Simulators and Operating Concepts for Hydrogen Production

Thomas A. Ulrich[a], Stephen Hancock[a], Roger Lew[b], Ronald L. Boring[a], Tyler Westover[a], Richard Boardman[a]
[a]Idaho National Laboratory, Idaho Falls, Idaho, USA
[b]University of Idaho, Moscow, Idaho, USA
[a]{Thomas.Ulrich, Stephen.Hancock, Ronald.Boring, Tyler.Westover, Richard.Boardman}@inl.gov
[b]{rogerlew}@uidaho.edu

Abstract: A human-in-the-loop study was performed to demonstrate and evaluate the concept of operators for a simulated thermal dispatch system that couples a nuclear power plant to a nearby hydrogen production plant. The thermal dispatch system diverts steam from the traditional electricity production to a nearby hydrogen plant as an alternative revenue stream to bolster the nuclear power plant's economic viability. The research entailed developing a full-scope nuclear control room simulator capability to dynamically represent operational contexts for the thermal dispatch system to evaluate potential operational impacts. Operators provided design feedback during the formative concept of operations development—human-machine interface and procedures, while a separate group of operators provided evaluation feedback during full-scope simulator scenario testing. Operators were able to successfully control the system across both normal and abnormal scenarios. This paper describes the activities required to develop the concept of operations and test this concept in a full-scope simulator.

---

1. INTRODUCTION

The U.S. fleet of light water nuclear reactors were built primarily during the 1970s and 1980s to serve as large baseload electricity generators. Over the ensuing last half century, the U.S. electric grids and electric energy markets are dramatically different, with economics that no longer favor slow maneuvering steady state operation. Instead, the electric grid is now much more complicated as it has grown to accommodate more variable and increased electrical demands of the nation. The grid is also more dynamic due to increasing adoption of renewable energy generators with variable generation based on environmental conditions. Furthermore, fossil fuel generators, such as combined-cycle natural gas plants, leverage inexpensive natural gas prices and boast the ability to ramp generation rapidly. The new more dynamic electric grid with more modern competing generators poses a significant challenge to existing nuclear power plants (NPPs), which must compete on the whole sale electricity market. Despite these challenges, the U.S. electric grid relies on the high capacity factors to ensure baseload generation, and NPPs account for 19% of the U.S. electrical generation [1]. In response to these increasing economic pressures, research is underway to provide alternative revenue streams to increase the existing nuclear fleet's economic viability and ensure the continued operation of these valuable generation assets.

Specifically, the Department of Energy's Light Water Reactor Sustainability program funds a research pathway dedicated to developing and demonstrating the technology and concept of operations for light water reactor NPPs to competitively sell thermal energy produced by an NPP to an industrial customer [2]. Idaho National Laboratory (INL) leads this multi-year effort. The flexible plant operations and generation concept central to this effort aims to allow NPPs to maintain a steady-state with reactor power at max capacity while diverting high quality, moderately high pressure steam from the turbine driven electricity generator to an industrial customer. NPPs produce large quantities of steam suitable for a high temperature steam electrolysis plant customer, which is one of the more promising and economically advantageous uses cases [2].

The flexible plant operations and generation research spans all aspects to support NPPs in adopting the thermal dispatch technology required to divert steam to an offsite industrial customer. The research activities include economic market analysis that determined NPPs can outperform existing natural-gas steam reforming methods associated with a levelized cost of hydrogen production (\$1.50/kg H_2 vs. \$2.00/kg H_2, respectively) [8]. To capitalize on the economics associated with the thermal dispatch capability, significant research efforts have been made over the last two years to develop the thermal dispatch technology. Limiting the impacts to existing systems and operations is the critical constraint governing the research activities to develop, demonstrate, and evaluate the thermal dispatch concept. The work presented in this paper describes the human-factors portion of this larger research effort and focuses on the simulation-based human-in-the-loop approach to evaluate concept of operations impacts and develop new concept of operations required to support the thermal dispatch concept.

