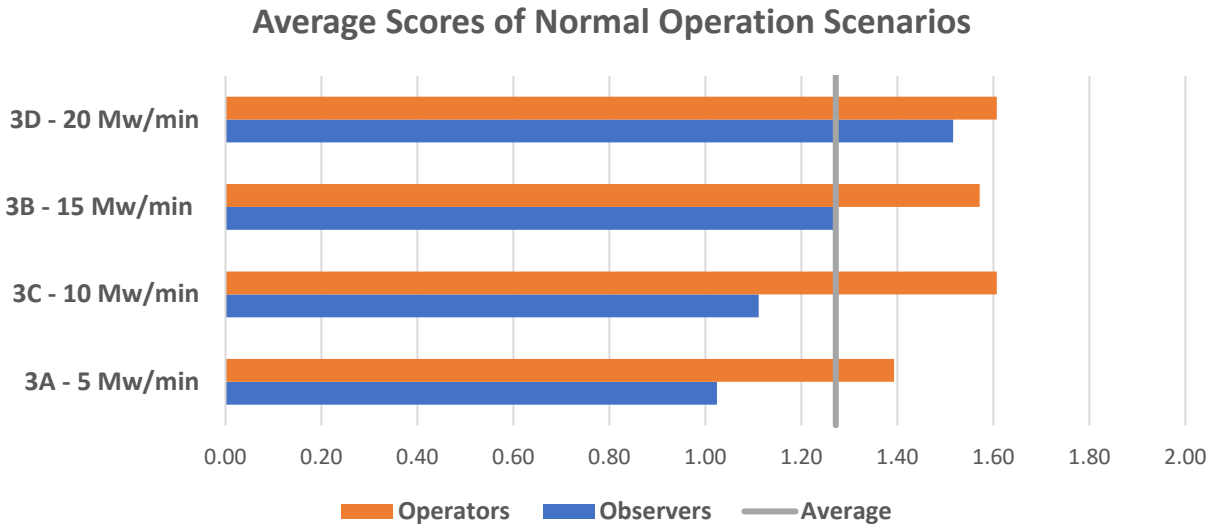
Figure C-8. Comparison of Normal Operations scenarios.

