INL/EXT-21-63226
Revision 1

Light Water Reactor Sustainability Program

Evaluation of Different Levels of Electric and Thermal Power Dispatch Using a Full-Scope PWR Simulator

October 2021

U.S. Department of Energy

Office of Nuclear Energy

INL/EXT-21-63226
Revision 1

Evaluation of Different Levels of Electric and Thermal Power Dispatch Using a Full-Scope PWR Simulator

Stephen Hancock, Tyler Westover, Yusheng Luo

October 2021

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy

SUMMARY

This report describes thermal-hydraulic modeling to support the development of a generic full-scope PWR plant simulator that includes thermal and electrical power dispatch, referred to as the Thermal Power Dispatch Generic Pressurized Water Reactor (TPD-GPWR) simulator. The TPD-GPWR simulator is based on a generic simulator available from GSE Systems, Inc. (Sykesville, MD, USA). The industrial heat user, in this case, a high-temperature steam electrolysis (HTSE) plant that produces hydrogen and oxygen from de-ionized water, is not explicitly simulated but is only included as a transient heat sink. A thermal power dispatch (TPD) system transfers heat between the secondary system at the nuclear power plant (NPP) and the hydrogen plant. The operational results from four versions of the modified simulator are discussed. Versions #1 and #2 both use synthetic oil as the media to deliver heat to the industrial user approximately one kilometer from the nuclear plant, while Versions #3 and #4 use steam as the heat delivery fluid. Versions #1 and #3 deliver a thermal power that is equal to 15% of the total reactor power, while Versions #2 and #4 deliver 50% of the total reactor power to the industrial user. These versions of the simulator provide a tool to study the feasibility of coupling a PWR to industrial processes that require different levels of thermal and electrical power dispatch. For example, 15% TPD could provide steam for high-efficiency high-temperature hydrogen production, while 50% TPD could provide heat for the production of synthetic fuels. All versions of the TPD-GPWR simulator have sought to keep the design as simple as reasonably possible by extracting steam from the main steam line, removing as much heat as practical from that steam, and then returning the condensate to the condenser.

A capability to include coupled thermal and electric power dispatch has also been enabled by connecting the TPD-GPWR simulator to power system real-time digital simulation (RTDS) capabilities at INL. A feasibility study of electrical coupling was performed and summarized in Section 2. Simulated industrial loads less than approximately 60 MWe can be couped to the TPD-GPWR as a house load while still being able to meet the requirement that a single unit auxiliary transformer (UAT) be able to support all auxiliary loads. The electrical connection to industrial loads larger than 60 MWe will need to follow a standard industrial facility connection to the bulk power grid in which the power connection is made on the high voltage side of the Generator Step-Up (GSU) transformer to protect the main generator of the NPP from sudden trips at the hydrogen plant or failures of the transmission line. Either situation would be similar to any nearby loss of load, and the impact to the generator would follow normal “generator load rejection” protection schemes and would be evaluated accordingly. As an example, General Electric (GE) generators have load rejection relaying that will trip the main generator on a 40% mismatch between reactor power and generator output. To avoid tripping the main generator due to a sudden loss of load at the hydrogen plant, it is anticipated that the hydrogen plant will be divided into multiple plants that each draw less than 40% of the electric power from the nuclear power plant and that have separate electric connections and transmission lines.

The design of the TPD-GPWR simulator versions that use steam as the heat delivery fluid has been modified from that of prior reports, which employed steam or synthetic oil in closed heat delivery loops. The new design still employs two separate systems to transfer steam between the NPP and the industrial user. The first system, which is an extraction steam line (XSL) removes steam from the main steam line of the NPP and delivers that steam to extraction heat exchangers. The extraction heat exchangers then boil demineralized water (DMW) to generate steam that is delivered in a second steam line, denoted “delivery steam line” (DSL), to the industrial user approximately one kilometer from the NPP. Key differences between the designs that use steam and oil as the heat delivery fluid are (1) three heat exchangers are used in the design that employs steam as the heat delivery fluid and (2) steam extracted from the nuclear plant is present in the tube side of each of the three heat exchangers. Steam extracted from the main steam line is at a much higher temperature (280 °C) and pressure than the steam that is needed by the hydrogen plant (approximately 10 °C), and consequently is confined in the tubes of the heat exchangers.

The baseline operation of the TPD-GPWR simulator comes with three principal operating TPD modes of the integrated nuclear power/hydrogen production system which are:

A. Cold Shutdown – the XSL and DSL both have zero flow and are at ambient temperature;
B. Hot Standby – the XSL and DSL have minimal flow to maintain hot conditions in both lines and at the hydrogen plant;
C. Thermal power dispatch (TPD) – the XSL and DSL have sufficient flow to provide the desired thermal power to the industrial process.

The transition from Hot Standby to TPD is an important task for this effort because it may be a frequently used procedure and it may involve substantial and rapid changes in thermal power flow while also maintaining the NPP reactor at near full thermal power generation. Simulation results show that this can be accomplished. Some additional work is needed to maintain the automatic control rod system functioning as intended throughout the transition. Supporting steady-state and transient thermal-hydraulic models for TPD using HYSYS and RELAP5-3D were also developed and presented with their simulation results, which serve as a baseline design for implementing the system design into the TPD-GPWR simulator. The design using three separate heat exchangers is effective in delivering superheated steam to the industrial user. The Version #3 of TPD-GPWR simulator that uses steam as the heat delivery fluid will be used in operator studies in July 2021 where the operators will perform changes in operational state of the simulator as well as selected transient analysis for potential accidents. These studies call for 15% of the thermal power to be extracted from the PWR system for use at a hydrogen plant, which will require approximately 600 lb/sec of main steam to be extracted from the main steam header. The electrical power dispatch will include all of the electricity generated by the remaining steam in the PWR.

With the change from oil as the heat delivery fluid to steam, the need for rapid, large changes in liquid flow rate has been eliminated. Since the flow rate of the steam in the DSL is significantly lower than the flow rate of oil at an equivalent amount of TPD, there is more freedom to adjust the fluid flow rate in the DSL because it will not require such a large amount of mass to circulate, which will mitigate thermal inertia challenges in the control system. The new design, however, does increase the magnitude of steam pressure fluctuations in the XSL and DSL as the system transitions from Hot Standby to TPD because the pressure in the DSL in coupled to temperature through the saturation pressure of steam in that line.

This report also details the impacts of keeping the design of the TPD system as simple as reasonably possible by extracting steam from the main steam line, removing as much heat as practical from that steam, and then returning the condensate to the condenser. During normal operation of the GPWR simulator at 100% reactor power, the steam flow in the main steam line is approximately 3,500 lb/s, and steam flow through the turbine generator system is approximately 3,200 lbs/s (some of the generated steam is used for house loads, such as the moisture separator reheater). At 50% TPD, the flow of steam in the main steam line is reduced to approximately 3,100 lbs/s because of energy balance requirements in the NPP steam generator, as shown in Figure 6 and Figure 17. Steam flow through the turbine generator system is reduced to less than 1,200 lbs/s, which is less than 36% of its design capacity. Turbine systems are not designed to operate effectively at this low steam flow rate.

The design of the TPD system can be optimized to reduce the impact on the NPP operations, especially the turbine generator system, the condenser, and the feed water heater trains. Steam of sufficient temperature and quality for high-temperature electrolysis can be extracted from the turbine system. For example, the temperature of steam at the hydrogen plant only needs to be approximately 130 °C, and steam between 200 and 240°C can be extracted from the high-pressure turbine. Also, condensate from the extraction steam line (XSL) is hotter than condensate in the NPP condenser and could be returned to the feed water heater train to avoid the waste of enthalpy and support heating the feed water. These improvements will be explored in a future version of the TPD-GPWR simulator.

CONTENTS

1. INTRODUCTION 1
    1.1 Overview 1
    1.2 Design Considerations 2

2. ELECTRICAL POWER DISPATCH 4
    2.1 Case #1: Electric Power Dispatch Less Than Approximately 60 MWe 4
    2.2 Case #2: Electric Power Dispatch Greater than Approximately 60 MWe 6

3. THERMAL POWER DISPATCH (TPD) SYSTEM MODELS WITH AN OIL DELIVERY HEAT LOOP (DHL) 6
    3.1 Overview 6
    3.2 Extraction Steam Line (XSL) and Delivery Heat Loop (DHL) 7

4. THERMAL POWER DISPATCH (TPD) SIMULATIONS WITH AN OIL DELIVERY HEAT LOOP (DHL) 9
    4.1 Procedure to Transition from Cold Shutdown to Hot Standby 9
    4.2 Procedures to Transition Between Hot Standby and Thermal Power Dispatch 10
    4.3 Simulator Results for Transitioning Between Hot Standby and Thermal Power Dispatch (TPD) 11

5. THERMAL POWER DISPATCH (TPD) DESIGN WITH A DELIVERY STEAM LINE (DSL) 15
    5.1 Extraction Steam Line (XSL) Design 15
    5.2 Implementation in the Thermal Power Dispatch GPWR (TPD-GPWR) 17
    5.3 Delivery Steam Line (DSL) Design 18

6. THERMAL POWER DISPATCH (TPD) SYSTEM MODELS WITH A DELIVERY STEAM LINE (DSL) 20
    6.1 HYSYS Base Model 20
    6.2 RELAP5-3D Model 22

7. THERMAL POWER DISPACTCH (TPD) SIMULATIONS WITH A DELIVERY STEAM LINE (DSL) 24
    7.1 Procedure to Transition from Cold Shutdown to Hot Standby 25
    7.2 Procedures to Transition Between Hot Standby and Thermal Power Dispatch (TPD) 25
    7.3 Simulator Results for Transitioning Between Hot Standby and TPD 26

8. CONCLUSIONS AND RECOMMENDATIONS 30

9. REFERENCES 32

Appendix A Operating Conditions for the Simulations 35

Appendix B TPD Requirements, Decisions, and Design 39

FIGURES

Figure 1. Simplified diagram of the Thermal Power Dispatch GPWR (TPD-GPWR) Simulator. Panel A: configuration for Versions #1 and #2. Panel B: configuration for Versions #3 and #4. The dashed line indicates the boundary of the NPP. 2

Figure 2. Single-line diagram of PWR-Hydrogen plant electric power connection for a demonstration-scale hydrogen production plant that is less than approximately 60 MWe. 5

Figure 3. Single-line diagram of GSE's GPWR simulator, including a connection to a demonstration-scale hydrogen plant. 5

Figure 4. Screenshot of the extraction steam line (XSL) components added to the ms1 drawing of GPWR. 7

Figure 5. Screenshot of the delivery heat loop (DHL) piping system drawing for Versions #1 and #2 of the TPD-GPWR simulator. 8

Figure 6. Steam flow rates for the transition to 15% and 50% TPD. 13

Figure 7. Feed water temperature and turbine power during the transition to 15% and 50% TPD. 13

Figure 8. Reactor power and RCS cold leg temperature during the transition 15% and 50% TPD. 14

Figure 9. RCS hot leg temperature and RCS average temperature during the transition to 15% and 50% TPD. 14

Figure 10. T_{ref} and T_{avg} for computing the mismatch in the control rod program during the transition to 15% and 50% TPD. 15

Figure 11. Simplified P&ID for the XSL and DSL systems. 16

Figure 12. Screenshot of the tpe1 drawing containing the XSL and the DSL system in the GPWR. 17

Figure 13. Diagram of a typical kettle reboiler. 20

Figure 14. Process model in Aspen HYSYS for the TPD system with steam as the heat delivery fluid. 21

Figure 15. Nodalization of the RELAP5-3D for the steam to steam thermal power extraction system. 23

Figure 16. Transient results of selected mass flow rates of the steam-to-steam RELAP5-3D model. 24

Figure 17. Steam flow rates for the transition to 15% and 50% TPD. 27

Figure 18. Feedwater temperature and turbine power during the transition to 15% and 50% TPD. 27

Figure 19. Reactor power and RCS cold leg temperature during the transition to 5% and 50% TPD. 28

Figure 20. RCS hot leg temperature and RCS average temperature during the transition to 15% and 50% TPD. 28

Figure 21. Turbine extraction flow to feed water heaters for 0%, 15%, and 50% TPD. 29

Figure 22. Power utilization breakdown of the TPD-GPWR simulator for 0%, 15%, and 50% TPD. 30

Figure 23. Simplified diagram of the improved TPD from a PWR showing steam extraction from the HP turbine and condensate return to the feed water heater train. 32

TABLES

Table 1. Summary of heat delivery media and percent thermal power dispatch (TPD) for the four simulator versions. 1

Table 2. Potential relative advantages and disadvantages of using superheated steam or synthetic oil as the heat delivery fluid.. 3

Table 3. Number of heat exchangers and their capital cost. 22

Table 4. RELAP5-3D model results for the XSL and DSL with 15% thermal power extraction 23

Table B-1. Design requirements for the thermal power extraction (TDP) System proposed for a PWR. 40

ACRONYMS

BOP	balance of plant
DBA	Design Basis Accidents
DHL	delivery heat loop
DI	deionized
DMW	demineralized water
DOE	Department of Energy
DRTS	digital real time simulator
DSL	delivery steam line
EDR	Exchanger and Design Rating
FCV	flow control valves
FDR HTR	feed water heater
GE	General Electric
GSU	Generator Step-Up
HP	high pressure
HSI	human/system interface
HSSL	Human System Simulation Laboratory
HTSE	high-temperature steam electrolysis
HYSYS	name of a chemical process simulation software
INL	Idaho National Laboratory
LMTD	log mean temperature difference
LP	Low pressure
LWR	light-water reactor
MOV	motor operated valve
MSH	min steam header
MSIV	main steam isolation valve
MSR	moisture separator reheater
NPP	nuclear power plant
NPS	national pipe standard
P&ID	piping and instrumentation diagram
PFD	process-flow diagram
PORV	pressure operated relief valve
PWR	pressurized water reactor

RTDS	real-time digital simulation
TBV	turbine bypass valve
TCV	turbine control valve
TEA	techno-economic analyses
TPD	thermal power dispatch
tpd	Tonnes per day
TPE	thermal power extraction
U.S.	United States (of America)
UAT	unit auxiliary transformer
UFSAR	Updated Final Safety Analysis Report
XSL	extraction steam line

Evaluation of Different Levels of Electric and Thermal Power Dispatch Using a Full-Scope PWR Simulator

1. INTRODUCTION

1.1 Overview

This report describes the development, modeling, and results of a generic pressurized water reactor power plant simulator that incorporates coupled electrical and thermal power dispatch (TPD) to an industrial process located approximately one kilometer from the nuclear power plant. The simulator is a commercial PWR simulator that has been modified to include TPD as described in past milestone reports [1, 2]. The commercial PWR simulator is a generic simulator available from GSE Systems, Inc. (Sykesville, MD, USA) that is built using RELAP5-HDTM Real-Time Solution and in-house software developed by GSE Systems. This generic PWR (GPWR) simulator performs real-time simulation of the complete power plant from the reactor neutronics to the electricity generation and distribution. All primary, secondary, and auxiliary systems are modeled including all control logic in order to provide the most accurate representation of actual nuclear power plant (NPP) operation, and the simulator results have been rigorously verified by an actual NPP operating at approximately 1 GWe. This report is a continuation of worked performed in previous years, and supplemental information from previous reports is included in the appendix for reference.

The operational results from four versions of the modified simulator are discussed in this report, as summarized in Table 1. Versions #1 and #2 both use synthetic oil as the media to deliver heat to the industrial user approximately one kilometer from the nuclear plant, while Versions #3 and #4 use steam as the heat delivery media. Versions #1 and #3 deliver a thermal power that is equal to 15% of the total reactor power, while Versions #2 and #4 deliver 50% of the total reactor power to the industrial user. These versions of the simulator provide a tool to study the feasibility of coupling a PWR to industrial processes that require different levels of thermal and electrical power dispatch. For example, 15% TPD could provide steam for high-efficiency high-temperature hydrogen production, while 50% TPD could provide heat for the production of synthetic fuels.

Table 1. Summary of heat delivery media and percent thermal power dispatch (TPD) for the four simulator versions.

	Synthetic oil	Steam
15% Thermal power dispatch	Version #1	Version #3
50% Thermal power dispatch	Version #2	Version #4

Previous versions of the simulator that employed 5% TPD were presented in a past milestone report submitted in June of 2020 [2]. Successful operation of the simulator using a 5% thermal power extraction system and a synthetic oil delivery loop was the focus of human factors studies with licensed operators in September of 2020 [3]. For this work, the same simulator was enhanced to include higher amounts of thermal power dispatch (15% and 50%), better controls for operability, and a more robust thermal-hydraulic model. The modeling details of Versions #1 and #2 of the simulator that use synthetic oil as the heat delivery media were described in a manuscript submitted to the journal *Energies* for publication and is currently in review. Version #3 of the simulator with 15% TPD and that uses steam as the heat delivery media will be used for in-person operator tests in July of 2021 to study the interoperability of an integrated energy system that includes a nuclear power plant that coupled thermally and electrically to a hydrogen production plant and electrically to a representative bulk electric grid. Dynamic interoperability issues will be studied for several normal and off-normal transient scenarios and will include human and equipment factors. Electric coupling to the bulk power grid and the hydrogen plant is accomplished by coupling the simulator to Digital Real-Time Simulation (DRTS), which will provide the power systems models of the grid and hydrogen plant that can run in real-time. The electrical load from the hydrogen plant is read as an input variable in the GPWR simulator and used to monitor the electrical power dispatch from the GPWR control room.