2. THERMAL DISPATCH CONCEPT OF OPERATIONS

Modifying existing light water reactors with thermal dispatch capability will undoubtably impact the existing concept of operations. It is important to understand these impacts to streamline the integration for the new capability. Once the impacts are understood, it is critical to ensure the new concept of operations does not comprise existing operations. There are several potential operational impacts that merit investigation. These impacts fall under the following three main categories, listed in order of importance:

1. Detecting, diagnosing, and mitigating new types of adverse conditions due to the thermal dispatch system
2. Inter-organization coordination that must be performed with the grid and the industrial user
3. Additional operations specific to monitoring and controlling the thermal dispatch system, which must be performed in tandem with existing operations

The primary operational impact resulting from the thermal dispatch augmentation is safety related and of critical importance. The thermal dispatch system renders the plant thermally coupled to the nearby industry thermal energy consumer. In some envisioned deployment configurations, the plant is also electrically coupled to the thermal energy consumer. To maintain licensing requirements, the licensed operators in the control room must have sole authority over the state of the plant and, most importantly, reactivity control. The thermal and electrical coupling has the potential to provide feedback that could impact plant reactivity, and therefore careful consideration was made to the concept of operations to ensure appropriate barriers prevent any external industrial consumer event from inadvertently controlling reactivity.

The concept-of-operations testing performed under the INL study placed a large emphasis on ensuring operators could maintain control over reactivity when faced with external events related to the thermal dispatch system. As a result, operators must be able to contend with a sudden electrical load loss from the thermal dispatch consumer, since the electrical consumption from this can proportionally account for the bulk of the electricity produced in some use cases. Thermal rejection must also be considered, but a contractual agreement may serve as a potential solution. In this agreement, the consumer would be required to ensure they can receive or dump the thermal energy to atmosphere in the event they have an operational disruption. Alternatively, though a potentially more costly approach, could include the plant maintaining their own capability to dump the thermal energy with existing or new equipment.

Providing thermal power to a nearby industrial user requires additional coordination. Operators currently coordinate with electrical grid dispatch, but now operators must also coordinate with thermal power consumers and electrical dispatch in tandem. The type of coordination is therefore different. The frequency of coordination will also increase since the typical use case to take advantage of electrical wholesale prices dictates frequent transitions between purely electric and electric and thermal modes of operation occurring once each day.

The new capability ushers in new operations required to transition the equipment states between the two modes of operation. Operationally, transitioning to the thermal and electric mode entails closing the governor vales while opening the control valves for the thermal dispatch system. Operators must perform this transition to minimally affect reactor power, as pressure deviations resulting from diverting the steam away from the turbine can adversely impact reactor power and induce undesired control rod movement. Therefore, this new operation to maintain flow balance while diverting the steam from the turbine to the thermal dispatch system requires a careful orchestration of the two systems. With the addition of the new system, maintenance must also be considered, since there is now a new and significant steam flow path that must be included when performing maintenance to both the existing main steam system, but also for the new thermal dispatch system.

To address these operational impacts, a human-in-the-loop approach was used. The following section describes the research approach and briefly outlines some of the key activities performed to develop, demonstrate, and evaluate a thermal dispatch concept of operations.

3. HUMAN-IN-THE-LOOP SIMULATION

A human-in-the-loop approach, also referenced as operator-in-the-loop, is a user-centered design approach employed in nuclear process control settings [3][4][5]. In this approach, representative scenarios are simulated with subject matter experts completing system specific tasks to evaluate the design at each step in the development. With each development and evaluation cycle, the fidelity of the scenarios supported by the simulator and procedures increases in parallel with the design maturity. Representative operational contexts with both subjective operator feedback and objective human and system performance metrics form the basis for design refinements for the development of the concept of operations, human-machine interface, and procedures.

3.2 Pre-Simulation Activities – Developing A Basic Concept of Operations

Operations are constrained by the design of the underlying system, and a design of sufficient maturity must be available to begin developing a concept of operations. However, flexibility in the design is desirable, since this allows insights from the concept of operations development to feed into the design. As a result, the initial preconceptual thermal dispatch system design was refined in tandem with the concept of operations development and evaluation activities described here.

Once an initial design was available, the concept of operations, human-machine interfaces, and procedures were developed to support monitoring and controlling the system based on process constraints and input from nuclear operations experts. Several former operators were recruited to provide operational feedback on the system design. These operators were continually engaged throughout the research, but care was taken to ensure a separate group of operators was used for the evaluation itself to ensure objectivity in their feedback to the concept of operations. A pair of operators was initially interviewed to capture operating experience for the systems relevant to and potentially impacted by the thermal dispatch concept, which are the main steam and turbine control systems. A basic conceptual design was provided to the operators to elicit feedback to develop the necessary information and control schemes needed to monitor and control the proposed system. An initial set of human-machine interfaces with procedures was developed as an initial concept of operations and refined through a series of static usability studies [6].