Average Scores of Load Rejection Scenarios
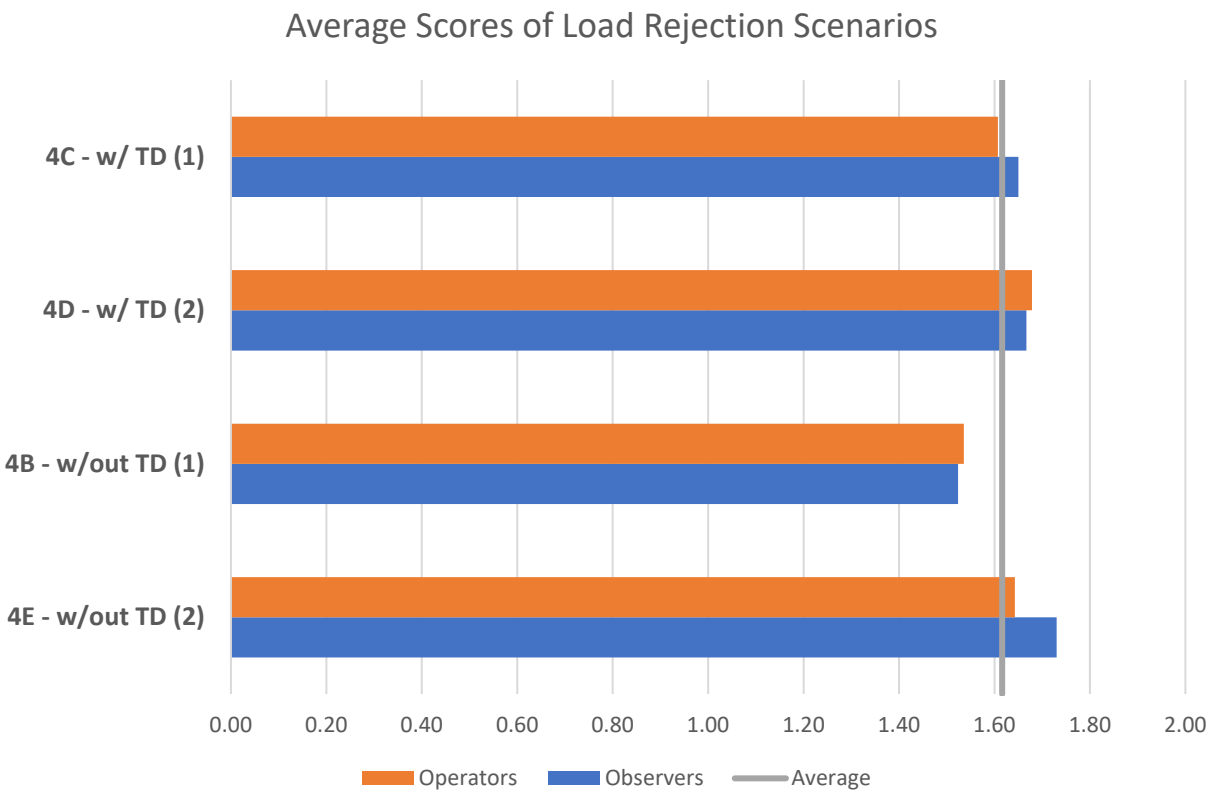
Figure C-9. Comparison of load rejection scenarios.
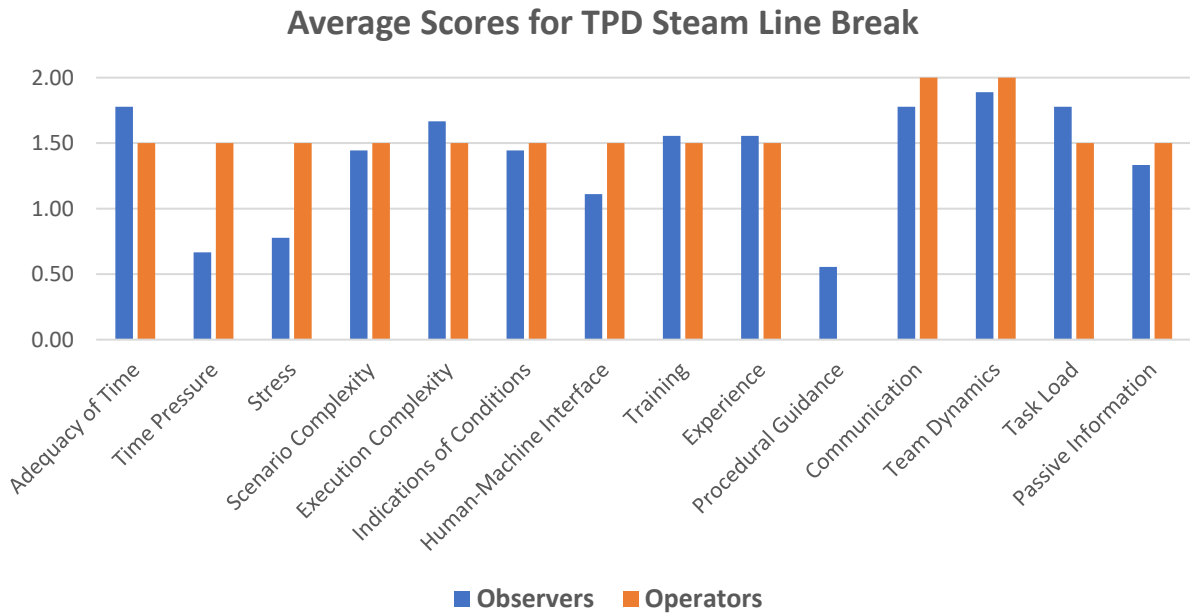
Figure C-10. Comparison of observers and operators scores for TPD steam line break scenario.
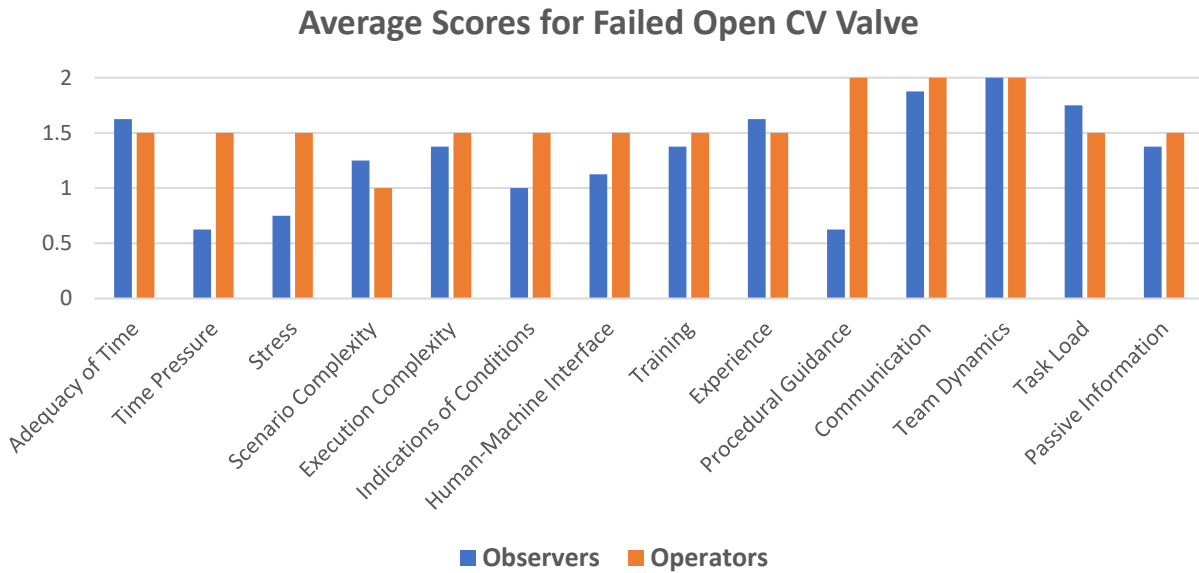
Figure C-11. Comparison of observers and operators scores per category for Scenario 5A.