1.2 Design Considerations

Simplified diagrams of the GPWR (generic PWR) simulator modified to enable TPD, hereafter referred to as the TPD-GPWR simulator, are shown in Figure 1. Versions #1 and #2 that employ synthetic oil as the heat delivery fluid are depicted in Panel A, and Versions #3 and #4 that employ steam as the heat delivery fluid are shown in Panel B. The industrial heat user, in this case, a high-temperature steam electrolysis (HTSE) plant that produces hydrogen and oxygen from de-ionized or DMW, is not explicitly simulated in this report but is only included as a transient heat sink. Two separate systems transfer heat between the NPP and the hydrogen plant. For all versions of the TPD-GPWR simulator, an extraction steam line (XSL) removes steam from the main steam line of the NPP and delivers that steam to extraction heat exchangers. In Versions, #1 and #2 of the TPD-GPWR (Figure 1, Panel A), a second loop containing synthetic oil, denoted the delivery heat loop (DHL), transports the heated oil to the hydrogen plant, where a second set of heat exchangers use the heated oil to generate steam for hydrogen production.

For Versions #3 and #4 of the TPD-GPWR in which steam is used as the heat delivery fluid, the design can be simplified somewhat as described in the Section 5 below. Briefly, if the heat delivery fluid is steam, it can be directly used to make hydrogen and oxygen, and consequently, the steam does not need to be returned, so the DHL can be simplified to a once-through delivery line. In this case, as shown in Panel B of Figure 1, the second set of heat exchangers are not needed. Instead, a pressure station is placed at the hydrogen plant to regulate the pressure of the steam entering the hydrogen production process.

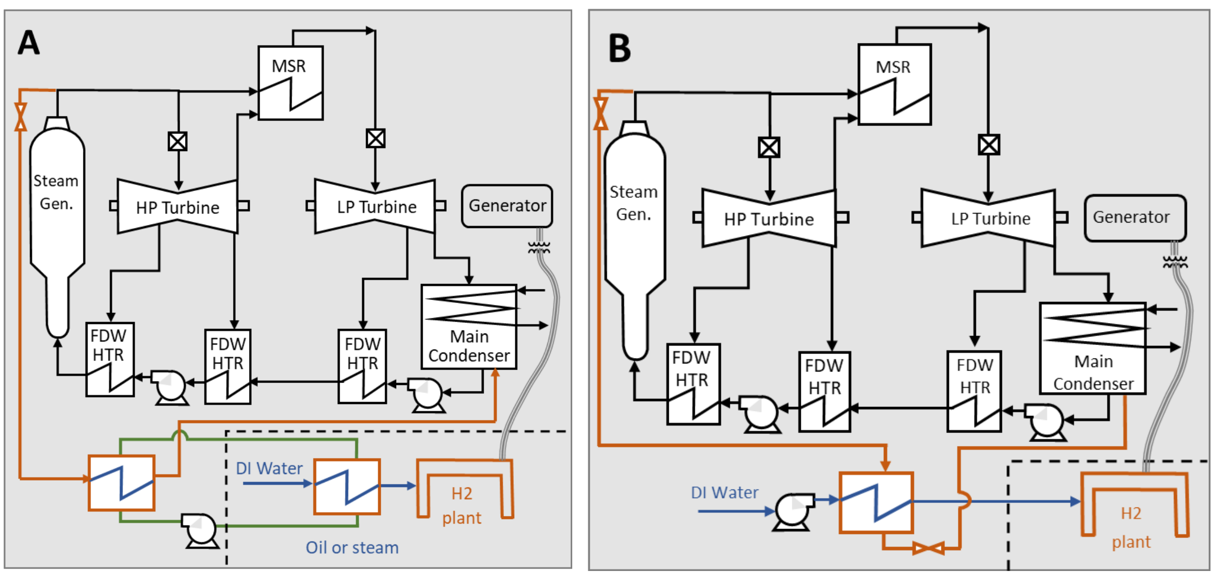

Figure 1. Simplified diagram of the Thermal Power Dispatch GPWR (TPD-GPWR) Simulator. Panel A: configuration for Versions #1 and #2. Panel B: configuration for Versions #3 and #4. The dashed line indicates the boundary of the NPP.

The design requirements for the steam extraction system are included in the appendix for reference. The requirements ensure multiple purposes are accomplished, including the safety of the NPP and efficient use of nuclear energy for the industrial purpose. As described further below, the design requirements do not necessarily ensure that the NPP operates at maximum efficiency during thermal power dispatch operations (TPD). A leading requirement that drives the design is that the reactor power and the primary system of the PWR are maintained at or near the 100% steady power condition while the secondary system is maneuvered to allow for thermal and electrical power dispatch to the coupled industrial process.

As noted in previous work, the heat transport fluid in the DHL may be either superheated steam or a synthetic oil [1]. Table 2 summarizes relative advantages and disadvantages of both options. Using steam as the heat delivery fluid has major potential advantages in terms of lower mass flow, lower pumping power requirement, compatibility with steam in the main steam line, high heat transfer coefficients in the heat exchangers, and increased flexibility because steam can be vented in the event of a sudden off-normal event. By comparison, the modest potential advantages of using synthetic oil as the heat delivery fluid, which are low operating pressure and simplified heat exchanger designs due to single-phase flow, do not appear sufficient to justify the added expenses and containment risks.

Table 2. Potential relative advantages and disadvantages of using superheated steam or synthetic oil as the heat delivery fluid.

	Superheated steam	Synthetic Oil
Potential advantages	Low mass flow required due to the high latent heat High heat transfer coefficients from phase change heat transfer allow low approach temperatures Steam is compatible with the main steam line in case of leaks across heat exchangers Lower delivery pump power requirement Preferred by nuclear operators due to existing familiarity with steam systems	Low vapor pressure of synthetic oil allows low operating pressure Single-phase flow simplifies heat exchanger design
Potential disadvantages	Vapor pressure of steam requires moderately high operating pressure Steam venting potentially required in the event of a delivery system or industrial process trip	Very high mass flow is required to transport required heat, which increases equipment sizes and complicates controls due to large thermal inertia Additional contamination risk if oil reaches the condenser due to a leak in the extraction heat exchangers Oil is more expensive with a cost in the range of $1,000,000. Very high delivery pump power requirement Unknown radiation transport characteristics, expensive cleaning procedure if radioactively contaminated

Section 2 describes electric power dispatch simulation options for coupled electric and thermal power dispatch from the Thermal Power Dispatch GPWR (TPD-GPWR) simulator. Section 3 describes the models for Versions #1 and #2 of the TPD-GPWR simulator that employ synthetic oil as the heat delivery fluid, and Section 4 presents the operating procedures for those versions of the simulator and the results obtained from following those procedures using the simulator. Section 5 describes the models for Versions #3 and #4 of the TPD-GPWR simulator that employ steam as the heat delivery fluid. Section 6 presents benchmark HYSYS and RELAP5-3D models that were used to support the development of Versions #3 and #4 of the TPD-GPWR simulator and validate thermal-hydraulic performance. Section 7 presents the operating procedures for Versions #3 and #4 of the simulator and the results obtained from following those procedures using the simulator. Section 8 summarized conclusions from the work.

2. ELECTRICAL POWER DISPATCH

Two specific electric dispatch cases are considered. The first case is applicable for hydrogen plants that consume less than approximately 60 MWe and can be treated essentially as an additional house load for the nuclear power plant. The associated thermal power requirement would be less than 15 MWth, which is less than 1% of the total available thermal power. This scale would likely be considered a technology demonstration with a relatively low safety risk to the PWR. The second case assumes that as much as 15% of the total available thermal power (2900 x 0.15 = 435 MWth) is extracted for use by multiple thermal energy users, including a hydrogen production plant. In this case, the hydrogen plant could be designed to consume as much as 795 MWe and 191 MWth. The remaining [435 – 191] = 244 MWth would be available to other thermal energy users. In this second case, the electric power dispatch is greater than can be supplied as a house load internal to the NPP, and the electrical connection between the PWR and the hydrogen plant must follow a “standard” industrial facility connection to a power plant in which the connection occurs after the high voltage transformer in the PWR switchyard.

2.1 Case #1: Electric Power Dispatch Less Than Approximately 60 MWe

Figure 22 shows a single-line diagram of the PWR-hydrogen plant electrical connection, assuming that the hydrogen plant can be treated as a house load for the PWR. The hydrogen plant will require a combination of AC and DC power. Approximately 90% of the total power requirement is needed as DC power at a voltage of 200-800 VDC, so the electric power from the PWR generator will need to be stepped down and converted to DC. Approximately 10% of the total power required by the hydrogen plant is needed as AC power to operate pumps and blowers and electric topping heaters. Figure 2 only shows a single power converter, but this system will likely be replicated multiple times so that the hydrogen plant can be installed and operated as separate modules on the scale of 5-25 MW each. For this case, the electrical connection between the PWR and the hydrogen plant could be modeled in GSE’s GPWR simulator. Figure 3 shows a single-line diagram of the GPWR power system and includes a line for the connection to the hydrogen plant. This figure does not show the needed power transformers and breakers, although these items would need to be modeled in the modified simulator. In this case, the hydrogen plant is powered from what would be a third unit auxiliary transformer (UAT).

A concern in this design is that in the event the hydrogen plant must be quickly isolated from the PWR, the power to the hydrogen plant would be diverted to the Generator Step-Up (GSU) transformer, which could actuate protective relays and potentially trip the main generator of the PWR. To avoid this unallowable event, the power being dispatched to the hydrogen plant must be very low relative to the total generator capability. Each of the UATs are rated at 67 MVA, and it is required that a single UAT be able to support all auxiliary loads, so in this design, electric dispatch to the hydrogen plant is limited to approximately 60 MWe.

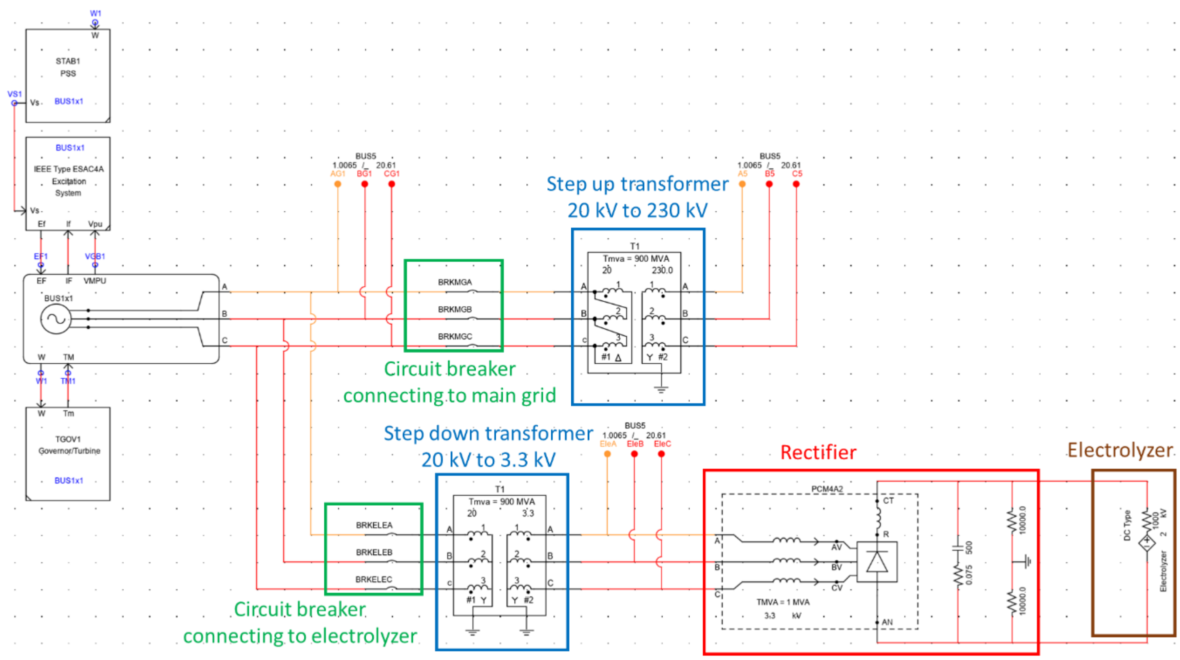

Figure 2. Single-line diagram of PWR-Hydrogen plant electric power connection for a demonstration-scale hydrogen production plant that is less than approximately 60 MWe.

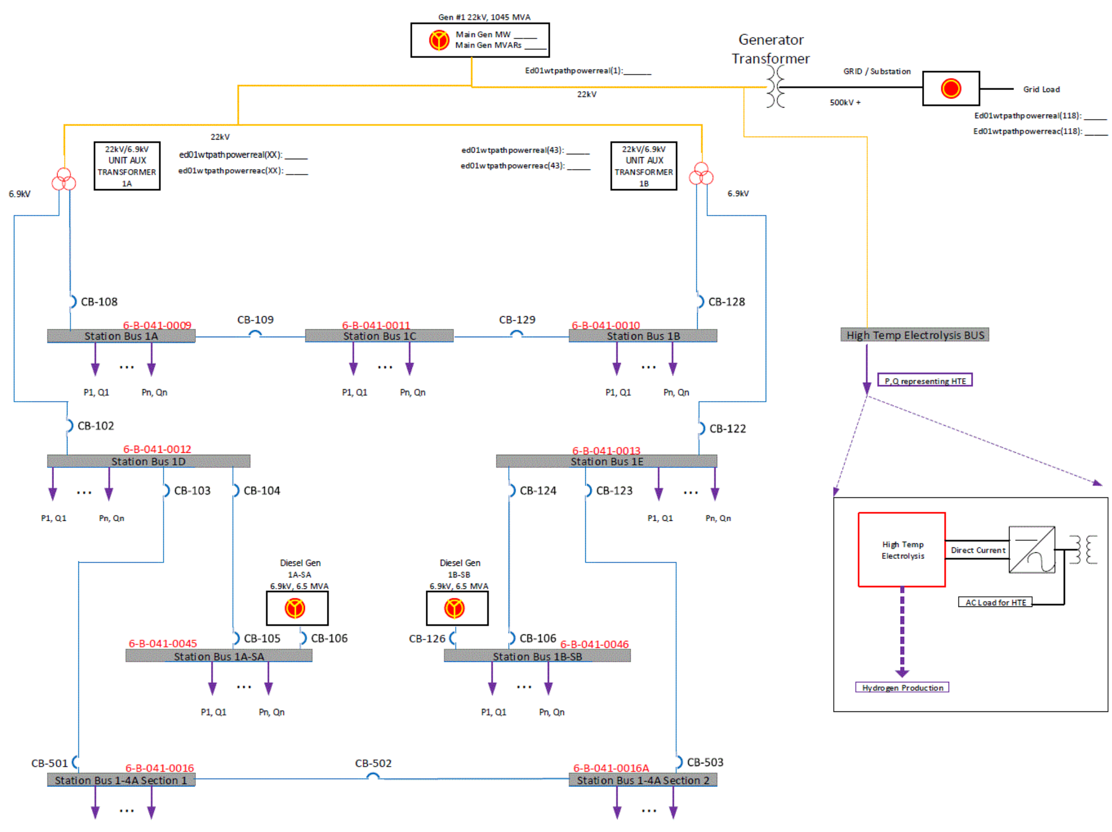

Figure 3. Single-line diagram of GSE's GPWR simulator, including a connection to a demonstration-scale hydrogen plant.

2.2 Case #2: Electric Power Dispatch Greater than Approximately 60 MWe

In this case, the connection of the hydrogen plant to the PWR will follow a standard industrial facility connection to a power plant in which the power connection is made on the high voltage side of the GSU. Transmission cables at switchyard voltage would carry power to the hydrogen plant approximately 1 km from the PWR. For large quantities of hydrogen production, the hydrogen plant must be located some distance (0.5-1.0 km) from the PWR to protect the PWR from potential hydrogen deflagration events. A sudden loss-of-load at the hydrogen plant would be similar to any nearby loss of load, and the impact to the generator would follow normal "generator load rejection" protection schemes and would be evaluated accordingly. As an example, General Electric (GE) generators have load rejection relaying that will trip the main generator on a 40% mismatch between reactor power and generator output. A notable issue for this case is the "Point of Interconnection" or POI that demarcates the equipment owned by the nuclear utility and the grid operator. There is interest to tap off the power line to the hydrogen plant after the GSU but before the POI, if possible, so that power can be supplied to the hydrogen plant without being subject to grid fees. This may be possible for plants in which the POI is at the first disconnect switch after the GSU going to the switchyard; however, it will likely not be possible for plants in which the POI is right at the connection to the high voltage bushing.

For the purposes of this report is to focus on TPD of 15% and 50%, it is assumed that the coupled electric power dispatch will be greater than 60 MWe, so the electrical connection to the hydrogen plant will follow a standard industrial facility connection. To avoid tripping the main generator due to a sudden loss of load at the hydrogen plant, it is anticipated that the hydrogen plant will be divided into multiple plants that each draw less than 40% of the electric power from the nuclear power plant and that have separate electric connections and transmission lines. The nuclear plant will still remain coupled to the bulk power grid so that evaluating the response of the nuclear plant to a sudden loss of load at a hydrogen plant will require a power systems simulation that includes the local power grid, the nuclear power plant, and the hydrogen plants. The power grid and the power systems of the hydrogen plants will be modeled using Real-Time Digital Simulation (RTDS). For coupled electric and thermal power dispatch simulations involving the TPD-GPWR simulator, the instantaneous values of the generator's three-phase terminal voltages will be sent to RTDS through an ethernet connection that has been established between INL's Human Systems Simulation Laboratory (HSSL) and INL's Digital Real-Time Grid Simulation Laboratory. A controllable voltage source is modeled inside RTDS to leverage the voltage input from the TPD-GPWR. Instantaneous output voltage of the voltage source closely follows the value sent from the TPD-GPWR. The load on the electric grid simulated inside RTDS draws current from the voltage source, and the current value caused by the load is sent back to the TPD-GPWR for computing the electric-mechanical reaction inside the generator model.