3.3 Full-Scope Simulator Environment

To address the ability of operators to perform these new operations and contend with the potentially negative impacts of the thermal dispatch design and control on existing operations, a study was performed. The study used a modified version of GSE Systems Generic Pressurized Water Reactor (GPWR) plant simulator and custom-built prototype that provided operators with the ability to monitor and control the thermal dispatch system [7] [7]. A virtual representation of the control room control boards was displayed in the Human Systems Simulation Laboratory (HSSL) using adjustable three-display bays (see Figures 1 and 2). The virtual control boards are connected to the GSE GPWR simulator was modified with a thermal dispatch system that interfaced with the existing plant model through the main steam system and the condenser.

Figure 1: HSSL with the GSE GPWR Control Boards Displayed Virtually on Adjustable Bays

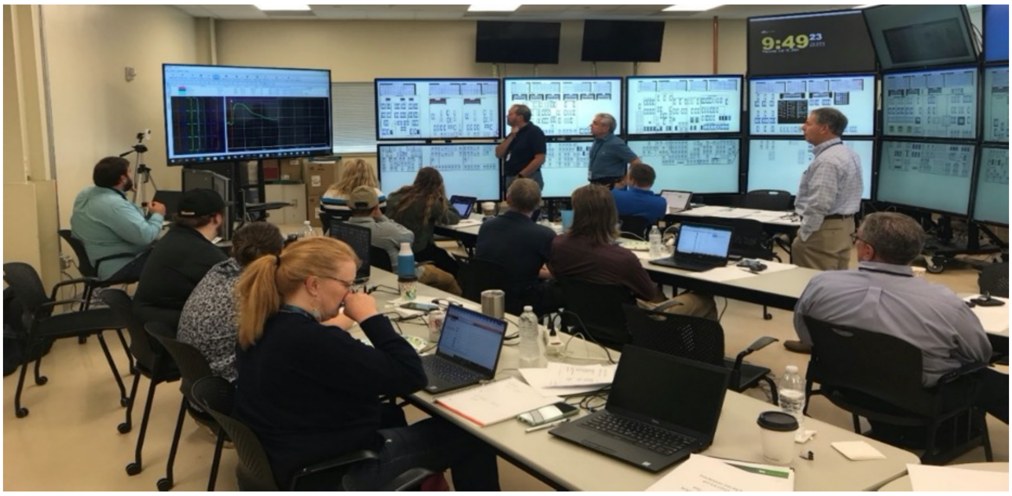


Figure 2: HSSL Configured with the Prototype Thermal Dispatch System HMI

With the modified GPWR, HSSL bays to represent the virtual control boards, and the prototype thermal dispatch HMI, an integrated testing platform allowed a crew of two operators to execute mock procedures written to support thermal dispatch operations. The participant operators performed a series of scenarios to address operational issues and evaluate the feasibility of performing normal and abnormal operations relevant to the thermal dispatch system.

3.4 Thermal Dispatch System Simulation Modelling

The thermal dispatch system was developed within the GSE GPWR software. The thermal dispatch system interfaces with the primary plant model through the main steam header and the condenser.

The primary constraint driving the system design was minimizing any impacts on reactivity due to thermal dispatch operations. Steam flow adjustments impact reactivity, and the system was designed to minimize these impacts. Furthermore, the thermal dispatch control valve and governor valve manipulations, comprising the central control actions for this system, directly impact turbine impulse pressure, which is an input for the T_{avg} and T_{ref} mismatch signal. The reactor control rod control system automatically responds to this mismatch signal, and therefore an adjustment was added to compensate for steam diverted from the turbine to the thermal dispatch system and ultimately returned through the condenser. With compensation, this mismatch can still fluctuate and potentially induce undesirable rod motion. The central constraint for operating the system is therefore ensuring the control manipulations are sufficiently small to establish zero mismatch or remain within the mismatch deadband range.