Average Scores for Failed Open CV Valve
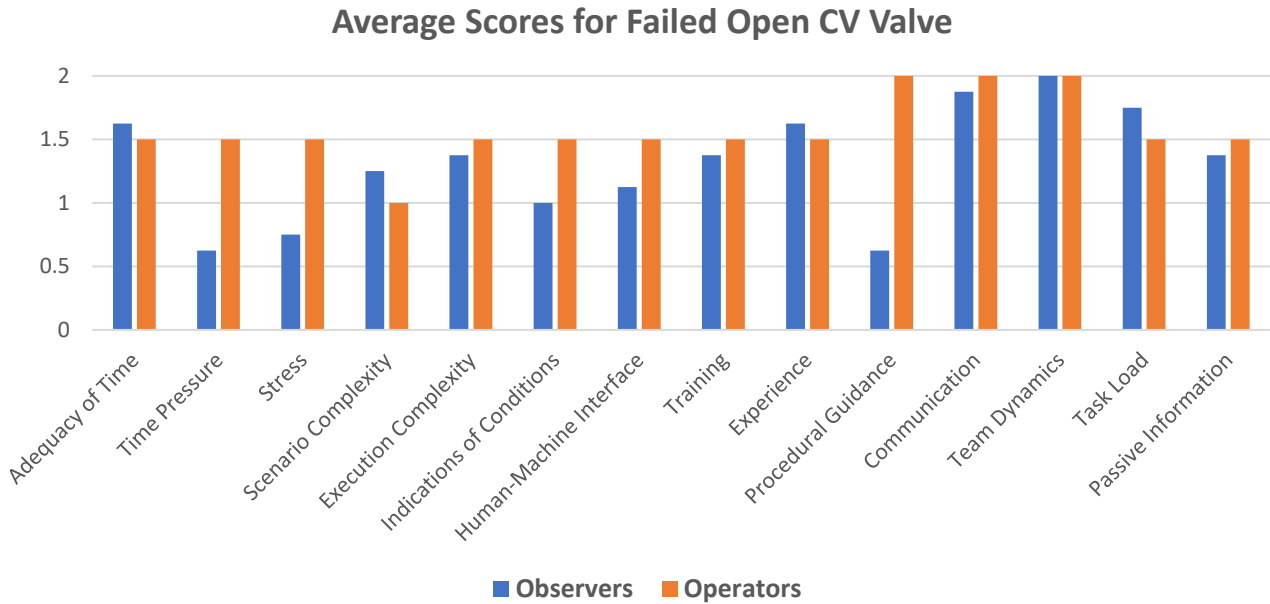
Figure C-12. Comparison of observers and operators scores for the failed open TPD control valve scenario.

Average Scores for Hot Standby Load Rejection
*data missing from operators
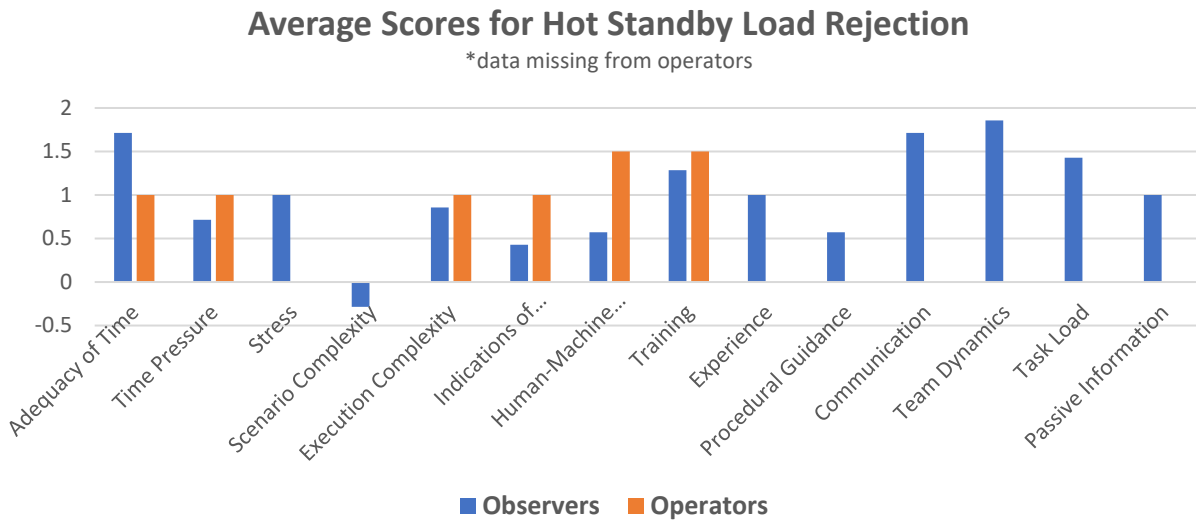
Figure C-13. Comparison of observers and operators scores per category for the TPD in hot standby with a load rejection scenario.