3. THERMAL POWER DISPATCH (TPD) SYSTEM MODELS WITH AN OIL DELIVERY HEAT LOOP (DHL)

3.1 Overview

The GPWR simulator is based on hundreds of FORTRAN source code files that invokes various programs in the JADE (Java-based) suite of software developed by GSE Systems. The turbine-generator system is represented by a high-pressure (HP) turbine, two moisture separator reheaters (MSRs), and two low-pressure (LP) turbines. The model includes a single main steam header (MSH) followed by divided steam headers prior to the turbine stop and governor valves and the HP turbine. The steam produced by the steam generators is saturated at (1,011.4 psia) and reaches the MSH at (1,008.6 psia). The total steam flow rate is (12.76 MPPH). There are five feedwater heater stages split into two parallel streams.

3.2 Extraction Steam Line (XSL) and Delivery Heat Loop (DHL)

Figure 4shows the modified ms1 drawing for Versions #1 and #2 of the TPD-GPWR, which features the Extraction Steam Line (XSL). The ms1 drawing contains the piping from the steam generators to the turbine governor valves and includes the MSH, pressure operated relief valves (PORVs), main steam isolation valves (MSIVs), and the atmospheric and condenser steam dump valves, which provide a direct line from the MSH to the condenser zones. These versions of the TPD system that use oil as the heat delivery fluid are complete and will not be modified further. They include the required pressure relief systems and high-level drains, each of which are connected to the condenser and controlled by manually input setpoints. The only addition that could benefit the design and operation of this TPD system design is the addition of a flash tank before the condenser dump on the main line that would serve to drop the pressure of the steam from the flash tank so that high-temperature fluid is not mixed into the condenser. This concept is similar to systems already present in the existing GPWR feed water heating system and represents an industry best practice but would not change the simulator operating results.

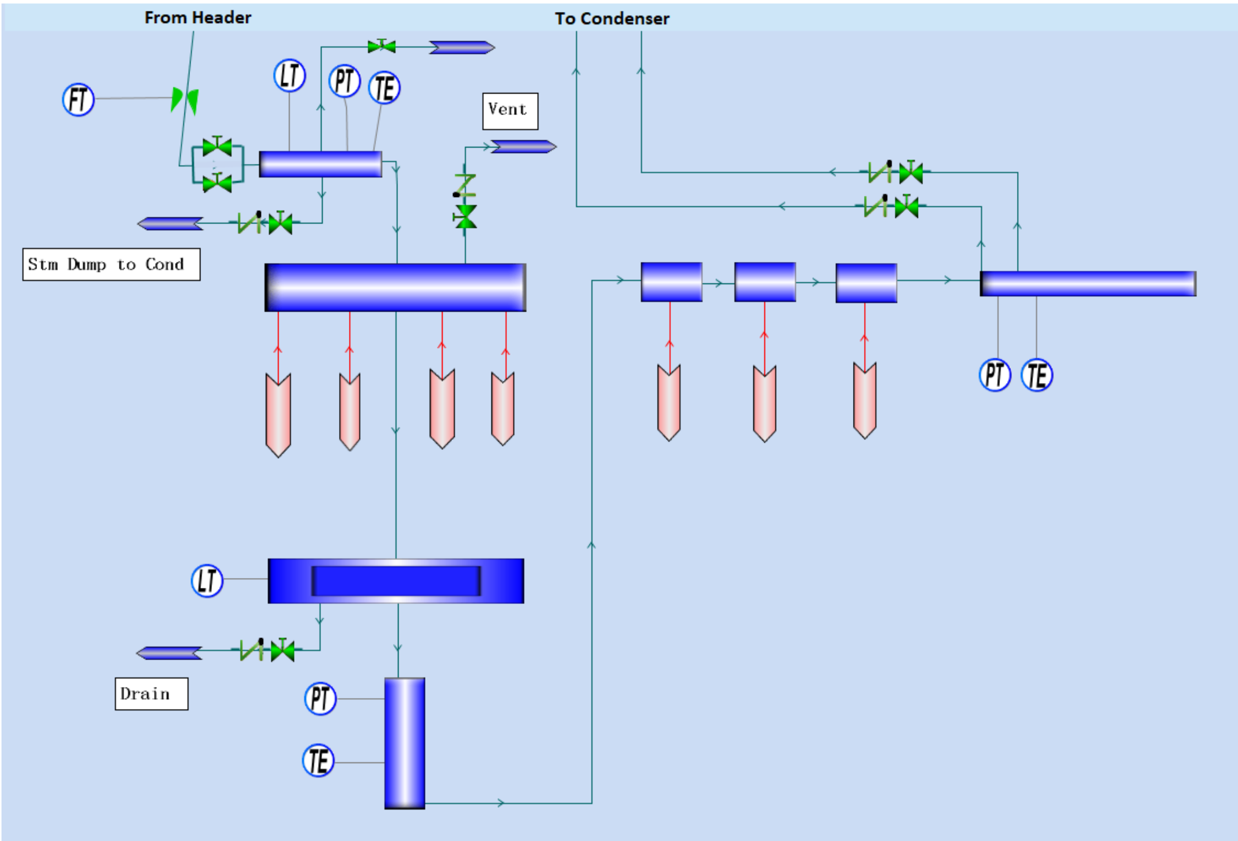

Figure 4. Screenshot of the extraction steam line (XSL) components added to the ms1 drawing of GPWR.

Figure 5shows the piping system model for the delivery heat loop (DHL) in JTopmeret™ for Versions #1 and #2 of the TPD-GPWR. Previously, the DHL was modeled as an open-loop with an appropriate mass sink and source at the hydrogen plant to represent the heat transfer needed to create steam for hydrogen production [2]. Although effective, this approach did not capture the physics of the heat exchange process with high fidelity, especially in terms of capturing transient effects during warm-up or other potential TPD power changes. In the new versions of the simulator, the DHL has been modeled as a closed loop with a heat sink to represent the transfer of heat at the hydrogen plant to generate steam for hydrogen production. The heat transfer is treated as a controlled variable to maintain the oil inlet to the pump at a constant temperature of 350 °F. For the closed-loop model to function properly, a pressure boundary condition is required at the pump outlet node. Physically, the pressure boundary condition represents a surge tank, which is placed between the pump and the control valve to absorb the pressure fluctuations caused by the actuation of the control valve. This design helps to maintain constant pressure in the modeled system. This pressure in the surge tank (pressure boundary condition) is set by the pressure of the boundary node, and the major and minor pressure losses associated with the surge tank and its connection to the system. For transient fluid dynamic simulation, a pressure versus flow rate curve is applied to the pump to provide the appropriate pressure rise as a function of desired pump flow rate.

Additionally, the control system for the delivery heat loop (DHL) was altered to include a temperature control system for the outlet temperature of the first heat exchanger. Previously, this system was controlled by a flow controller and flow set point, which required the oil flow in the DHL and the steam flow in the XSL to be manually adjusted simultaneously by the operator during TPD transitions. The addition of the flow controller with a setpoint of 510 °F allows the oil system to slowly ramp up as the steam flow rate increases during the transition to TPD. This improved control scheme also eliminates a potential pressure issue in the extraction steam loop (XSL). In hot standby mode, the steam pressure is approximately 650 psia because of heat transfer limitations associated with the low mass flow rate of synthetic oil. During the transition to TPD, the pressure in the delivery heat loop (DHL) decreased dramatically to approximately 160 psia due to voids created by the rapid change in heat transfer. The pressure slowly recovered as the heat transfer stabilized during the transition and did not impact steady-state operations for which the operating pressure is 960 psia at the outlet of the second heat exchanger. Still, large pressure swings are undesirable not only because of increased wear on equipment but also the additional monitoring they require by the operator with increased potential for operator confusion and error. The sudden depressurization during power transitions is avoided by using the temperature after the first heat exchanger as the control variable for the oil flow rate. This improved control scheme allows the pressure to be maintained relatively high during transitions from Hot Standby to TPD.

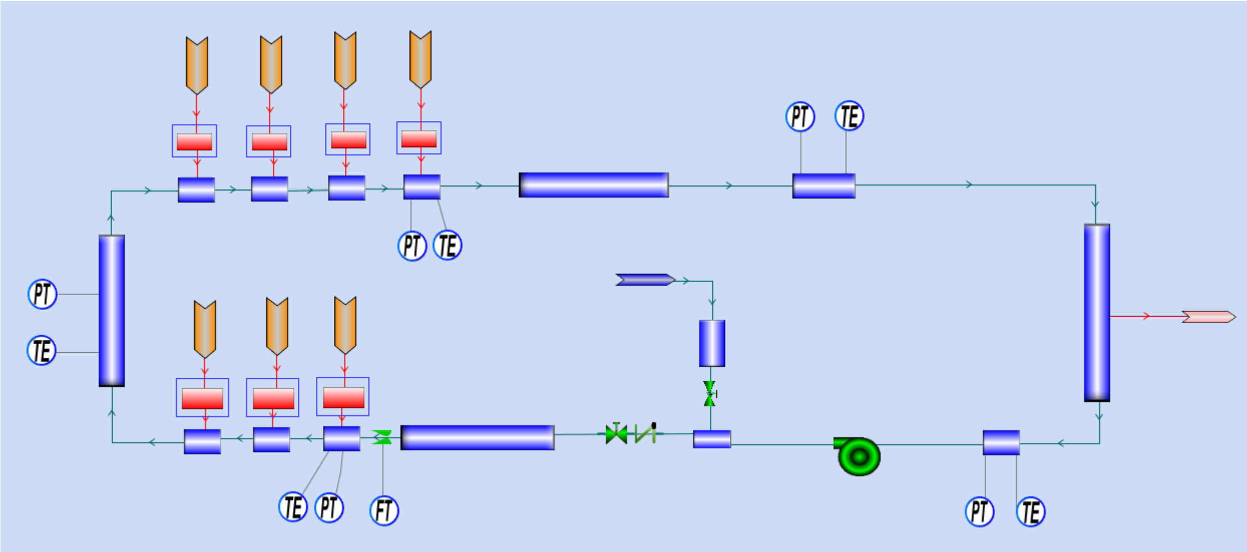

Figure 5. Screenshot of the delivery heat loop (DHL) piping system drawing for Versions #1 and #2 of the TPD-GPWR simulator.

Additional improvements which would be desired for the TPD system would include a modeled heat exchanger as opposed to a heat sink to represent the heat transfer occurring at the hydrogen plant. This would require an additional drawing for the small steam system at the hydrogen plant which would consist of a source of saturated liquid water, the shell side of the heat exchanger for vaporization, and a mass sink for the saturated vapor generated in the heat exchanger. A control system for the liquid level in the vaporizer would be implemented. This would be similar to the DSL control system which will be explained in the next section. The intent is to not pursue these final improvements to the TPD system that uses oil as the heat delivery fluid because future work will focus on the TPD system design that uses steam as the heat delivery fluid for the reasons discussed in Section 1. Those improvements are not needed in the TPD system design with steam as the heat delivery fluid because that system does not require heat exchangers in the delivery steam line (DSL) at the hydrogen plant (the steam in the DSL can be directly used for hydrogen production without passing through additional heat exchangers).

4. THERMAL POWER DISPATCH (TPD) SIMULATIONS WITH AN OIL DELIVERY HEAT LOOP (DHL)

This section explains the operating and transition modes for the TPD-GPWR simulator that employs synthetic oil as the heat delivery fluid. The principal operating TPD modes of the integrated nuclear/hydrogen system include:

A. **Cold Shutdown –** the extraction steam line (XSL) and delivery heat loop (DHL) both have zero flow and are at ambient temperature;

B. **Hot Standby** – the XSL and DHL have minimal flow to maintain hot conditions in both loops and at the hydrogen plant;

C. **Thermal Power Dispatch (TPD)** – the XSL and DHL have sufficient flow to provide the desired thermal power to the industrial process.

The discussion below focuses on the transition between Hot Standby and TPD because that transition is the one that will be performed the most frequently in short time intervals and also has the highest risk for unexpected events. It is worth noting that the TPD required to maintain hot standby is expected to be about 5% of the maximum TPD amount, so the infrequent transition from Cold Shutdown (0% TPD) to Hot Standby mode does not represent a significant challenge to NPP operations.

Initial conditions are established in the simulator that correspond to each principal operating mode so that the test procedures involve transitioning from one operating mode to another to understand how both the operator and the power plant respond to operational changes. Each operating mode refers to an operation of the extraction steam line (XSL) and delivery heat loop (DHL) and has no bearing on the primary system of the NPP because the reactor operates at 100% thermal power generation for all standard operating modes of the TPD system. A key goal of the simulator and operator tests is to understand how to safely maintain the NPP at near 100% thermal power output while transitioning between TPD operating modes.

4.1 Procedure to Transition from Cold Shutdown to Hot Standby

The turbine load needs to be decreased before the TPD system is engaged in Hot Standby mode to prevent unintentionally increasing the reactor power above 100%. Opening the XSL control valve will have the same effect on reactor power as a minor steam leak in the main steam line or an increase in turbine load, both of which cause an increase in the reactor power. To avoid the reactor power exceeding 100%, the turbine load is decreased to 920 MW, which causes the reactor power to slightly decrease. After the reactor power decreases, the steam may be diverted to the extraction steam line (XSL) to begin pressurizing and warming up that line. The process is performed as follows with the set points for 15% and 50% TPD shown in parenthesis following appropriate steps:

1. Decrease the turbine load to the Hot Standby setpoint at a ramp rate of 5 MW/min (920 MW, 895 MW).

2. Turn on the DHL oil circulation pump.

3. Place the DHL flow controller into automatic control mode at the Hot Standby setpoint (330 lb/sec, 1100 lb/sec).
4. Slowly open the XSL control bypass valve manually to initiate pressurization of the XSL. Do not let the XSL steam flow rate exceed the Hot Standby setpoint (27 lb/sec, 90 lb/sec).
5. Place the hot well level controller into automatic control model with a liquid level setpoint of 10 ft.
6. Monitor the system conditions as the XSL slowly pressurizes.
7. Once the XSL pressure has stabilized at the expected operating pressure, place the XSL flow controller into automatic mode at the Hot Standby setpoint.
8. Manually close the XSL control bypass valve to transfer flow to the main XSL flow control valves.
9. Change the DHL controller to temperature control mode with a setpoint of 510 °F.
10. Monitor the control systems to ensure setpoints are met and system parameters are at the expected values.

It is important that the oil flow in the DHL be established before opening the XSL main valve so that the flowing oil can remove heat from steam in the XSL. However, if the oil flow is initiated in the DHL while the XSL is pressurizing, any sudden increase in heat transfer across the heat exchangers can cause a spike in steam condensation at the heat exchanger as well as a spike in steam flow through the manually operated bypass valve. Such rapid spikes in extraction steam flow can result in an unallowable increase in reactor power. To avoid such an outcome, the transition between operating modes of the TPD system should be performed carefully over significant amounts of time to allow the different systems to slowly reach the expected operating temperatures and pressures.

4.2 Procedures to Transition Between Hot Standby and Thermal Power Dispatch

Each transition is designed to be performed in approximately 30 minutes. During normal plant operations, the reactor and turbine generator system are ramped together with the turbine ramp rate set to 5 MW/min. However, during the transition between Hot Standby and TPD, the reactor power is maintained approximately constant, so the turbine can ramp at a much higher rate of approximately 20 MW/min. The high-level steps to transition from Hot Standby to TPD are given below.

1. Prepare the turbine system for the ramp down in power by inputting the specified ramp rate (12 MW/min, 20 MW/min).
2. Ensure the DHL controller is in temperature mode with a setpoint of 510 °F.
3. Place the XSL flow controller into manual mode.
4. Input the turbine load setpoint and place the system into "GO" (705 MW, 320 MW).
5. Monitor the reactor power and prepare to manually open the XSL valve as the turbine power decreases.
6. Maintain the reactor power around 99% by manually controlling the steam flow through the XSL system using the XSL control valve.
7. Reactor power should be maintained between 98.5% and 99.5% to avoid the risk of reactor overpower during the transient and prevent movement of the control rods caused by a mismatch between T_{ref} to T_{avg}.
8. Adjust the XSL flow set point to its target steady state value (537.9 lb/sec, 1793.0 lb/sec).

9. When the turbine control system reaches the power set point, continue to open the XSL flow valve until the set point is reached. Then place the XSL flow controller into automatic flow mode control.
10. TPD mode has been achieved.

With the DHL Loop controller in temperature mode, the oil flow will increase as needed as the XSL steam flow rate increases. This helps to maintain the XSL steam pressure and minimize the operator interactions. The procedure to transition from TPD system back to Hot Standby is the reverse of the process described above, with minor adjustments.

1. Prepare the turbine system for the ramp-up in power by inputting the specified ramp rate (12 MW/min, 20 MW/min).
2. Place the XSL flow controller into manual mode.
3. Manually close the XSL flow control valve until a reactor power of 99% has been achieved.
4. Input the turbine load setpoint and place the system into "GO" (920 MW, 895 MW).
5. Maintain the reactor power between 98.5% and 99.5% by manually decreasing the steam flow rate in the XSL system.
6. Adjust the XSL controller set point to the hot standby value (27.0 lb/sec, 90.0 lb/sec).
7. When the XSL flow set point has been reached, place the XSL controller into automatic mode control while the turbine finishes the load ramping process.
8. Hot Standby mode has been achieved.