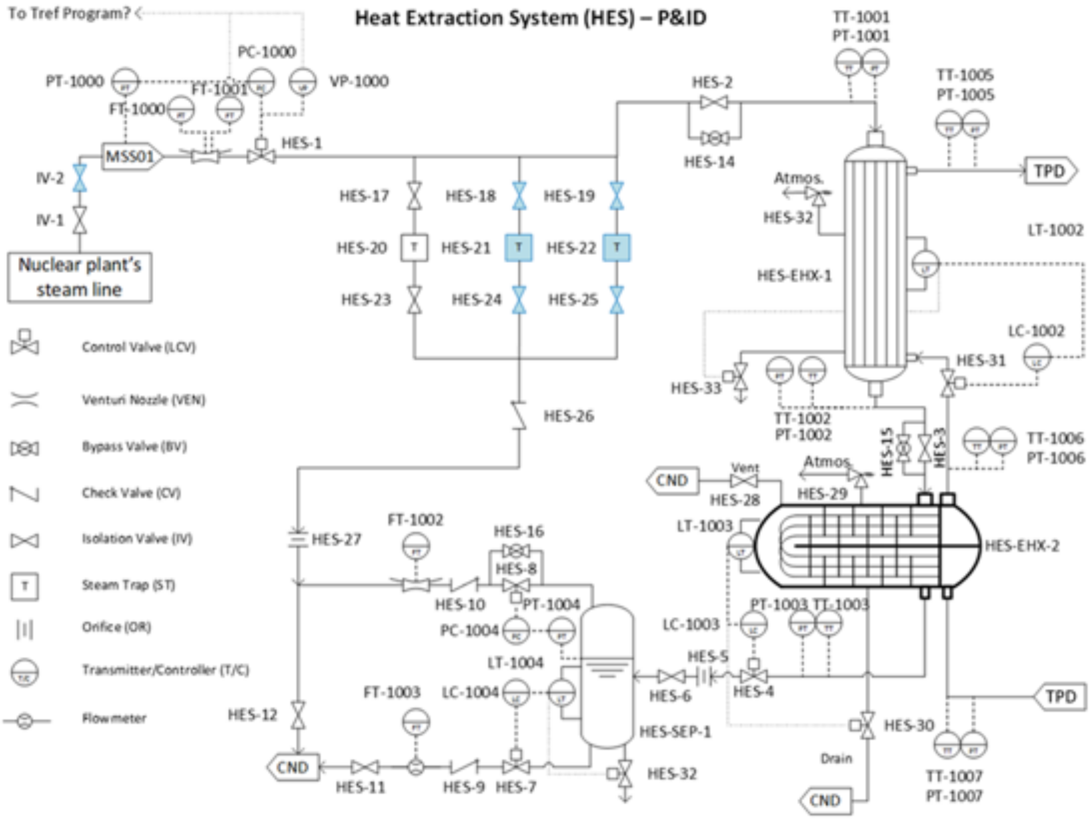


Figure 3: Thermal Dispatch System Design

The existing GPWR model was modified at the steam header and condenser with thermal dispatch input and output interfaces. The thermal dispatch model was developed using the native GSE GPWR software such that it integrated seamlessly with the existing plant model.

3.5 Human-Machine Interfaces

Thermal dispatch requires the operators to extract thermal energy from the main steam line through a steam extraction line via a series of heat exchangers. The heat exchangers are coupled to a steam delivery line that sends thermal energy via steam to a nearby industrial consumer. The thermal dispatch system has four modes of operation, which includes online thermal delivery, hot standby, warm-up, and cold shutdown. The basic operation of the system entails an initial longer duration warming process for the system with a minimal level of steam flow to achieve a hot standby mode. During economically advantageous periods of the day, operators can quickly move from hot standby to online thermal delivery mode within a 15–30-minute period as identified in the operator study. The online to hot standby process requires an equivalent amount of time to perform. The critical control aspects for the thermal dispatch operation occur during these two transitions from hot standby to online and online to hot standby. The operators use a custom-built overview and control display (see Figures 1 and 2, respectively) to monitor the process. The primary control actions include opening the primary control valve to allow flow into the thermal dispatch system while reducing the collective governor valve position proportionally to reduce flow to the turbine. In the current implementation, the operators set a ramp rate for the turbine and then manually manipulate the thermal dispatch control valve as the ramp rate program is automatically executed by the turbine control system. Future designs are planned to automate the operator's manual control, but as a first step in understanding the operations it was important to understand whether an operator could manually perform this manoeuvre.