Average Scores for Stress

Average Scores for Scenario Complexity

Average Scores for Adequacy of Time

Average Scores for Time Pressure

Average Scores for Human-Machine Interface

Average Scores for Training
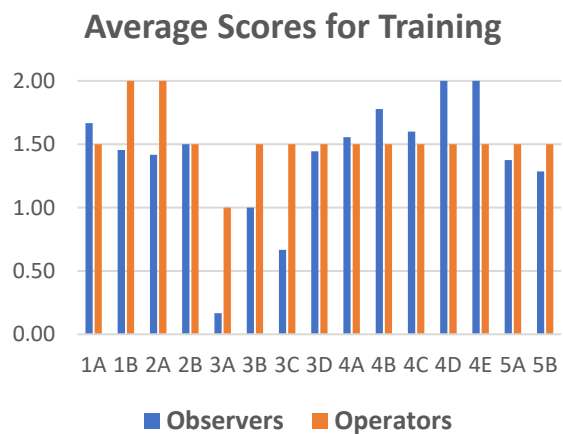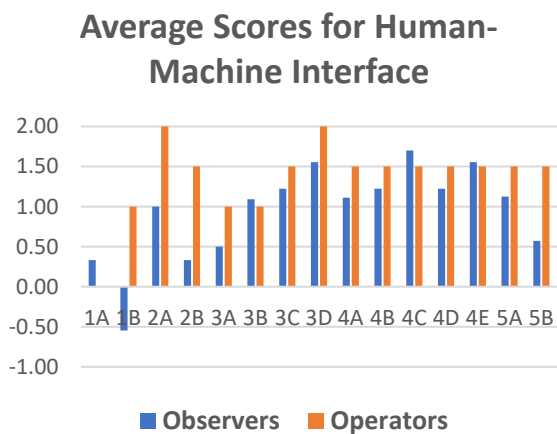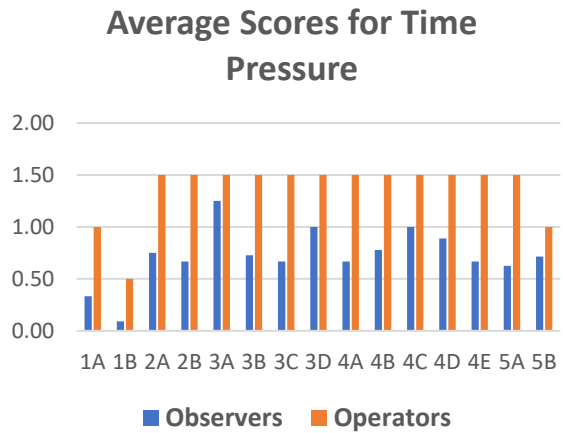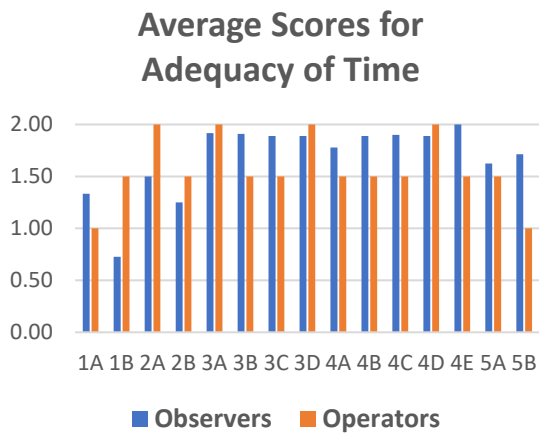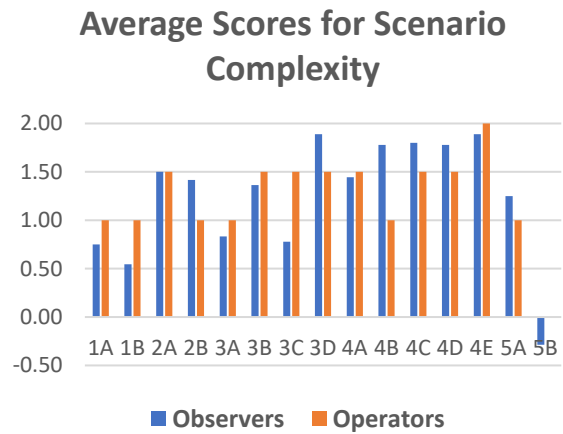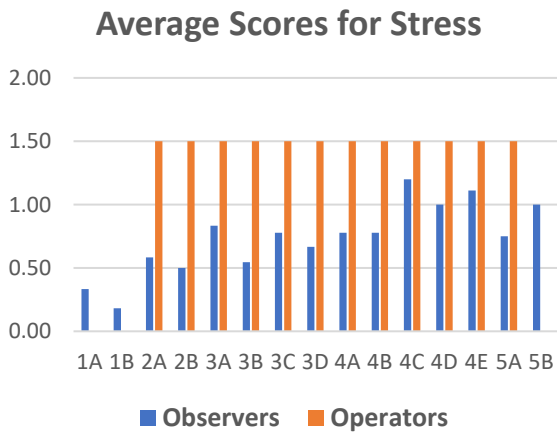
Note. Figure continues onto next page.
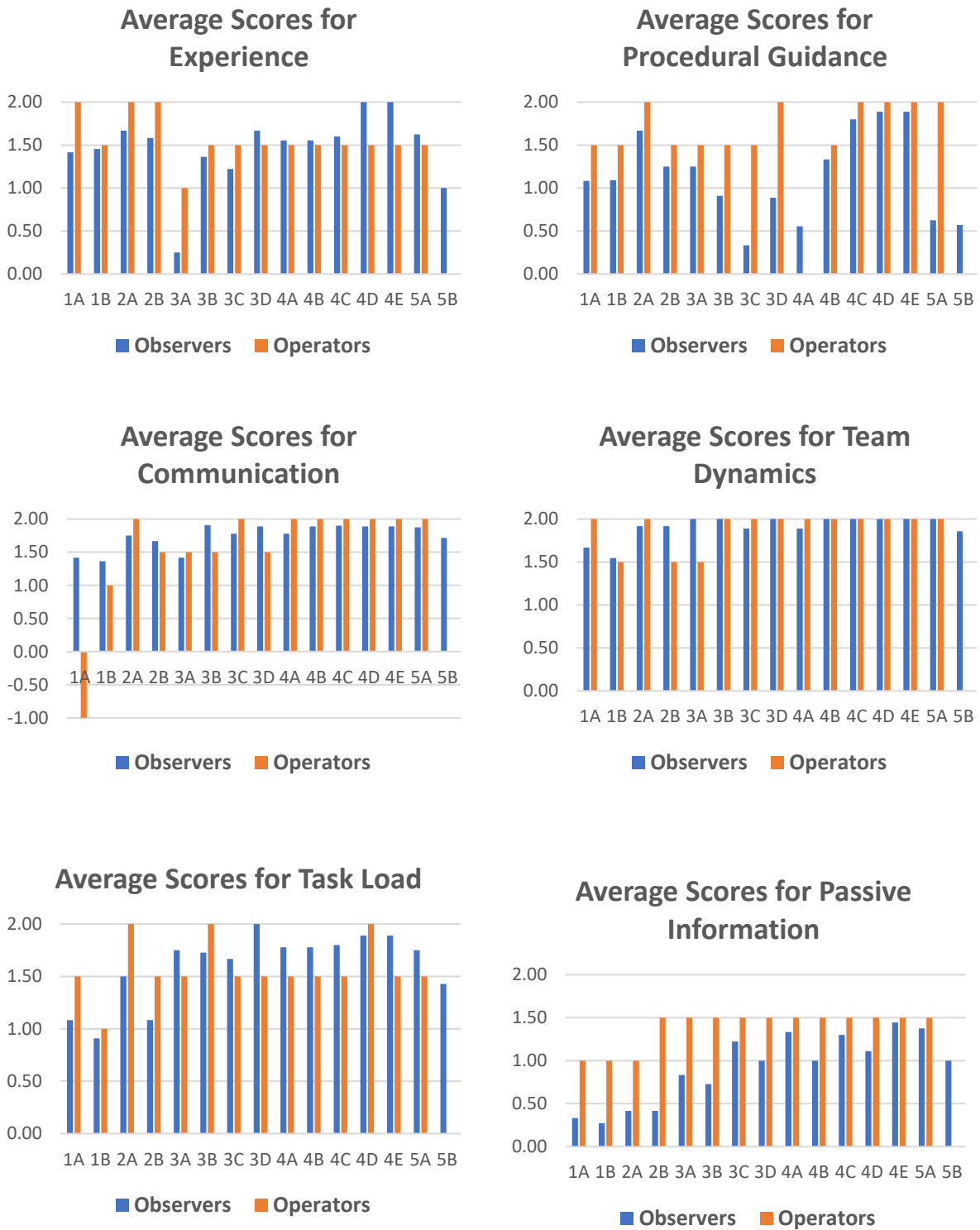
Figure C-14. Operator and observer scores per scenario for each category.