4.3 Simulator Results for Transitioning Between Hot Standby and Thermal Power Dispatch (TPD)

Simulations were performed for TPD at both 15% and 50% of the maximum rated reactor power using Versions #1 and #2 of the Thermal Power Dispatch GPWR (TPD-GPWR) presented in Sections 1 and 3 above. Results from benchmark RELAP5-3D simulations have been presented in a prior report [2] and are not repeated here. Figure 6 shows the flow in the main steam line, the steam flow to the turbine, and the steam flow to XSL for the transition from Hot Standby to TPD and back to Hot Standby. The trends in the steam flow rates behave as expected. However, the amount of steam extracted through the XSL system at 50% TPD is higher than 50% of the total steam flow, and the amount of turbine flow is less than 50% of the total steam flow. An important parameter to note in Figure 6 is the flow rate of steam in the main steam line, which decreases as the amount of steam flowing in the XSL increases. This effect is shown in Figure 7 for both 15% and 50% TPD. At 15% TPD, the temperature of the feed water entering the steam generator decreases from 435°F to 420°F, which represents a change of approximately 3%. At 50% TPD, the temperature of the feedwater to decreases to approximately 342°F, which is a decrease of approximately 21%, indicating a strongly nonlinear relationship between steam flow in the XSL and the temperature of the feed water.

To understand the cause of the decrease in the feed water temperature with the increasing flow of steam in the XSL, it is helpful to review Figure 1, which shows that the steam that provides heat for the feed water heater train comes from the turbine system. As shown in Figure 6, increasing the flow of steam in the XSL, decreases the flow of steam to the turbine system, and consequently reduces the heat available in the feed water heaters, so that the feed water temperature entering the steam generator decreases with the increasing flow of steam in the XSL. Because the heat from the reactor is constant, as the temperature of the feed water decreases, the flow of steam in the main steam line must decrease to maintain the temperature in the main steam line. It is also important to note in Figure 6that decrease in steam flow in the main steam line with increasing steam flow in the XSL causes a disproportionate decrease in the turbine steam flow, which is also a factor in the nonlinear relationship between steam flow in the XSL and the temperature of the feed water.

In addition to the large drop in feedwater temperature due to the design of the extraction steam line (XSL), there is also a significant decrease in turbine power, more than might be expected. For example, a thermal power extraction of 50% would result in approximately 50% of the main steam being extracted through the XSL, and the remaining 50%, be available for expansion in the turbine for electricity generation. This is inaccurate because 100% of the main steam is not available for the turbine system even for 0% TPD due to house steam load requirements, such as in the MSR and the feed water heaters. Still, it is desired to achieve as close as possible to 50% of full electrical power generation at 50% TPD. If the maximum electrical power produced by the turbine system is approximately 970 MWe as shown in Figure 7, then it is desirable to achieve close to 485 MWe of electric power production by the turbine generator system at 50% TPD. However, Figure 15 shows that the simulator predicts the electric power production at 50% TPD to be 278 MWe, signaling a significant loss in thermal to electrical power conversion efficiency in the system.

Many factors may be responsible for the derated performance of the turbine. First, as noted above, the flow of steam in the main steam line decreases with increasing steam flow in the XSL, such that flow in the turbine system is greatly impacted. At 50% TPD, the flow of steam in the turbine system decreases from 3,234 lb/s to 1,163 lbs/s, corresponding to a decrease to only 36% of its rated steam flow capacity. Turbine systems are not designed to operate effectively at this low steam flow rate.

Multiple options can be pursued to mitigate these undesirable effects. One option is to return the condensate from the XSL system to the feed water heaters rather than to the NPP condenser. Because the condensate temperature in the XSL is hotter than the condensate temperature in the condenser, returning condensate from the XSl to the condenser wastes enthalpy and stresses the feed water heating system. The condensate from the XSL instead could be returned to the feed water heater train at points to minimize the waste of enthalpy and support heating the feed water. This option is especially important for high levels of TPD above 15%. Another option for relatively lower levels of TPD is to extract steam from the HP or LP turbines, rather than from the main steam line to reduce the enthalpy that is removed from the turbine system (and from the feed water heaters). For any option that is explored, the turbine performance curves should be consulted to quantify any potential decrease in turbine performance or lifetime.

Figure 8 highlights the importance of maintaining the thermal balance on the steam generator for keeping the reactor at 100% thermal power. The reactor power and cold leg temperature are shown in this figure, and they are plotted in such a way that the reactor power follows the exact shape of the cold leg temperature. Since the temperature of the cold leg water affects the moderation of the neutrons in the reactor core, this is the expected result from the system. The axes have been modified so that the cold leg temperature is inverted, going from high temperature to low temperature as the reactor power goes from low power to high power. An increase in the thermal load in the steam generator causes a decrease in the cold leg temperature, which increases reactor power. Figure 9 shows the modulation in the hot leg and reactor coolant system (RCS) average temperature values throughout the transients. The fluctuation in the hot leg temperature is not as large as the fluctuation in the cold leg temperature.

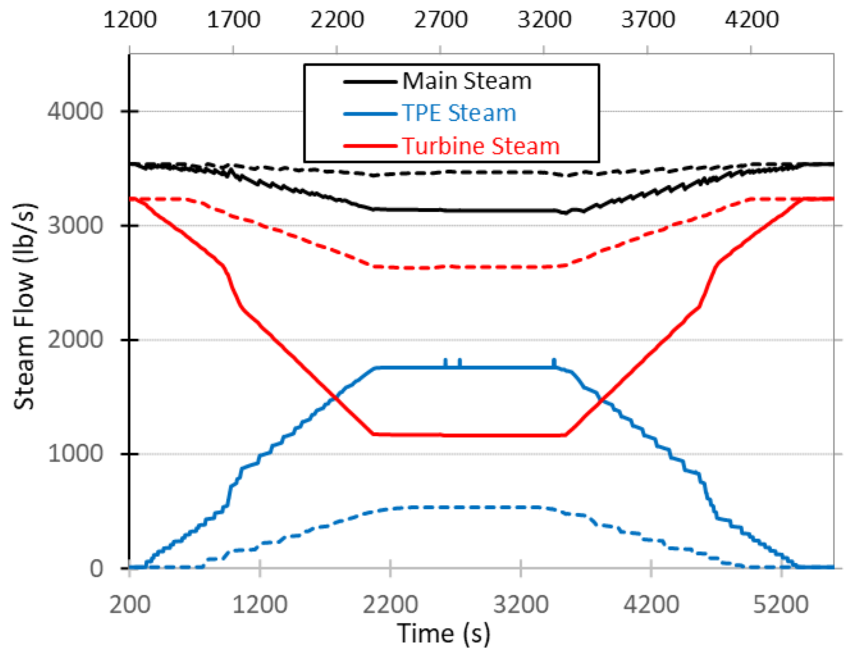

Figure 6. Steam flow rates for the transition to 15% and 50% TPD.

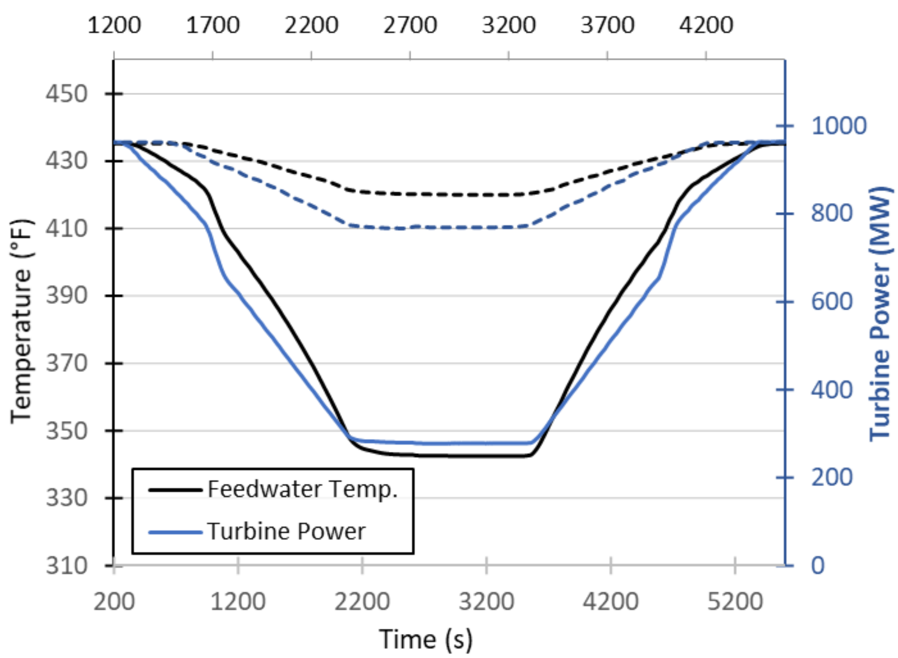

Figure 7. Feed water temperature and turbine power during the transition to 15% and 50% TPD.

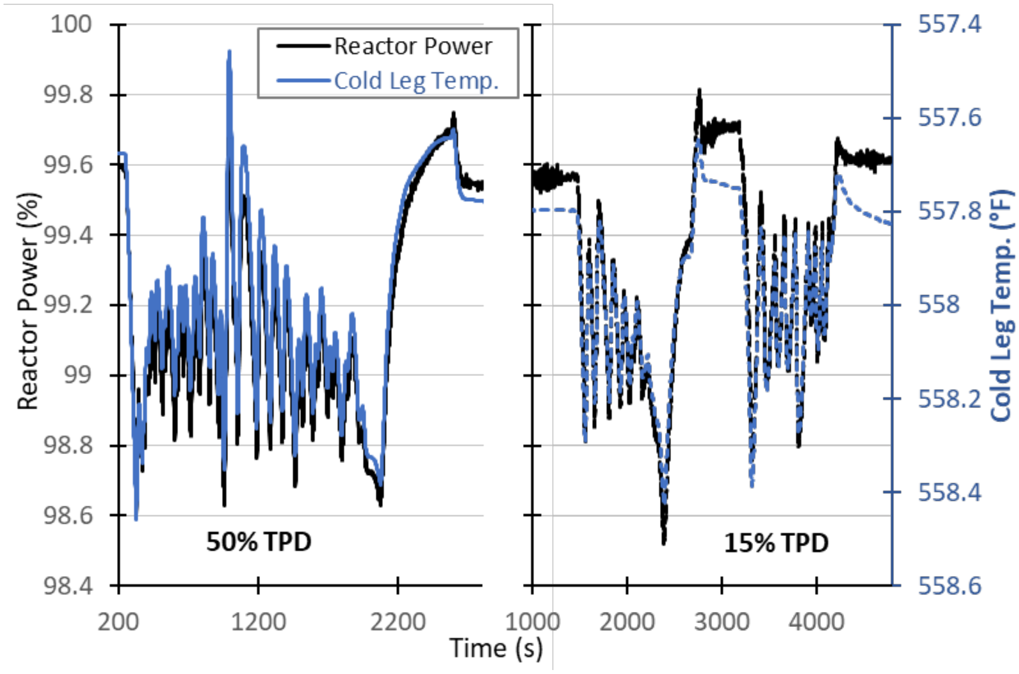

Figure 8. Reactor power and RCS cold leg temperature during the transition 15% and 50% TPD.

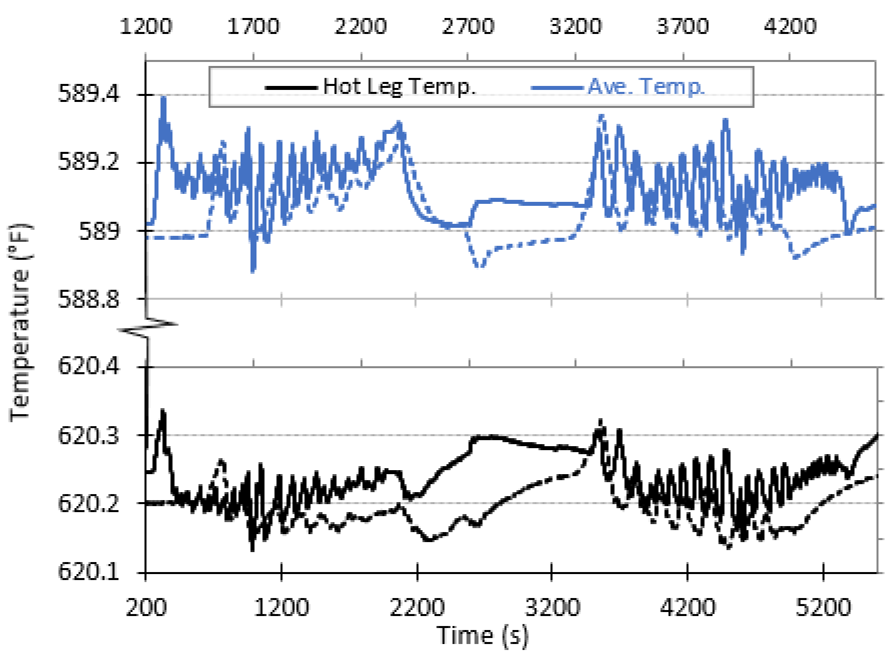

Figure 9. RCS hot leg temperature and RCS average temperature during the transition to 15% and 50% TPD.

Figure 9 shows the RCS average temperature compared to the control rod system calculated reference temperature. These temperatures are important to the operation and control of a PWR system. The reference temperature is a representation of the secondary system load, or in other words the turbine power. The RCS average temperature is a representation of the primary reactor system load. These loads must match for the system to be in thermal equilibrium. The calculated difference in these temperature values determines the control rod movement. One of the design decisions is that the control rods do not move during the transition to TPD to avoid increasing risk within the NPP. To achieve that goal, a bias that scaled linearly with the steam flow in the XSL was added to the reference temperature calculation. The results in Figure 10 show that for 15% TPD, the linear bias held the reference temperature to a reasonably constant value to prevent control rod movement, while it was not as a success for this purpose for 50% TPD. Further adjustments will be needed to the reference temperature calculation for 50% TPD to prevent control rod movement if the control rods are placed in automatic mode. Based on the results presented above, it appears the newly added bias must account for the nonlinear steam flow effects through the turbine and feed water heater systems discussed above. Implementing changes in where steam is extracted and returned for TPD has the potential to greatly simplify the changes that are needed in the calculation of the reference temperature.

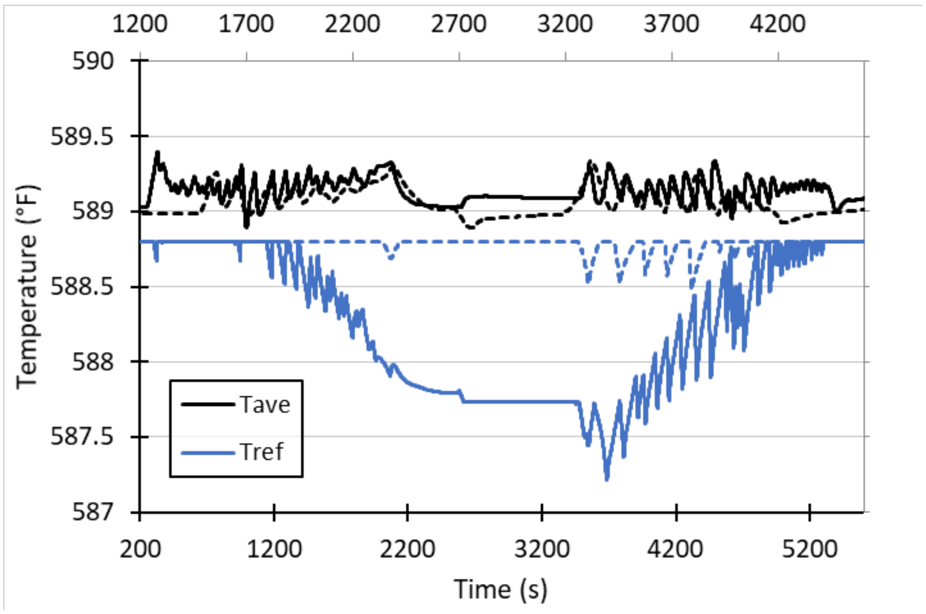

Figure 10. T_{ref} and T_{avg} for computing the mismatch in the control rod program during the transition to 15% and 50% TPD.

5. THERMAL POWER DISPATCH (TPD) DESIGN WITH A DELIVERY STEAM LINE (DSL)

5.1 Extraction Steam Line (XSL) Design

This section and the next section focus on the system design that employs steam as the heat delivery fluid. Similar to the design that employs synthetic oil as the heat delivery fluid, and as shown in the piping and instrumentation diagram of Figure 11, two separate systems transfer steam between the NPP and the hydrogen plant. First, an extraction steam line (XSL) removes steam from the main steam line of the NPP and delivers that steam to extraction heat exchangers. The extraction heat exchangers then boil demineralized water (DMW) to generate steam that is delivered in a second steam line, denoted “DSL”, that transfers the steam to an industrial user approximately one kilometer from the NPP. Key differences between the designs that use steam and oil as the heat delivery fluid are (1) three heat exchangers are used in the design that employs steam as the heat delivery fluid and (2) steam extracted from the nuclear plant is present in the tube side of each of the three heat exchangers. Steam extracted from the main steam line is at a much higher temperature (280°C) and pressure than the steam that is needed by the hydrogen plant (approximately 150°C), and consequently is confined in the tubes of the heat exchangers.