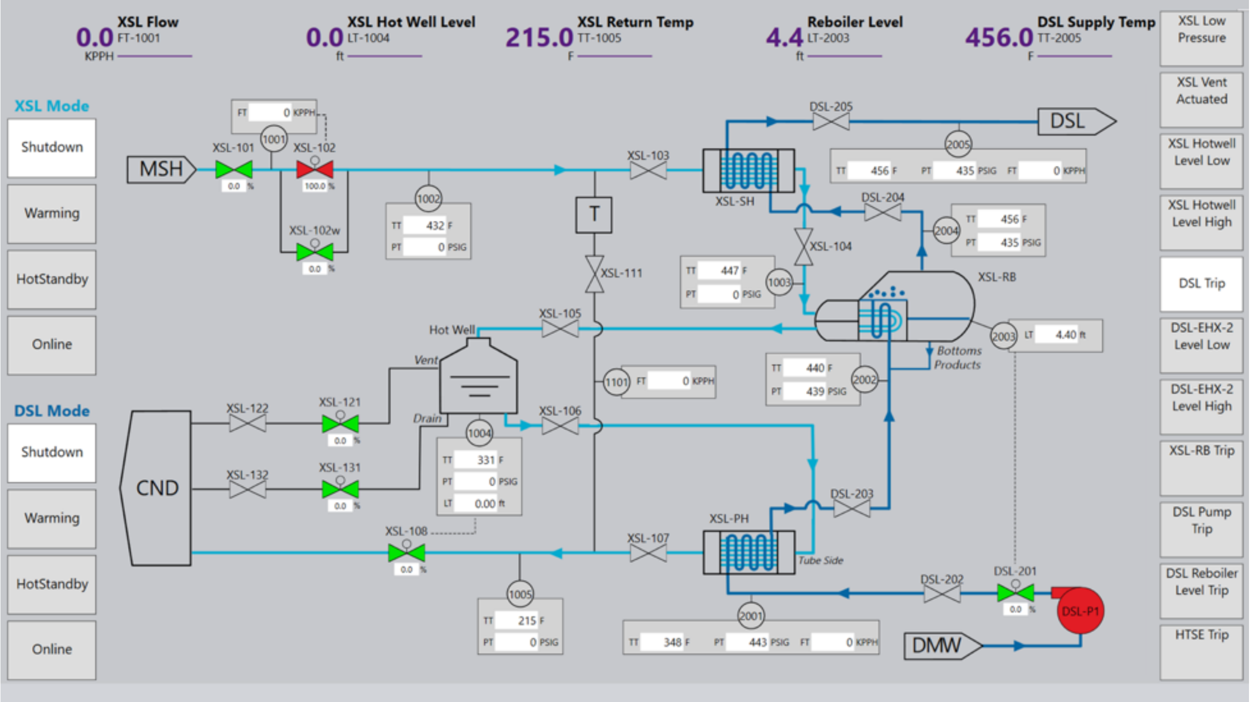
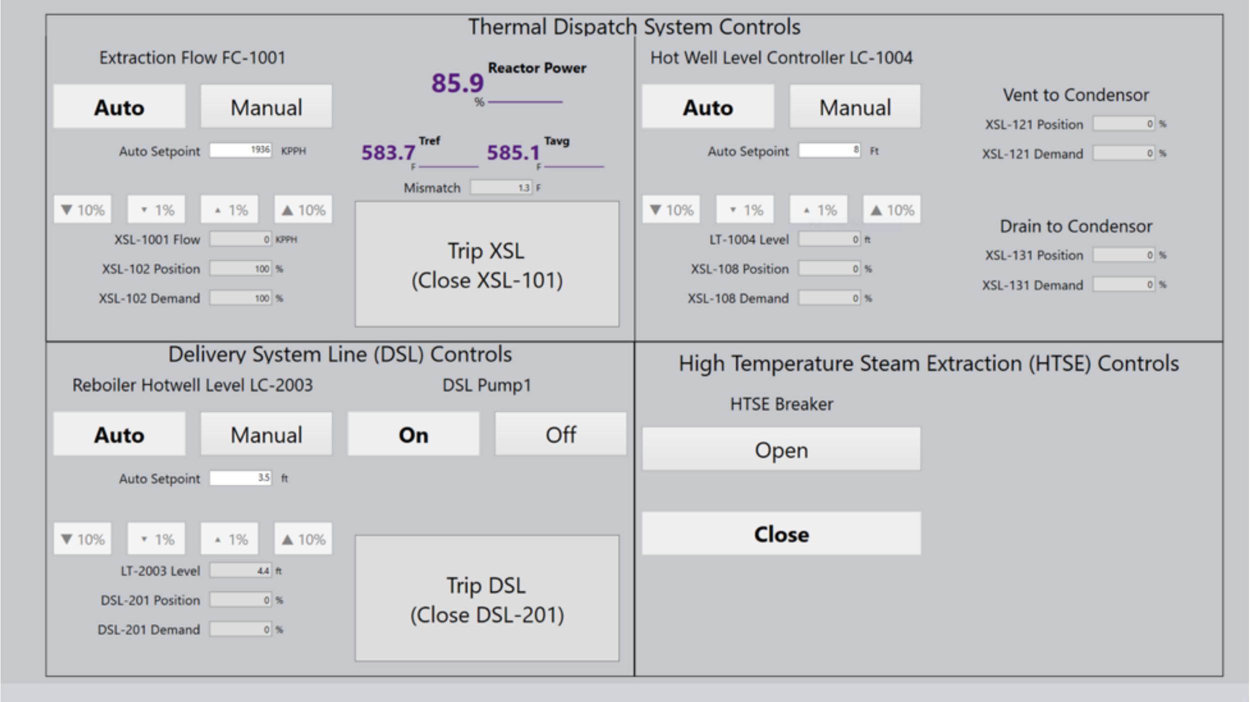