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**Appendix D
Eye-Tracking Data**

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Appendix D
Eye-Tracking Data

In Figure D-1, the two panels on the top show the distribution of fixations across all display elements for the two operators. The absence of a color overlay indicates no or a negligible number of fixations, whereas the presence of the color gradient indicates the time spent on a specific display element across a scenario (blue = minimal time, red = maximal time for a scenario). Two placeholders (a symbol for a face and a file symbol) were added for each display bay that represent fixations by an operator directed at the other operator or PP respectively (see Figure 14). The two panels on the bottom show the time course of fixations across the entire scenario. Each vertical red element in the top bar indicates fixations in the TPD display. Dark vertical bars in the six central beige lines indicate fixations in the GPWR display bays (D1 = left-most display, B2 = right-most display). The vertical bars in the two bottom rows indicate inter-operator communication (comm: an operator looking at the other operator) and looking at PP.

Figure D-1. Overall spatial and temporal distribution of fixations for Scenario 1: SGTR using GPWR without the TPD in operation.

Figure D-2. Overall spatial and temporal distribution of fixations for Scenario 2: SGTR with TPD Failed Manual Trip.

Figure D-3. Overall spatial and temporal distribution of fixations for Scenario 3: SGTR with TPD Automatic Trip.

Figure D-4. Overall spatial and temporal distribution of fixations for Scenario 4: SGTR with TPD Manual Trip.

Figure D-5. Overall spatial and temporal distribution of fixations for Scenario 6: Hot Standby to Online at 15 MW / min ramp.

Figure D-6. Overall spatial and temporal distribution of fixations for Scenario 7: Online to Hot Standby at 10 MW/min ramp.

Figure D-7. Overall spatial and temporal distribution of fixations for Scenario 8: Online to Hot Standby at 20 MW/min ramp.

Figure D-8. Overall spatial and temporal distribution of fixations for Scenario 9: TPD Steam Line Leak.

Figure D-9. Overall spatial and temporal distribution of fixations for Scenario 10: Load Rejection GPWR (governor valve failed close).

Figure D-10. Overall spatial and temporal distribution of fixations for Scenario 11: Load Rejection (GV fail close) with TPD.

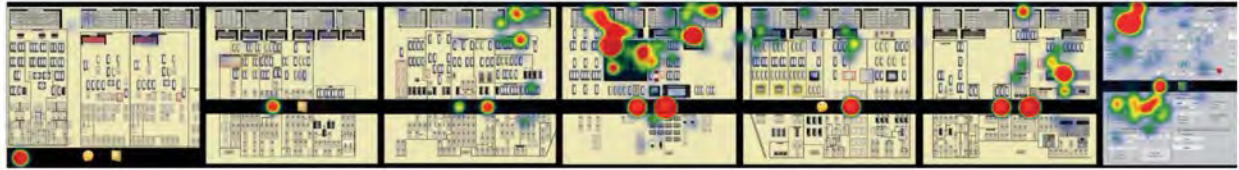Figure D-11. Overall spatial and temporal distribution of fixations for Scenario 12: Load Rejection (GV fail close) with TPD.

Scenario 13: Load Rejection GPWR (GV fail close)