In this report, each of the TPD heat exchangers is referred to by their function in the system. The preheater (XSL-PH) is used to bring the delivery system DMW close to its saturation temperature before entering the kettle reboiler (XSL-RB). It also functions to subcool the extraction steam, maximizing the enthalpy that is removed from the PWR coolant. The kettle reboiler is referred to as such because its design is similar to that of kettle reboilers used in distillation columns. This design is well suited for condensing the extraction steam on one side and boiling delivery DMW water on the other side (two-phase to two-phase heat transfer). In this design, the tubes are highly effective at condensing the extraction steam they contain, and the delivery steam leaving the shell side at the top of the kettle is saturated or close to saturation. The condensate of the extraction steam is collected in a hot well to ensure that only liquid is present in the tubes of the preheater. The superheater (XSL-SH) serves to superheat the delivery steam before entering the 1 km pipeline to the industrial process user. The saturated steam is superheated to prevent condensation in the delivery pipeline. Due to the HP and velocity of the steam in the pipeline, moisture could cause excessive erosion, which is avoided by superheating the delivery steam. The superheater (XSL-SH) also partially condenses the extraction steam before it enters the kettle reboiler (XSL-RB).

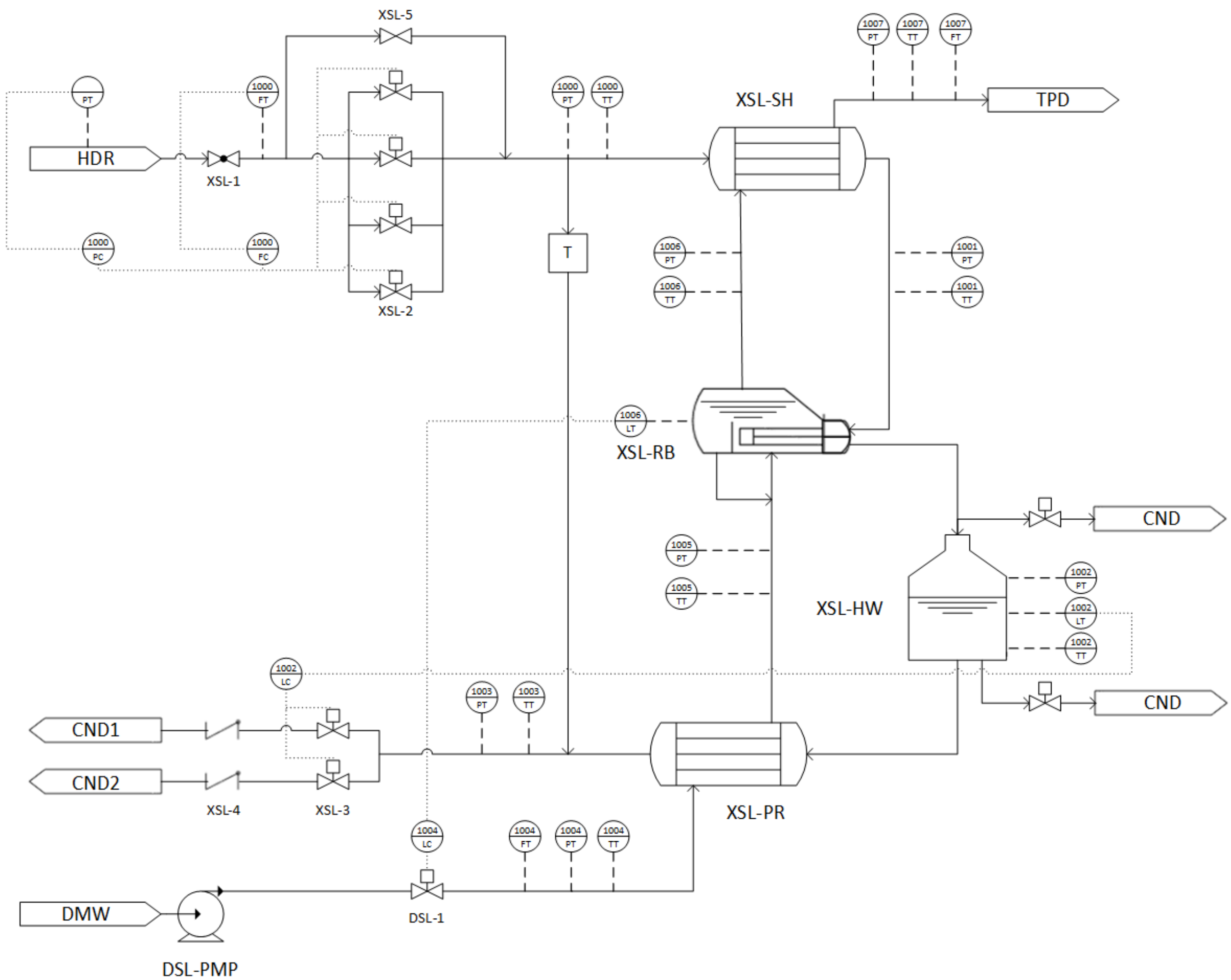

Figure 11. Simplified P&ID for the XSL and DSL systems.

The superheater and the preheater are standard shell and tube design heat exchangers with baffled flow on the shell side. The kettle reboiler follows the design of existing kettle reboilers used at the bottom of distillation columns in chemical process plants with a key difference being that the liquid in the shell side is recycled into the inlet stream to maintain a water level in the kettle reboiler.

The heat exchangers and extraction steam pipelines in Figure 11are all labelled with the identifier XSL, while the pipelines in the delivery steam line are labelled with the identifier DSL. XSL-1 is the isolation valve at the outlet of the MSH in the PWR secondary system. This is the most safety-significant valve in the TPD system [4]. XSL-2 is a combination of four valves all controlled by the same controller. This is a design choice due to the increase in the baseline flowrate of the steam in the XSL. At 5% TPD, the steam flow is 179.3 lb/s and at 15%, it is 537.9 lb/s. Since these valves are operated manually during transitions in power, an array of valves provides better control and a lower margin of error than a single valve. If the flow uses all four valves at the same valve position, the manual adjustments performed by the operator during the transition in operation will have more room for error than a single valve. XSL-3 is the level control valve for the hot well system in the XSL and consists of two valves, one for each of the main condenser zones present in the GPWR. These valves are positioned downstream of the preheater (XSL-PH) instead of immediately after the hot well to ensure that the XSL pressure in the preheater is maintained during operation.

5.2 Implementation in the Thermal Power Dispatch GPWR (TPD-GPWR)

The XSL and DSL have been included in the GPWR model using a new drawing called tpe1, which is shown in Figure 12. The XSL and DSL systems can be included in a single drawing because both systems use the same working fluid. Including both systems in a single stand-alone drawing has an added benefit in that the attachment point of the XSL and DSL system to the NPP can be easily moved. For example, the drawing could be attached to HP turbine outlet to extract steam from that location instead of from the MSH. As discussed below, this modification could have substantial benefits for a NPP that is coupled to a hydrogen production plant and will be the focus of future work.

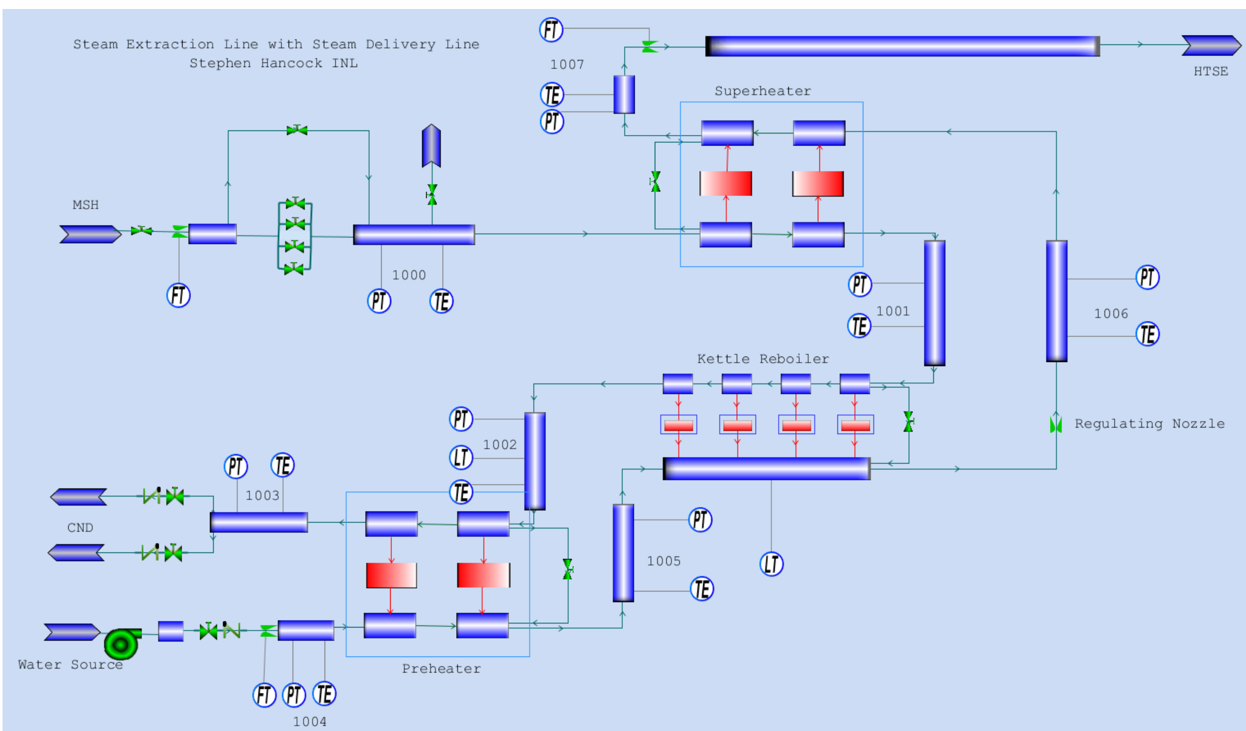

Figure 12. Screenshot of the tpe1 drawing containing the XSL and the DSL system in the GPWR.

For this milestone, the XSL system still draws steam from the MSH at main steam pressure and supplies the thermal power to a DSL at elevated pressure (~500 psia). This matches the HYSYS and RELAP5-3D models and is consistent with previous designs where steam acts as the working fluid in a closed thermal power delivery loop. The closure of the loop has been avoided, as discussed, in favor of a once-through line that draws DMW from the PWR plant site and sends the steam directly to the hydrogen plant. Any excess unreacted water can be collected in a tank at the hydrogen plant and pumped back at low temperature and pressure to the PWR to be stored in a reservoir for use in the DSL system.

The XSL model in the TPD-GPWR operates similarly to the RELAP5-3D described below and uses the same volume geometry. As a simplification which is possible in the GPWR simulator, the parallel heat exchangers have been collapsed into a single heat exchanger with the equivalent volume of the parallel heat exchangers. The XSL drawing begins at the outlet of the MSH to the XSL system. There is an isolation valve that is capable of isolating the system in the event of a transient or hydrogen plant/DSL trip. This isolation valve is the most significant safety component in the XSL systems as it isolates this system from the remainder of the plant. Following the isolation valve, there are four parallel control valves for manual and automatic control of the steam flow in the XSL, as explained above. A bypass valve is included and is used for initial system pressurization and can be used to more easily maneuver the system into hot standby.

The superheater is modeled as a standard heat exchanger with two volumes in either system. These are all cross-flow heat exchangers, using more than one volume (typically) to allow for the temperature difference to be recognized by the system since the JTopmeret™ equations do not use the log mean temperature difference (LMTD) approach for heat exchanger calculations. The exception is the DSL shell side of the reboiler, which is modeled as one large volume. The XSL loop is slightly condensed in the superheater prior to entering the reboiler where it is fully condensed in the four volumes. The multiple volumes are used to monitor the condensation rate of the XSL steam and allow for improved accuracy in the heat transfer since this heat exchanger is responsible for the majority of the heat transfer in the XSL system. Following the reboiler, the XSL condensate is collected in a hot well which serves as a separator and supplies saturated liquid to the preheater. This hot well has a level controller associated with it, but due to the nature of the system at full power, the level is not necessary to control. At lower amounts of TPD and at hot standby the level is controlled to prevent draining of the hot well system. Following the two-volume superheater, the flow is redirected towards the condenser and split into two flow paths, corresponding to the two condenser zones in the main condenser system. These paths contain level control valves for maintaining the XSL hot well level at hot standby and check valves to prevent depressurization of the system. The level controllers are located at the condenser entrance instead of the hot well exit to maintain the preheater at pressure and to avoid a depressurization in the event of a trip.

5.3 Delivery Steam Line (DSL) Design

The design for the DSL is included in Figure 8and shows that the DSL is a once-through steam generation system that sends steam to the hydrogen plant using DMW at the NPP. The demineralized steam molecules are split at the hydrogen plant to produce hydrogen (and potentially oxygen). The hydrogen plant is not necessarily a once-through steam system, and some of the demineralized steam passes through the hydrogen plant and is collected as condensate DMW. Depending upon the operating conditions at the hydrogen plant, there may be sufficient low-temperature heat to boil this DMW to provide additional steam for hydrogen production, or the unreacted DMW may be stored at the hydrogen plant in a reservoir and pumped back to the PWR plant at LP and temperature where it can re-enter the process.

There are several benefits to this type of design compared to a closed DHL. The first and main advantage is the elimination of an entire heat transfer system located at the hydrogen plant, which has many benefits. First, the temperature drop across the second set of heat exchangers is eliminated such that lower temperature steam can be sourced at the nuclear plant, which opens additional options to be discussed later to extract lower temperature steam from the turbine generator system instead of the main steam line. Second, the complexity of constructing and operating the system is greatly reduced. Third, a once-through design eliminates the need to have a backup condenser for the delivery steam system in the case of a sudden trip at the hydrogen plant or in the DSL. In the case of a sudden trip, steam in the DSL could typically be contained without damaging the pump or it could simply be vented to the atmosphere without the concern of depressurizing the system.

The water supply for the DSL comes from the water supply at the PWR. It is pumped through the DSL system and sent to the hydrogen plant. The DSL contains a pump at the DMW inlet followed by a control valve. The preheater is modeled as a two-volume system for the DSL, similar to the superheater for the same reasons as discussed previously. The major system in the DSL is the reboiler. The flow control valve (DSL-1) following the DSL pump is best controlled to maintain the water level in the kettle reboiler. Maintaining the water level in the kettle reboiler is integral to the operation of the two-phase to two-phase heat transfer design. Since the water level is maintained at a point above the bank of tubes in the kettle reboiler, only localized boiling occurs on the tubes. The bulk of the shell fluid for heat transfer purposes is still water and therefore behaves as a single-phase fluid. This design is similar to that of a steam generator in a PWR or the core design in a boiling water reactor (BWR), although much simpler due to the absence of nuclear safety concerns related to a failure to maintain the water level in the reboiler. In a PWR steam generator, the tubes must remain covered by the liquid on the secondary side to ensure effective heat transfer and prevent the steam generator dry out. Similarly, the reactor core of the BWR must remain completely covered by the primary coolant liquid to prevent a dangerous increase in the fuel temperature caused by the drop in heat transfer effectiveness. The water level in the kettle reboiler must also be maintained to avoid dry out.

Figure 13shows a basic diagram of the operation of a kettle reboiler and highlights that steam is used in the tube side of the heat exchanger to generate vapor from a liquid input on the shell side of the heat exchanger. This is another difference from the PWR steam generator which uses liquid only on the tube side of the heat exchanger. The kettle reboiler in Figure 13is slightly different from that shown in Figure 11in that shell-side bottoms product is combined with the liquid feed of the reboiler rather than being a separate product of the heat exchanger, which helps to keep the steam quality of the shell side low. The shell volume, separator, and liquid recycle are all modeled in a single volume, which is treated as a separator. The DSL control valve is used to control the liquid level in this separator volume. The intended operation of this system is for the tubes in which the XSL steam is fully condensed to remain underwater at all times so that the heat exchanger behaves as a single-phase to a two-phase heat exchanger with localized nucleate boiling. The heat slab, where the heat transfer occurs, is modeled to be at an elevation below the specified level control of the system. Within GPWR, the shell side of the heat exchanger, the separator, and the liquid fall back and recycle must all be modeled as a single volume. The vapor outlet of the separator has an increased pressure loss caused by what would be a flow restrictor on the outlet. This restricts the amount of steam that can leave the separator, causing a constant vapor flow rate leaving the volume. When the separator level is maintained, the vapor flow rate matches the liquid inlet flow rate and the unit is balance. Following the superheater, there is a final flow meter to allow the operator to monitor the steam flow rate in the DSL system entering the delivery pipe to the hydrogen plant. The 1 km delivery pipe is included as the final volume in the DSL model prior to the steam being used at the hydrogen plant.

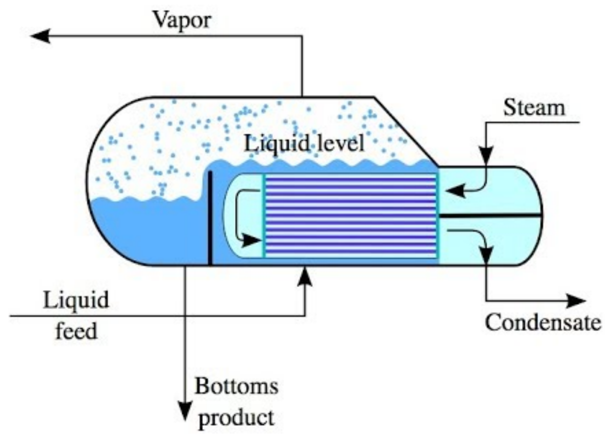

Figure 13. Diagram of a typical kettle reboiler.