Figure 4: Thermal Power Dispatch Indication Display



Reactor Power 85.9 %
Tref 583.7 F
Tavg 585.1 F
Mismatch 1.3 F

Extraction Flow FC-1001
Auto Setpoint 1936 KPPH
XSL-1001 Flow 0 KPPH
XSL-102 Position 100 %
XSL-102 Demand 100 %

Hot Well Level Controller LC-1004
Auto Setpoint 8 Ft
LT-1004 Level 0 ft
XSL-108 Position 0 %
XSL-108 Demand 0 %

Vent to Condensor
XSL-121 Position 0 %
XSL-121 Demand 0 %

Drain to Condensor
XSL-131 Position 0 %
XSL-131 Demand 0 %

Reboiler Hotwell Level LC-2003
Auto Setpoint 3.5 ft
LT-2003 Level 4.4 ft
DSL-201 Position 0 %
DSL-201 Demand 0 %

Figure 5: Thermal Power Dispatch Control Display

Figure 4 depicts the two flow loops (extraction steam line [XSL] and delivery steam line [DSL]) as a piping and instrumentation diagram with embedded instrument cluster displays. System modes are represented along the left side, and alarms are represented along the right side of the display. Figure 5 depicts the thermal power dispatch system controls using a task-based display approach to provide pertinent parameters near the main flow controller (FC-1001) used for normal thermal power dispatch operations.

4. SIMULATOR STUDY OUTCOMES

The results of the study demonstrated the operations required for the thermal dispatch system fit within the existing normal, abnormal, and emergency operations, i.e., they did not impose any additional significant challenges beyond the existing operations. Therefore, the thermal system dispatch did not impose any undue operator burden regarding the time pressure, workload, situational awareness, or ability to perform their current activities. The crew of operators were able to successfully identify abnormal conditions both specific to the thermal dispatch and for the existing plant systems. Furthermore, the coordination with grid dispatch and scheduling were similar to current practices associated with power manoeuvres, with the exception that the reactor is maintained at 100% power while performing the thermal dispatch mode change as opposed to a traditional turbine manoeuvre associated with a power change as well. The manual configuration of the control system required operators to perform a series of tedious valve manipulations to control the thermal dispatch system. The manual configuration was necessary to ensure operators could perform needed control actions in the absence of automation, but future designs strongly emphasize an automatic transfer program to execute the transfer under the supervision of the operator. The results are promising and provide an initial basis for the apparent feasibility of integrating the new thermal dispatch operations into existing plant operations. The overview of the results provided here is a brief description of the extensive set of measures collected and analysed for this study. Several operator performance measures were collected during each scenario, including eye tracking for attention and workload evaluation, operator self-report ratings, expert observer ratings of operator performance, and scenario debriefs. Additional details on the scenario and simulator configuration can be found in [13] for each of the fifteen scenarios executed in the study which are outlined in Table 1.