Spatial Distribution of Fixations [Heat Map]   Operator on Controls
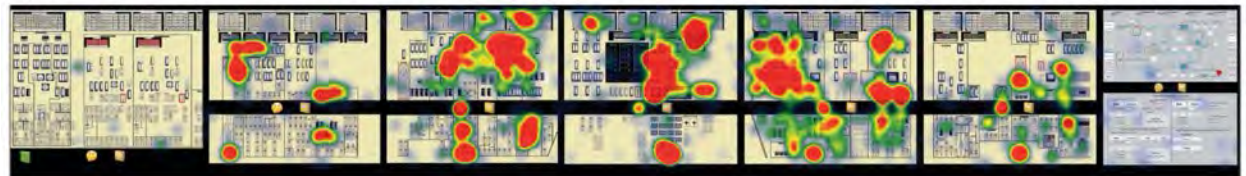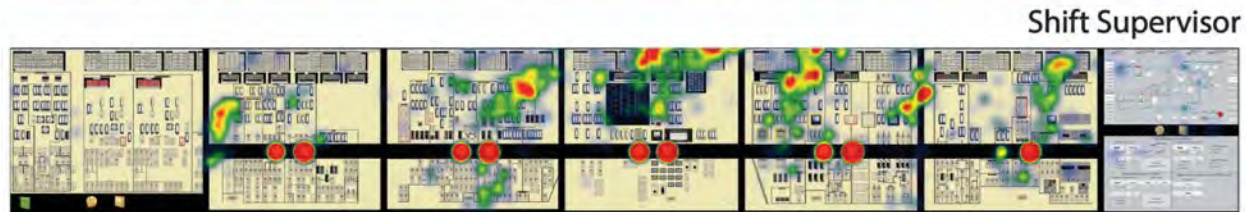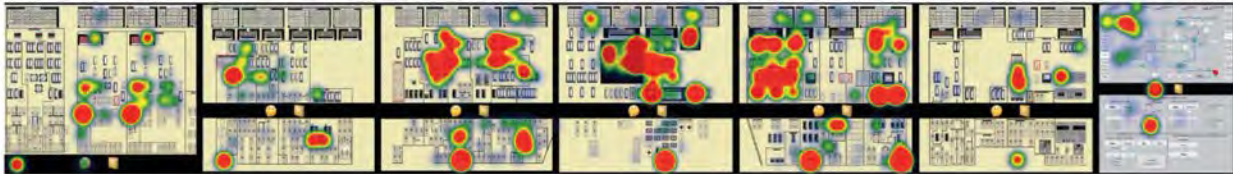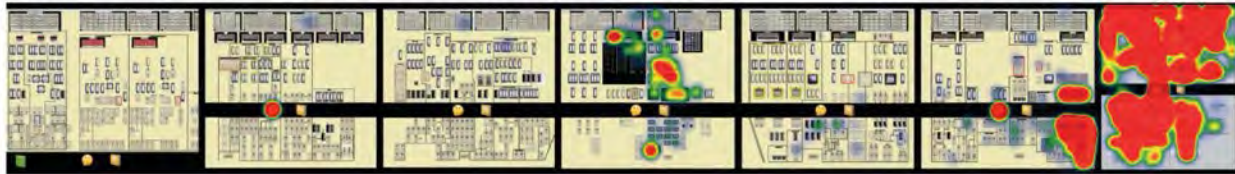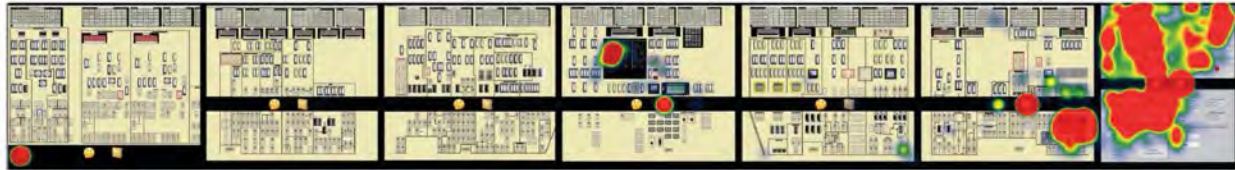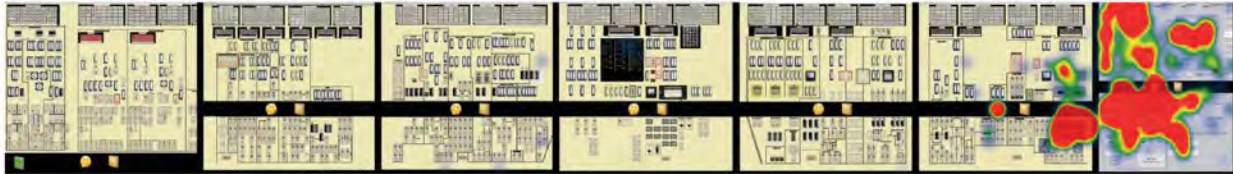