6. THERMAL POWER DISPATCH (TPD) SYSTEM MODELS WITH A DELIVERY STEAM LINE (DSL)

This section presents the thermal-hydraulic models used to verify the ability of DSL system to generate and superheat steam as intended. HYSYS is used as a thermodynamic balancing tool and to assist in the design of each of the heat exchangers. RELAP5-3D serves as the transient modelling tool for verifying the geometry of the system.

6.1 HYSYS Base Model

The basic design was modeled in Aspen HYSYS to determine the steady-state thermodynamic operating conditions, and the corresponding model is shown in Figure 14. As in Figure 11, the preheater and the superheater are simple shell and tube heat exchangers. The reboiler is modeled as a shell and tube heat exchanger with a separator on the shell side outlet. The liquid product from the separator is recycled back into the feed water inlet of the shell side. The numbers used in this representation are for 5% TPD, corresponding to a steam extraction flow rate of 179.3 lb/sec. This was uprated to the design amount for 15% TPD with a flow rate of 537.9 lb/sec in the heat exchanger design portion of the work. This model was used to establish a starting point for the system design. The DSL flow rate in this model is 182.2 lb/s, which was later decreased to about 160.0 lb/s to increase the superheating of the steam in the DSL.

An important aspect of this system is the steam quality exiting the reboiler shell and tube heat exchanger before the separator. The quality at this point is 0.0741, such that the majority of the fluid exiting the kettle reboiler is liquid. As discussed earlier, this condition is essential for the system to operate as intended.

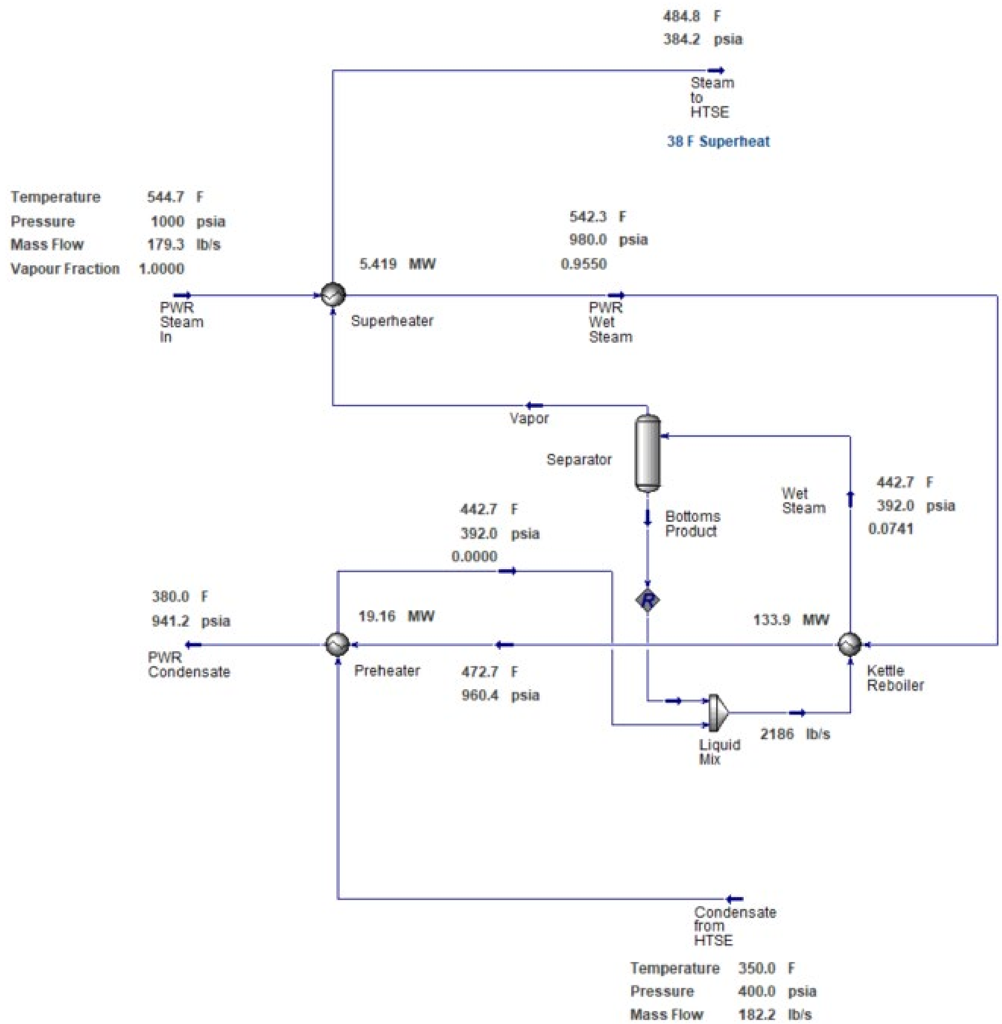

Figure 14. The process model in Aspen HYSYS for the TPD system with steam as the heat delivery fluid.

The results from this model and the uprated model were used to generate the geometric heat exchanger designs for each of the three heat exchangers in this HYSYS model. The Aspen Exchanger and Design Rating (EDR) program was used to produce these heat exchanger designs. This software uses known heat exchanger geometries to best match the desired operation. The results of the heat exchanger design for the 15% TPD system gave a single heat exchanger design for the preheater and six heat exchangers in parallel for both the kettle reboiler and the superheater. In addition to the heat exchanger design for each system, the EDR program also gives an estimate for the capital cost of each of the heat exchangers (all shells). The estimated capital cost for this steam-to-steam heat transfer system is $5.6 million, as shown in Table 3. This cost does not include installation costs at an NPP and assumes the material of construction is stainless steel. These numbers can be used in future techno-economic analyses (TEAs) of this system design for TPD from NPPs.

Table 3. Number of heat exchangers and their capital cost.

Heat Exchanger	Number in Parallel	Capital Cost (all shells)
Superheater (XSL-SH)	6	$812,424.00
Kettle Reboiler (XSL-RB)	6	$2,919,138.00
Preheater (XSL-PH)	1	$1,931,438.00
Total Cost		$5,663,000.00

6.2 RELAP5-3D Model

The RELAP5-3D models of the XSL and DSL systems are generated using the heat exchanger design information from the Aspen EDR program. Additional dimensions are included for the piping systems connecting the heat exchangers and the different systems. The complete RELAP5-3D models includes flow of extraction steam from the MSH to the outlet of the preheater on the XSL side as well as flow from the DMW pump to the hydrogen plant inlet on the DSL side. The RELAP5-3D model does not include controls so that the flows are driven by the pressure differences and the geometry of the system components.

The superheater is modeled as six parallel heat exchangers with a two-tube pass on the XSL side and a single shell pass on the DSL side. The kettle reboiler is modeled as six parallel heat exchangers with u-tubes on the XSL side and a single shell pass on the DSL side. The DSL side includes a separator at the shell exit, a liquid fallback area with a connection to the shell side inlet, and a vapor outlet at the top. The preheater is a single heat exchanger with a single tube pass on the XSL side and a single shell pass on the DSL side. The DSL steam at the outlet of the superheaters is recombined and sent to the delivery pipeline which delivers the fluid to the hydrogen plant approximately 1 km away.

Figure 15shows the nodalization of the steam-to-steam RELAP5-3D model. For simplicity, the parallel heat exchangers are not shown in the nodalization and instead are marked by the amount in parallel to the left of the XSL side nodes. The black boxes represent areas where heat transfer occurs in the model between systems. Table 4shows the steady-state results of the model. The node numbers refer to the node numbers in Figure 15and are representative of each of the parallel systems. Notice that some of the numbers are different than provided in the original HYSYS model in Figure 14. This is a result of some changes in the flow rate on the DSL side as well as the DSL operating pressure to improve the model convergence. Compared to the HYSYS model results, a higher temperature is achieved by the delivery steam entering the pipeline (498.8°F vs. 484.8°F), and the delivery steam is also at a significantly higher pressure (475.71 psia vs. 384.2 psia). Figure 16shows time-dependent plots of selected mass flow rates in the system and shows that steady-state is achieved quickly. Mass flow rates in Figure 16indicate vapor flow in the XSL and liquid flow in the DSL. The design of the kettle reboiler system fully resolves challenges in achieving steady operation of the two-phase to the two-phase heat transfer system. After the system achieves steady state at around 250 s, the noise in the mass flow rates is small, except for localized, brief incidences, which are a result of momentum fluctuations.

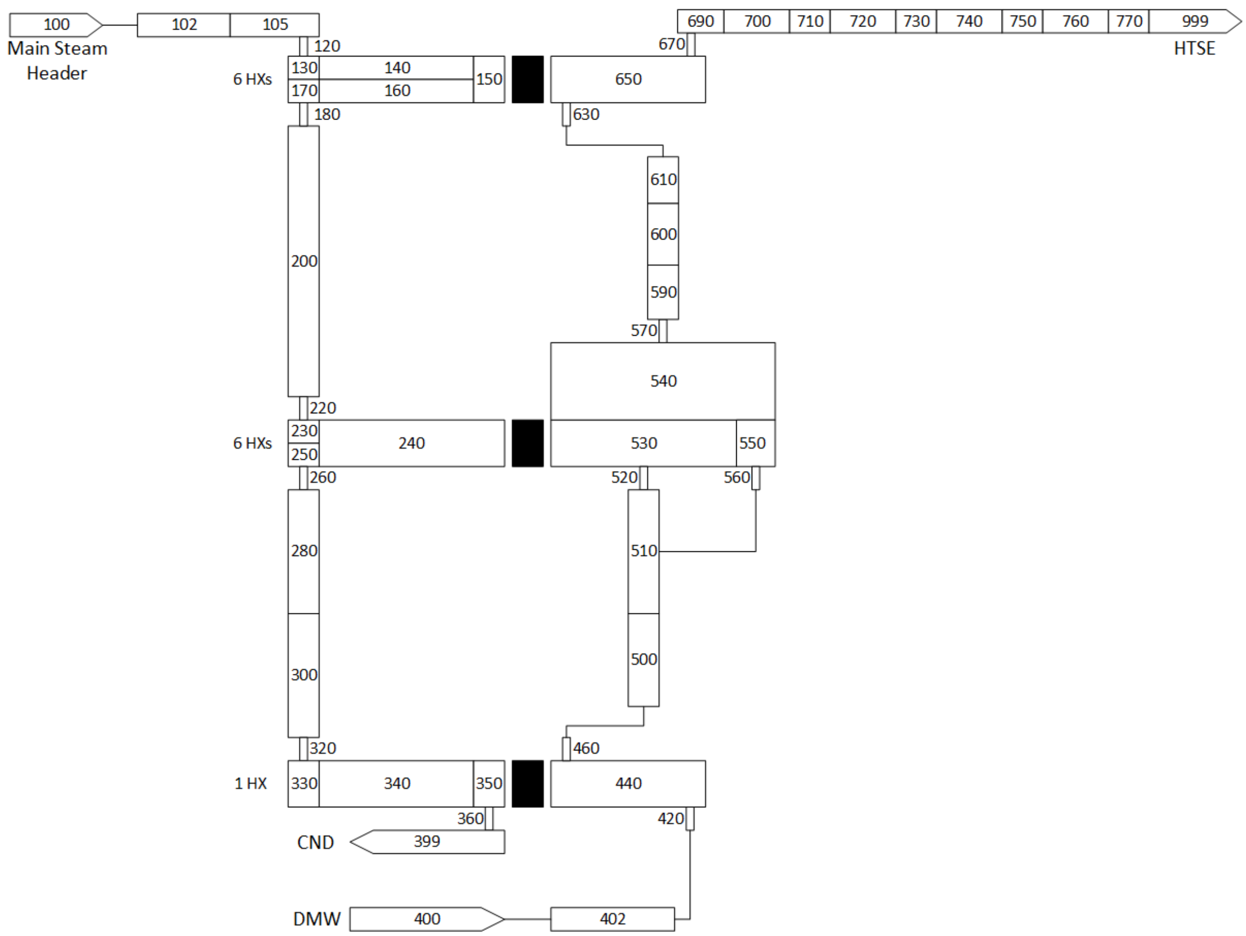

Figure 15. Nodalization of the RELAP5-3D for the steam to steam thermal power extraction system.

Table 4. RELAP5-3D model results for the XSL and DSL with 15% thermal power extraction

Node\Description	**Pressure, (psia)**	**Temperature, (°F)**	**Quality**	**Mass Flow, kg/s (lb/s)**
XSL (saturated steam to condensate)				
100 (MSH)	1000.0		1	
102 (Pipe to Superheater)				537.9
120 (Superheater Inlet)	965.7	540.3	0.993	
180 (Superheater Outlet)	964.7	540.2	0.944	
220 (Reboiler Inlet)	964.4	540.2	0.961	
260 (Reboiler Outlet)	965.4	525.2	0.0	
320 (Preheater Inlet)	966.8	525.5		
360 (Preheater Outlet)	968.4	401.6		
399 (Mass Sink)	970.0	401.6		
DSL				
400 (DM Water Supply)	580.0	350.0		
402 (Pipe to preheater)				479.2
420 (Preheater Inlet)	502.2	349.9		
460 (Preheater Outlet)	480.7	462.8		

Node\Description	Pressure, (psia)	Temperature, (°F)	Quality	Mass Flow, kg/s (lb/s)
520 (Reboiler Inlet)	479.0	462.6	0.0	
530 (Separator Inlet)	479.2	462.7	0.0654	
560 (Recycled Water)	480.1	462.6	0.0	7200.0
570 (Reboiler Outlet)	476.8	461.8	1.0	
630 (Superheater Inlet)	477.2	462.7		
670 (Superheater Outlet)	475.7	498.8		
770 (H2 Plant Inlet)	420.1	487.3	1.0	

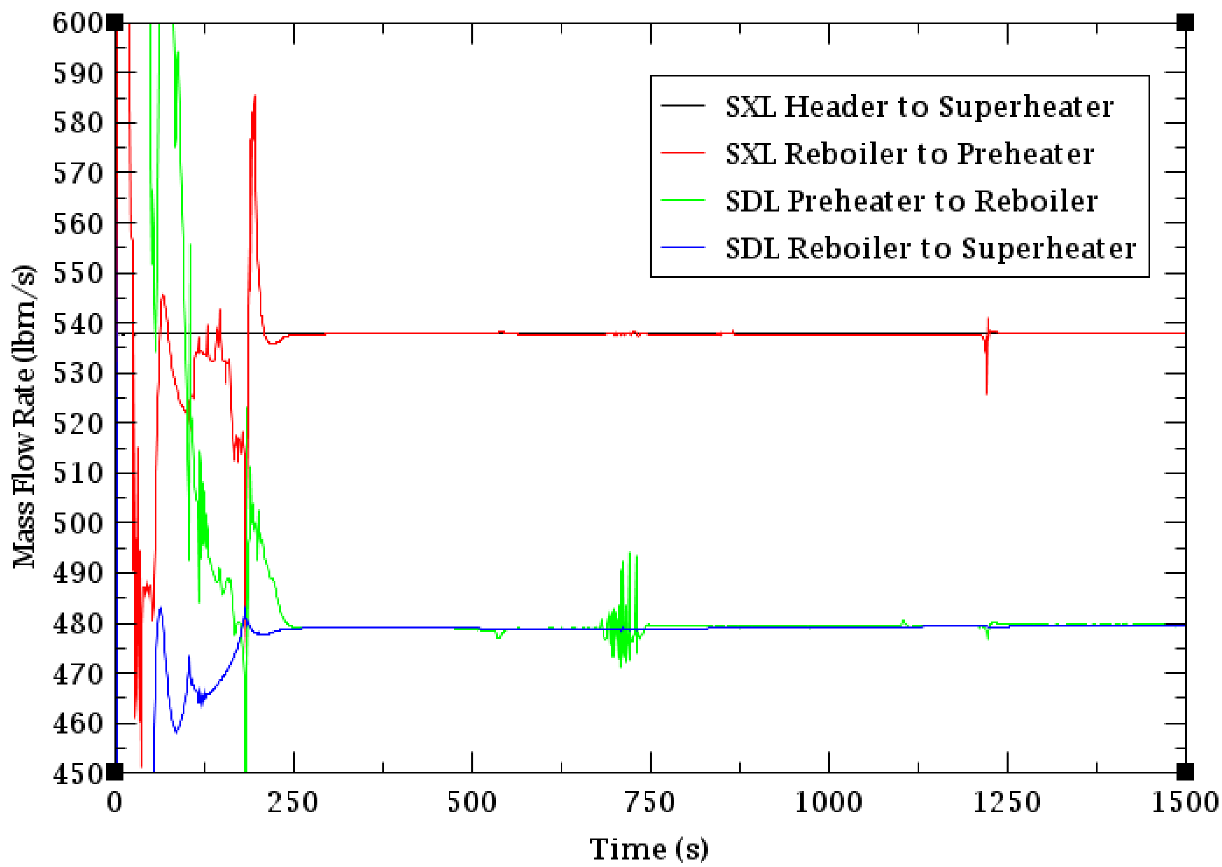

Figure 16. Transient results of selected mass flow rates of the steam-to-steam RELAP5-3D model.