Table 1: Scenarios Performed to Evaluate the Thermal Dispatch Concept of Operations

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

5. CONCLUSION

This paper describes the activities performed to develop and evaluate a thermal dispatch system concept of operations for hydrogen production using a simulator driven human-in-the-loop approach. Tightly coupling the development and evaluation activities with direct input from the nuclear control room operators is a critical element driving the philosophy of this approach. Operators were involved throughout the research in different capacities, first providing design input and then operational and usability inputs during scenarios in the study itself. This was an initial preconceptual design and associated concept of operations. It represents a promising start to the overall research activities required to enable an existing NPP to deploy the thermal dispatch system coupled to a hydrogen plant.

Future research must address several implementation specific details that were not covered in the current research scope. In concept, the work here establishes the potential to deploy this basic concept of operations, but given the complexity of LWR NPPs, the devils are in the details, and additional research is needed to refine the design based on a specific NPP configuration and hydrogen plant. Specifically, the inter-organization concept of operations must be developed to determine how the operators of an NPP coordinate with grid dispatch and the hydrogen plant to optimize thermal energy use while meeting electrical demands. To evaluate this coordination, additional research is underway to develop the simulation capabilities and concept of operations that integrate these different organizations as they work towards their individual and joint tasks. This is a large effort that entails incorporating several virtual models representing the electric grid and hydrogen plant. The scenario testing is also planned to extend into physical system integration, such that scaled systems of the thermal dispatch system and hydrogen production will be included at a subsequent stage to support human- and equipment-in-the-loop testing as the designs mature.

Acknowledgements

This work of authorship was prepared as an account of work sponsored by Idaho National Laboratory (under Contract DE-AC07-05ID14517), an agency of the U.S. Government. Neither the U.S. Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

References

[1] U.S. Energy Information Administration (March, 2022). *Electric Power Monthly*, February 2022.

[2] Boardman, R. D., Rabiti, C., Hancock, S. G., Wendt, D. S., Frick, K. L., Bragg-Sitton, S. M., ... & Elgowainy, A. (2019). *Evaluation of Non-Electric Market Options for a Light-Water Reactor in the Midwest. Light Water Reactor Sustainability Program* (No. INL/EXT-19-55090-Rev000). Idaho National Lab.(INL), Idaho Falls, ID (United States).

[3] Boring, R. L., Ulrich, T. A., Lew, R., Kovesdi, C. R., & Al Rashdan, A. (2019). A comparison study of operator preference and performance for analog versus digital turbine control systems in control room modernization. *Nuclear Technology*, *205*(4), 507-523.

[4] Boring, R., Ulrich, T., Lew, R., Kovesdi, C., Rice, B., Poresky, C., ... & Savchenko, K. (2017). *Analog, digital, or enhanced human-system interfaces? results of an operator-in-the-loop study on main control room modernization for a nuclear power plant* (No. INL/EXT-17-43188-Rev000). Idaho National Lab.(INL), Idaho Falls, ID (United States).

[5] Boring, R.L., Lew, R., & Ulrich, T.A. (2016). Epistemiation: An approach for knowledge elicitation of expert users during product design. *Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society, 60,* 1699-1703.

[6] Ulrich, T. A., Lew, R., Boring, R. L., Mortenson, T., Park, J., & Medema, H. (2020, December). Developing an integrated energy system interface for electricity-hydrogen hybrid

nuclear operations. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 64, No. 1, pp. 92-96). Sage CA: Los Angeles, CA: SAGE Publications.

[7] Hancock, S., & Westover, T. (2022). Simulation of 15% and 50% Thermal Power Dispatch to an Industrial Facility Using a Flexible Generic Full-Scope Pressurized Water Reactor Plant Simulator. *Energies*, *15*(3), 1151.

[8] Knighton, L. T., Shigrekar, A., Wendt, D. S., Murphy, B., Boardman, R. D., & James, B. D. (2020). *Markets and Economics for Thermal Power Extraction from Nuclear Power Plants Aiding the Decarbonization of Industrial Processes* (No. INL/EXT-20-58884-Rev001). Idaho National Laboratory (INL), Idaho Falls, ID (United States).

[9] Ulrich, T. A., Lew, R., Hancock, S. G., Westover, T. L., Medema, H. D., Boring PhD, R. L., ... & Minard, N. (2021). *Dynamic Human-in-the-Loop Simulated Nuclear Power Plant Thermal Dispatch System Demonstration and Evaluation Study* (No. INL/EXT-21-64329-Rev000). Idaho National Lab.(INL), Idaho Falls, ID (United States).