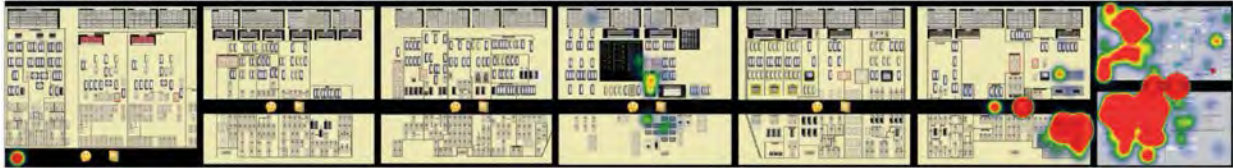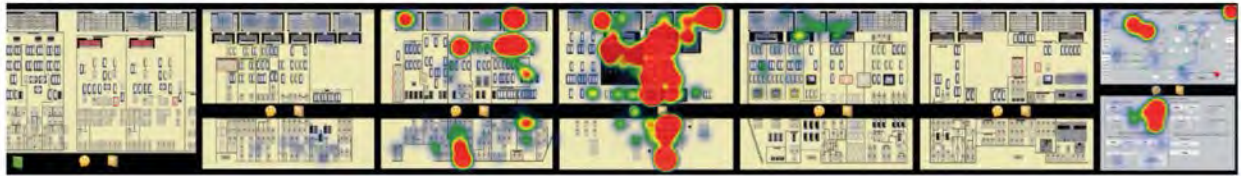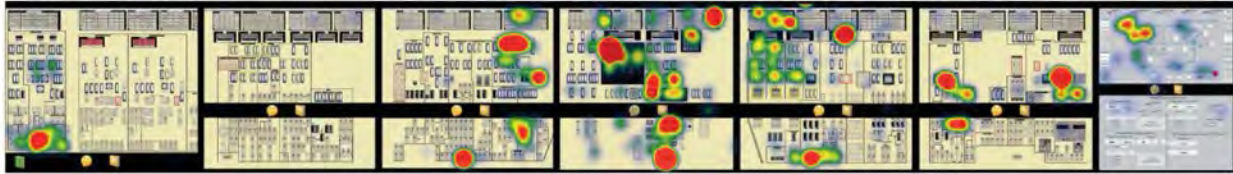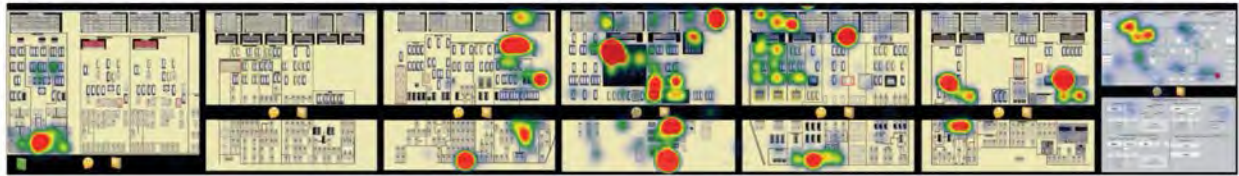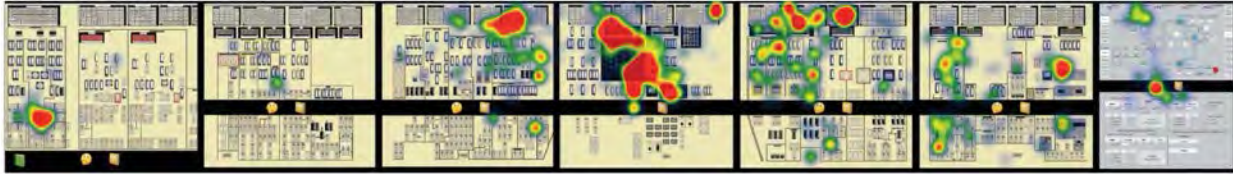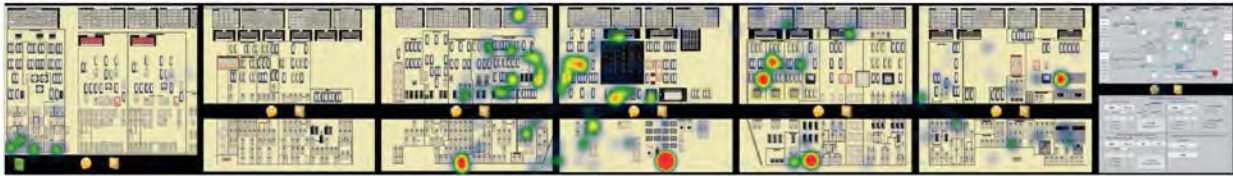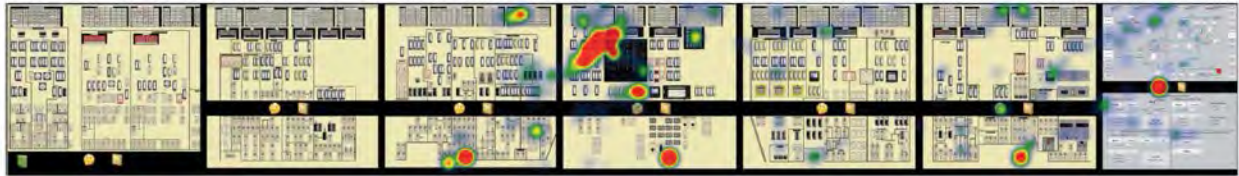
Shift Supervisor