7. THERMAL POWER DISPACTCH (TPD) SIMULATIONS WITH A DELIVERY STEAM LINE (DSL)

The operating and tests modes established for the Thermal Power Dispatch GPWR (TPD-GPWR) Simulator with a DSL are the same as for the simulator with an oil delivery heat loop (DHL) and include Cold Shutdown, hot standby, and TPD. There are differences in the performances of the systems. For example, using steam as the heat delivery fluid will significantly increase pressure fluctuations in the XSL during mode transitions compared to the system design that uses oil as the heat delivery fluid. The cause of the increasd pressure fluctuations is that in hot standby mode or during transitions when the steam flow in the XSL is low, thermal equilibrium in the XSL will be close to the temperature of the steam in the DSL loop, which will cause the operating pressure of the XSL to be close to that of the DSL with relatively higher pressure fluctuations.

7.1 Procedure to Transition from Cold Shutdown to Hot Standby

As in the design with an oil delivery heat loop (DHL), the turbine load needs to be decreased before the TPD system is placed in hot standby. The procedure to transition from Cold Shutdown to Hot Standby is similar to that for the design with an oil delivery loop (DHL) but with minor differences. The setpoints for 15% and 50% TPD are shown in parenthesis following the appropriate steps:

1. Decrease the turbine load to the hot standby setpoint at a ramp rate of 5 MW/min (920 MW, 895 MW).
2. Turn on the DSL pump to being water flow to establish a level in the reboiler.
3. Place the DSL controller into automatic with a level set point of 3.5 ft.
4. Slowly open the XSL control bypass valve manually to initiate pressurization of the XSL system. Do not let the XSL steam flow rate exceed the hot standby setpoint (27 lb/sec, 90 lb/sec).
5. Place the hot well level controller into automatic control model with a level setpoint of 8 ft.
6. Monitor the XSL and DSL conditions as the XSL line slowly pressurizes.
7. Once the XSL line pressure has stabilized at the expected operating pressure, place the XSL flow controller into automatic mode at the hot standby setpoint.
8. Manually close the XSL control bypass valve to transfer flow to the XSL flow control valves.
9. Monitor the control systems to ensure setpoints are met and system parameters are at the expected values.

In the design with the DSL, it is important that the water level be established in the reboiler before flow begins in the XSL so that the correct heat transfer can occur and the XSL hot well can begin to collect condensate.

7.2 Procedures to Transition Between Hot Standby and Thermal Power Dispatch (TPD)

For the design with a DSL, the XSL hot well utilizes the level controller to achieve hot standby mode. This controller remains automatic throughout the transition to TPD and during TPD operation; however, the level during transition is higher than the setpoint during TPD operation. The reason for this is unknown and will be the focus of future work. It is clear that decreasing the liquid level in the hot well by changing the design of the system results in a significant decrease in the pressure of the XSL system. For the purposes of this study, the hot well liquid level controller is maintained in automatic mode, with a high setpoint level to ensure adequate pressure following the hot well in the XSL. The high-level steps to transition from Hot Standby to TPD are

1. Prepare the turbine system for the ramp down in power by inputting the specified ramp rate (12 MW/min, 20 MW/min).
2. Ensure the DSL controller is maintaining a reboiler level of 3.5 ft.
3. Place the XSL flow controller into manual mode.
4. Input the turbine load setpoint and place the system into "GO" (705 MW, 320 MW).
5. Monitor the reactor power and prepare to manually open the XSL valve as the turbine power decreases.
6. Maintain the reactor power around 99% by manually controlling the steam flow through the XSL system using the XSL control valve.

7. Reactor power should be maintained between 98.5% and 99.5% to avoid the risk of reactor overpower during the transient and prevent movement of the control rods caused by the T_{ref} to T_{avg} mismatch.
8. Adjust the XSL flow set point to the XSL setpoint (537.9 lb/sec, 1793.0 lb/sec).
9. When the turbine control system reaches the power set point, continue to open the XSL flow valve until the setpoint is reached. Then place the XSL flow controller into automatic mode.
10. TPD mode has been achieved.

The procedure to return to hot standby from TPD mode follows the same pattern in reverse order

1. Prepare the turbine system for the ramp-up in power by inputting the specified ramp rate (12 MW/min, 20 MW/min).
2. Place the XSL flow controller into manual mode.
3. Manually close the XSL flow control valve until a reactor power of 99% has been achieved.
4. Input the turbine load setpoint and place the system into "GO" (920 MW, 895 MW).
5. Maintain the reactor power between 98.5% and 99.5% by manually decreasing the steam flow rate in the XSL system.
6. Adjust the XSL controller set point to the hot standby value (27.0 lb/sec, 90.0 lb/sec).
7. When the XSL flow set point has been reached, place the XSL controller into automatic mode while the turbine finishes the load ramping process.
8. Hot Standby mode has been achieved.

7.3 Simulator Results for Transitioning Between Hot Standby and TPD

Simulations were performed for TPD at both 15% and 50% of the maximum rated reactor power using Versions #3 and #4 of the TPD-GPWR simulator presented in Sections 1 and 3 above. Figure 17shows the flow in the main steam line, the steam flow to the turbine, and the steam flow to XSL for the transition from Hot Standby to TPD and back to hot standby. The results are nearly identical to those obtained using Versions #1 and #2 of the TPD-GPWR simulator that employs an oil delivery heat loop (DHL). The nearly identical results are expected because both system designs operate in similar ways with similar impacts on the NPP systems. Similarly, the feedwater temperature and turbine power predicted by the TPD-GPWR simulator shown in Figure 18are nearly identical to those in Figure 4-2 for the system design with an oil delivery heat loop (DHL). Figure 19and Figure 20show the reactor power, RCS cold leg, and RCS average temperature are also similar to the corresponding figures in Section 4 for the system design that employs an oil delivery heat loop (DHL). The figures here for the system design with a DSL do manifest slightly higher fluctuations, which are indicative of slightly less stable controls as noted above. Of particular concern, is that in Figure 19, the reactor power briefly spiked to slightly greater than 100%, which cannot be allowed. To avoid that occurrence in future simulations or real operations, the reactor power and turbine power setpoint should be reduced below 98.5% prior to transitioning between Hot Standby and TPD modes.

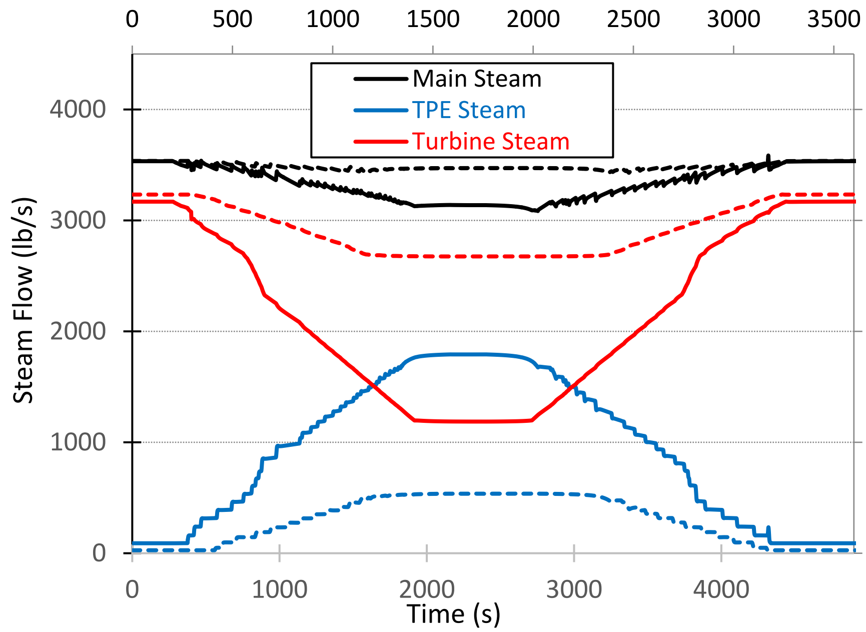

Figure 17. Steam flow rates for the transition to 15% and 50% TPD.

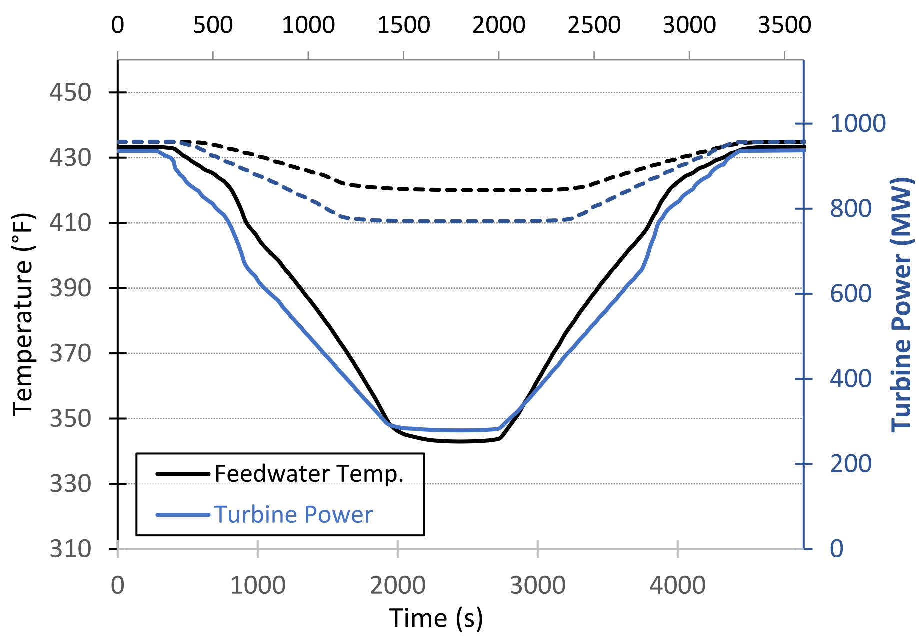

Figure 18. Feedwater temperature and turbine power during the transition to 15% and 50% TPD.

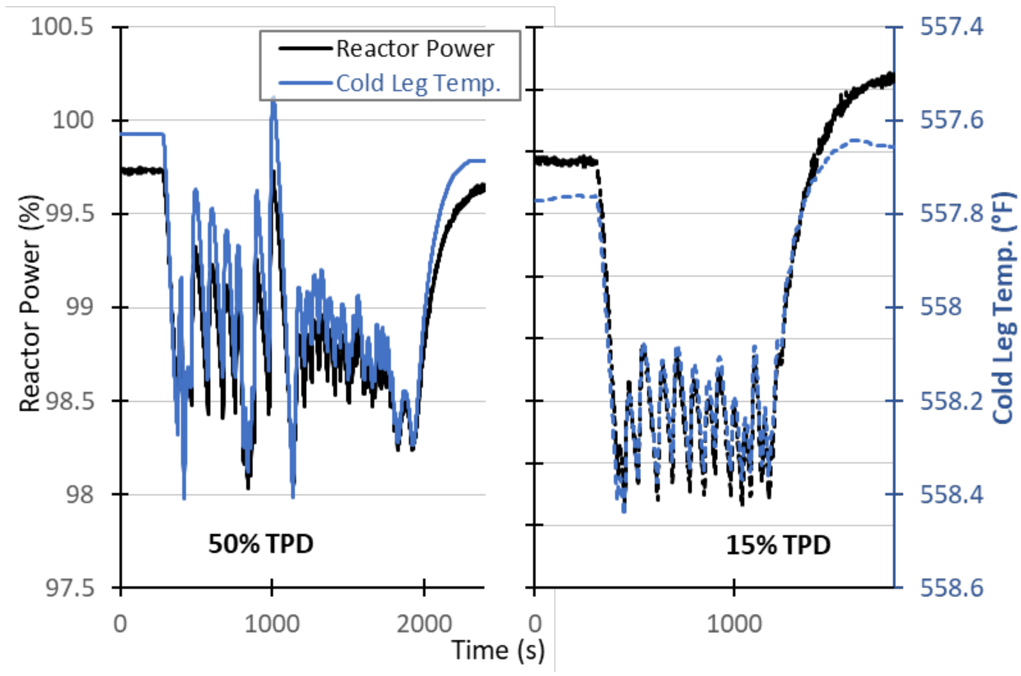

Figure 19. Reactor power and RCS cold leg temperature during the transition to 5% and 50% TPD.

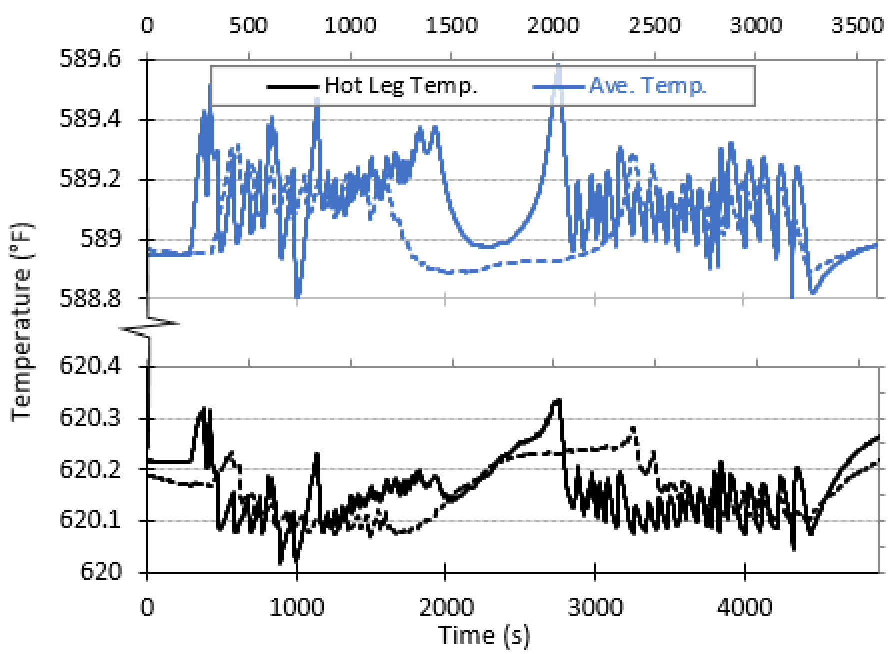

Figure 20. RCS hot leg temperature and RCS average temperature during the transition to 15% and 50% TPD.

In Section 4 it was noted that the relationship between increasing TPD and decreasing turbine power production is super-linear. From Figure 6, it was observed that at 50% TPD, the flow of steam in the turbine system decreased from 3,234 lb/s to 1,163 lbs/s, corresponding to a decrease to only 36% of the turbine system's design steam flow capacity, which is below the range it was designed to operate effectively. Figure 17 shows a similar result for the TPD system that uses steam as the heat delivery fluid. Looking simply at the total loss of steam flow through the turbine system does not fully describe the issue, and it is important to understand that the impact of the decrease in steam flow to the turbines is not equally distributed. One way to visualize the distribution of the steam flow from the turbines is to plot the mass flow of steam extracted from the turbines and sent to the feedwater heaters, as shown in Figure 21. At 0% TPD, the approximate amount of turbine extraction flow to the feedwater heaters is close to 1,000 lb/s with 171 lbs/s going to feedwater heater 1 and 221 lb/s going to Feed Water Heat 5. At 50% TPD, those values decrease to 41 lb/s and 136 lbs/s, respectively, indicating a loss of 76% of the heating capacity to feedwater heater 1 and a loss of 38% of the heating capacity to feedwater heater 5. These unequal changes to the feedwater heater heating capacities indicate the NPP is operating far from its designed operating condition.

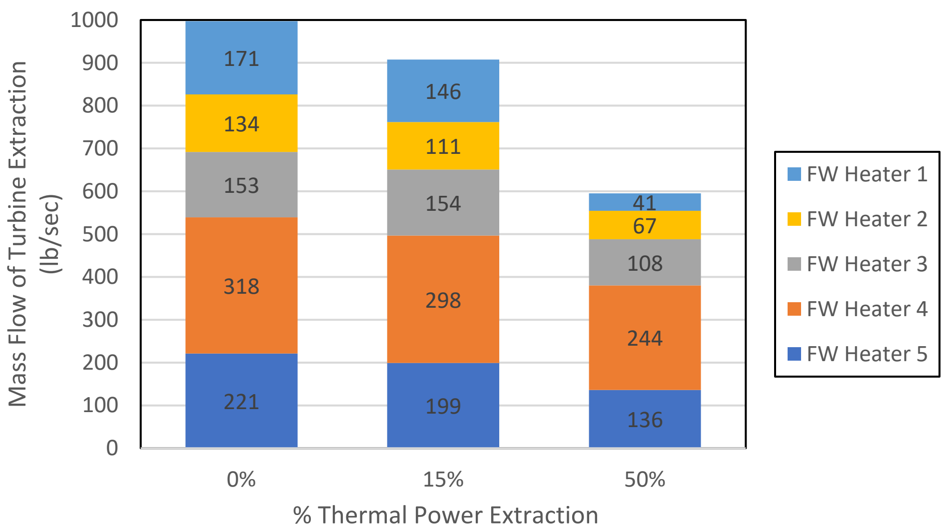

Figure 21. Turbine extraction flow to feedwater heaters for 0%, 15%, and 50% TPD.

Figure 22 shows a distribution breakdown of the thermal power utilization for the Thermal Power Dispatch GPWR (TPD-GPWR) Simulator at full electrical power (0% TPD) as well as 15% and 50% TPD, including the thermal power used for electricity generation, thermal power dispatch, and exhausted to the environment through the condenser. The thermal power dissipated by the condenser decreases with increasing TPD, indicating that utilization of the nuclear thermal power (plant power factor) increases with increasing TPD. In fact, at 50% TPD, the power utilization increases from 968 MW (electric) to 1,819 MW (combined electric and thermal), indicating the plant power factor is nearly doubled. However, electric power is more valuable than thermal power, so effective use of the thermal power is crucial for practical and economic TPD.