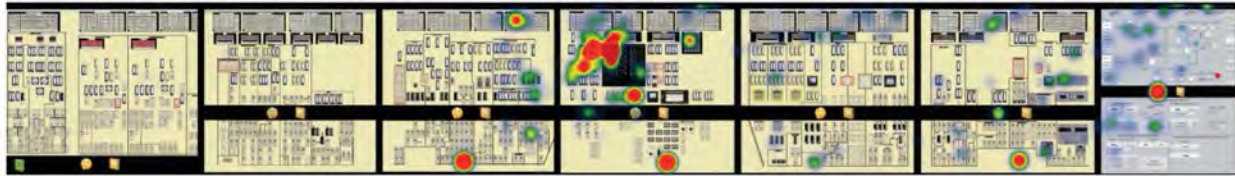## Time Course of Eye Gaze   Operator on Controls

Shift Supervisor

Figure D-12,. Overall spatial and temporal distribution of fixations for Scenario 13: Load Rejection GPWR (GV fail close).

Figure D-13. Overall spatial and temporal distribution of fixations for Scenario 14: Hot Standby Failed CV (looks like main steam leak).

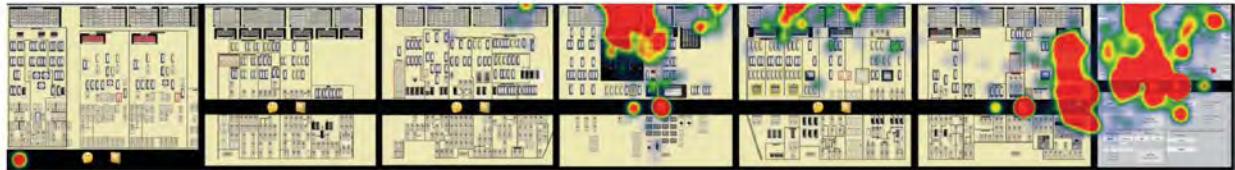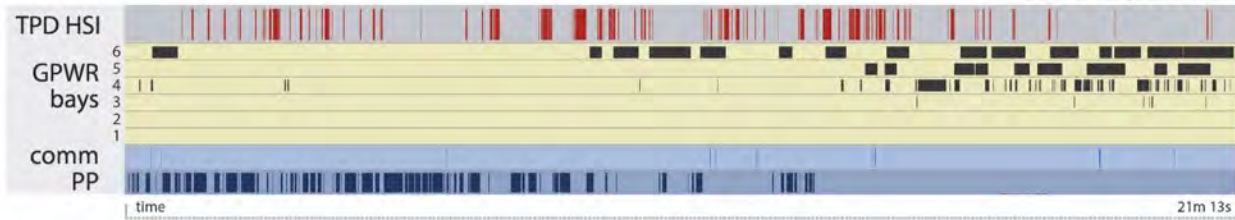Figure D-14. Overall spatial and temporal distribution of fixations for Scenario 15: Hot Standby Evolution Interrupted with load rejection.