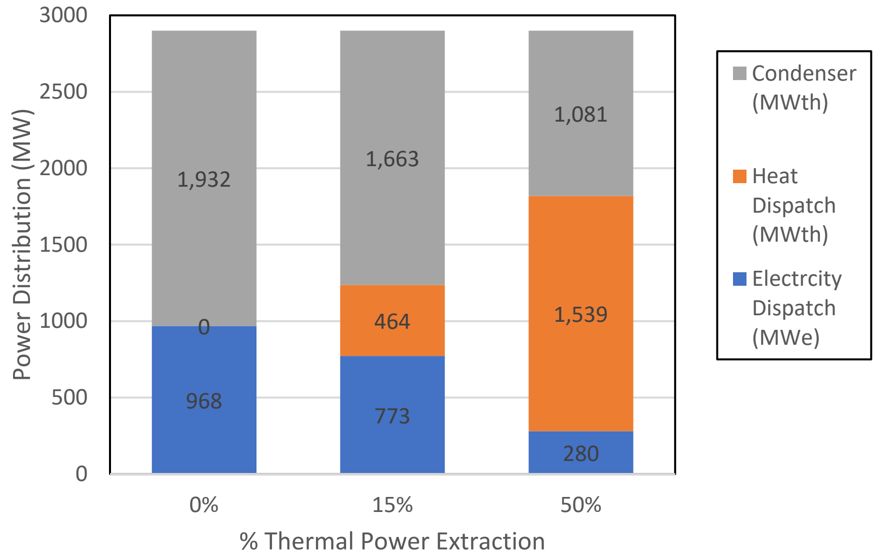

Figure 22. Power utilization breakdown of the TPD-GPWR simulator for 0%, 15%, and 50% TPD.

8. CONCLUSIONS AND RECOMMENDATIONS

This report has described thermal-hydraulic modeling to support the development of a generic full-scope PWR plant simulator that includes thermal and electrical power dispatch, referred to as the Thermal Power Dispatch GPWR (TPD-GPWR) simulator. The TPD-GPWR simulator is based on a generic simulator available from GSE Systems, Inc. (Sykesville, MD, USA). The industrial heat user, in this case, a HTSE plant that produces hydrogen and oxygen from de-ionized water, is not explicitly simulated but is only included as a transient heat sink. A TPD system transfers heat between the secondary system at the NPP and the hydrogen plant. The operational results from four versions of the modified simulator were discussed. Versions #1 and #2 both use synthetic oil as the media to deliver heat to the industrial user approximately one kilometer from the nuclear plant, while Versions #3 and #4 use steam as the heat delivery fluid. Versions #1 and #3 deliver a thermal power that is equal to 15% of the total reactor power, while Versions #2 and #4 deliver 50% of the total reactor power to the industrial user. These versions of the simulator provide a tool to study the feasibility of coupling a PWR to industrial processes that require different levels of thermal and electrical power dispatch. For example, 15% TPD could provide steam for high-efficiency high-temperature hydrogen production, while 50% TPD could provide heat for the production of synthetic fuels. All versions of the TPD-GPWR simulator have sought to keep the design as simple as reasonably possible by extracting steam from the main steam line, removing as much heat as practical from that steam, and then returning the condensate to the condenser.

A capability to include coupled thermal and electric power dispatch has also been enabled by connecting the TPD-GPWR simulator to power system RTDS capabilities at INL. A feasibility study of electrical coupling was performed and summarized in Section 2. Simulated industrial loads less than approximately 60 MWe can be couped to the TPD-GPWR as a house load while still being able to meet the requirement that a single UAT be able to support all auxiliary loads. The electrical connection to industrial loads larger than 60 MWe will need to follow a standard industrial facility connection to the bulk power grid in which the power connection is made on the high voltage side of the GSU transformer to protect the main generator of the NPP from sudden trips at the hydrogen plant or failures of the transmission line. Either situation would be similar to any nearby loss of load, and the impact to the generator would follow normal “generator load rejection” protection schemes and would be evaluated accordingly. As an example, GE generators have load rejection relaying that will trip the main generator on a 40% mismatch between reactor power and generator output. To avoid tripping the main generator due to a sudden loss of load at the hydrogen plant, it is anticipated that the hydrogen plant will be divided into multiple plants that each draw less than 40% of the electric power from the nuclear power plant and that have separate electric connections and transmission lines.

The design of the TPD-GPWR simulator versions that use steam as the heat delivery fluid has been modified from that of prior reports, which employed steam or synthetic oil in closed heat delivery loops. The new design still employs two separate systems to transfer steam between the NPP and the industrial user. The first system, which is an extraction steam line (XSL) removes steam from the main steam line of the NPP and delivers that steam to extraction heat exchangers. The extraction heat exchangers then boil DMW to generate steam that is delivered in a second steam line, denoted "DSL", that transfers the steam to an industrial user approximately one kilometer from the NPP. Key differences between the designs that use steam and oil as the heat delivery fluid are (1) three heat exchangers are used in the design that employs steam as the heat delivery fluid and (2) steam extracted from the nuclear plant is present in the tube side of each of the three heat exchangers. Steam extracted from the main steam line is at a much higher temperature (280 °C) and pressure than the steam that is needed by the hydrogen plant (approximately 10 °C), and consequently is confined in the tubes of the heat exchangers.

The baseline operation of the TPD-GPWR simulator comes with three principal operating TPD modes of the integrated nuclear power/hydrogen production system which are:

A. Cold Shutdown – the XSL and DSL both have zero flow and are at ambient temperature;

B. Hot Standby – the XSL and DSL have minimal flow to maintain hot conditions in both lines and at the hydrogen plant;

C. Thermal power dispatch (TPD) – the XSL and DSL have sufficient flow to provide the desired thermal power to the industrial process.

The transition from Hot Standby to TPD is an important task for this effort because it may be a frequently used procedure and it may involve substantial and rapid changes in thermal power flow while also maintaining the NPP reactor at near full thermal power generation. Simulation results show that this can be accomplished. Some additional work is needed to maintain the automatic control rod system functioning as intended throughout the transition. Supporting steady-state and transient thermal-hydraulic models for TPD using HYSYS and RELAP5-3D were also developed and presented with their simulation results, which serve as a baseline design for implementing the system design into the TPD-GPWR simulator. The design using three separate heat exchangers is effective in delivering superheated steam to the industrial user. The Version #3 of TPD-GPWR simulator that uses steam as the heat delivery fluid will be used in operator studies in July 2021 where the operators will perform changes in the operational state of the simulator as well as selected transient analysis for potential accidents. These studies call for 15% of the thermal power to be extracted from the PWR system for use at a hydrogen plant, which will require approximately 600 lb/sec of main steam to be extracted from the MSH. The electrical power dispatch will include all of the electricity generated by the remaining steam in the PWR.

With the change from oil as the heat delivery fluid to steam, the need for rapid, large changes in liquid flow rate has been eliminated. Since the flow rate of the steam in the DSL is significantly lower than the flow rate of oil at an equivalent amount of TPD, there is more freedom to adjust the fluid flow rate in the DSL as it will not require such a large amount of mass to circulate, which will mitigate thermal inertia challenges in the control system. The new design, however, does increase the magnitude of steam pressure fluctuations in the XSL and DSL as the system transitions from Hot Standby to TPD because the pressure in the DSL in coupled to temperature through the saturation pressure of steam in that line.

This report also details the impacts of keeping the design of the TPD system as simple as reasonably possible by extracting steam from the main steam line, removing as much heat as practical from that steam, and then returning the condensate to the condenser. During normal operation of the GPWR simulator at 100% reactor power, the steam flow in the main steam line is approximately 3,500 lb/s, and steam flow through the turbine generator system is approximately 3,200 lbs/s (some of the generated steam is used for house loads, such as the moisture separator reheater). At 50% TPD, the flow of steam in the main steam line is reduced to approximately 3,100 lbs/s because of energy balance requirements in the NPP steam generator, as shown in Figures 4-1 and 7-1. Steam flow through the turbine generator system is reduced to less than 1,200 lbs/s, which is less than 36% of its design capacity. Turbine systems are not designed to operate effectively at this low steam flow rate.

The design of the TPD system can be optimized to reduce the impact on the NPP operations, especially the turbine generator system, the condenser, and the feedwater heater trains. Steam of sufficient temperature and quality for high-temperature electrolysis can be extracted from the turbine system. For example, the temperature of steam at the hydrogen plant only needs to be approximately 130°C, and steam between 200 and 240°C can be extracted from the HP turbine. Also, condensate from the extraction steam line (XSL) is hotter than condensate in the NPP condenser and could be returned to the feedwater heater train to avoid the waste of enthalpy and support heating the feed water. A simplified diagram of this improved TPD system is shown in Figure 8-1. These improvements will be explored in a future version of the TPD-GPWR simulator.

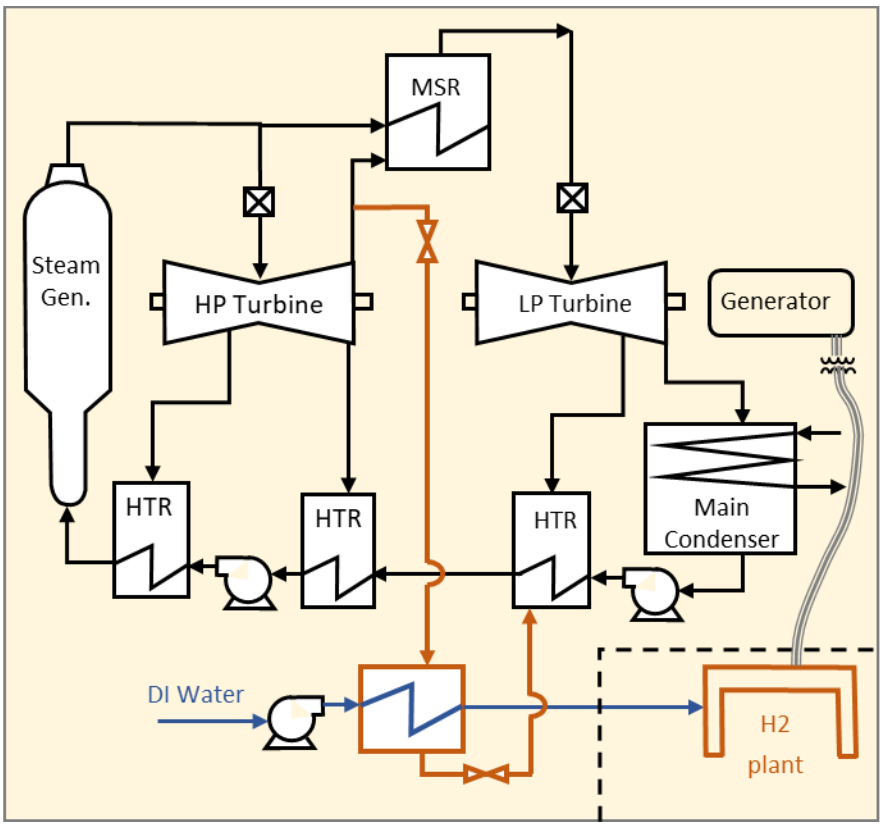

Figure 23. Simplified diagram of the improved TPD from a PWR showing steam extraction from the HP turbine and condensate return to the feedwater heater train.

9. REFERENCES

[1] T. L. Westover, S. Hancock, A. Shigrekar. Monitoring and Control Systems Technical Guidance for LWR Thermal Energy Delivery. INL/EXT-20-57577, February 2020.

[2] S. Hancock, T. L. Westover. LWR Energy Dispatch Technical Feasibility Screening Study and Recommendations. INL/LTD-19-54530, June 2019.

[3] T. Ulrich, R. Lew, T. Mortense, J. Park, H. Medema, R. Boring. An Integrated Energy Systems Prototype Human-System Interface for a Steam Extraction Loop System to Support Joint Electricity-Hydrogen Flexible Operations. INL/EXT-20-57880, September 2020.

[4] K. Vedros, R. Christian, C. Rabiti. Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High Temperature Electrolysis Hydrogen Production Plant. INL/EXT-20-60104, October 2020.

Appendix A

Operating Conditions for the Simulations

Appendix A
Operating Conditions for the Simulations

Operating conditions of streams in base case – 150 MW, 1000 m

Thermal power extraction heat exchanger parameters				Thermal power delivery heat exchanger parameters			
Stream	**Parameter**	**Quantity**	**Units**	**Stream**	**Parameter**	**Quantity**	**Units**
Steam In	Temperature	285.4	C	TPD Loop-HX In	Temperature	259.4	C
	Pressure	6950	kPa		Pressure	195.6	kPa
	Mass Flow Rate	77.11	kg/s		Mass Flow Rate	997.9	kg/s
Steam Out	Temperature	193.3	C	TPD Loop-HX Out	Temperature	176.4	C
	Pressure	6791	kPa		Pressure	57.73	kPa
	Mass Flow Rate	77.11	kg/s		Mass Flow Rate	997.9	kg/s
Oil In	Temperature	176.7	C	From H2 Plant	Temperature	160	C
	Pressure	438.2	kPa		Pressure	617.7	kPa
	Mass Flow Rate	997.9	kg/s		Mass Flow Rate	71.06	kg/s
Oil Out	Temperature	259.4	C	To H2 Plant	Temperature	174.1	C
	Pressure	376.2	kPa		Pressure	517.7	kPa
	Mass Flow Rate	997.9	kg/s		Mass Flow Rate	71.06	kg/s

Operating conditions for 15 MW, 100 m

Thermal power extraction heat exchanger parameters				Thermal power delivery heat exchanger parameters			
Stream	**Parameter**	**Quantity**	**Units**	**Stream**	**Parameter**	**Quantity**	**Units**
Steam In	Temperature	285.4	C	TPD Loop-HX In	Temperature	259.2	C
	Pressure	6950	kPa		Pressure	375.9	kPa
	Mass Flow Rate	7.701	kg/s		Mass Flow Rate	99.9	kg/s
Steam Out	Temperature	193.3	C	TPD Loop-HX Out	Temperature	176.7	C
	Pressure	6791	kPa		Pressure	315.9	kPa
	Mass Flow Rate	7.701	kg/s		Mass Flow Rate	99.9	kg/s
Oil In	Temperature	176.7	C	From H2 Plant	Temperature	160	C
	Pressure	438.2	kPa		Pressure	617.7	kPa
	Mass Flow Rate	99.9	kg/s		Mass Flow Rate	7.074	kg/s
Oil Out	Temperature	259.2	C	To H2 Plant	Temperature	174.1	C
	Pressure	376.1	kPa		Pressure	517.7	kPa
	Mass Flow Rate	99.9	kg/s		Mass Flow Rate	7.074	kg/s

Operating conditions for 200 kW, 100 m

Thermal power extraction heat exchanger parameters				Thermal power delivery heat exchanger parameters			
Stream	**Parameter**	**Quantity**	**Units**	**Stream**	**Parameter**	**Quantity**	**Units**
Steam In	Temperature	285.4	C	*TPD Loop-HX In*	Temperature	255.4	C
	Pressure	6950	kPa		Pressure	376.1	kPa
	Mass Flow Rate	0.103	kg/s		Mass Flow Rate	1.332	kg/s
Steam Out	Temperature	193.3	C	*TPD Loop-HX Out*	Temperature	179.6	C
	Pressure	6791	kPa		Pressure	238.3	kPa
	Mass Flow Rate	0.103	kg/s		Mass Flow Rate	1.332	kg/s
Oil In	Temperature	176.7	C	*From H2 Plant*	Temperature	160	C
	Pressure	438.2	kPa		Pressure	617.7	kPa
	Mass Flow Rate	1.332	kg/s		Mass Flow Rate	8.66E-02	kg/s
Oil Out	Temperature	259.2	C	*To H2 Plant*	Temperature	174.1	C
	Pressure	376.1	kPa		Pressure	517.7	kPa
	Mass Flow Rate	1.332	kg/s		Mass Flow Rate	8.66E-02	kg/s

Appendix B

TPD Requirements, Decisions, and Design

Appendix B
APPENDIX B: TPD Requirements, Decisions, and Design

As noted in Section 1, a thermal power dispatch (TPD) system must be incorporated into the nuclear plant to transfer thermal power from the PWR to the hydrogen plant. The TDP system includes an extraction steam line (XSL) that removes steam from the main steam header, passes this steam through extraction heat exchangers that condense the steam, and then returns the condensate to the NPP condenser. A separate delivery steam loop (DSL) transfers the heat from the extraction heat exchangers to the industrial heat user, which may be located a kilometer or more away. Design requirements for the TDP system are summarized in Table B-1.

Table B-1. Design requirements for the thermal power extraction (TDP) System proposed for a PWR.

#	Design requirement
1	Use of the TDP system or any connection to the hydrogen plant will not impact safety operations at the NPP;
2	The nuclear plant operators must have full control of the steam flow in the TPE Line with prerogative to completely stop steam flow without possibility of interference from the hydrogen plant;
3	During operation of the TDP system, total thermal power must not be exceed 100% reactor power (2900 MWth) due to changing the rate of steam diverted to the TDP system from 0% (0 steam flow) to 5% (2.9·105 kg/hr, 6.5·105 lb/hr steam) of total thermal power;
4	Use of the TDP system must not adversely affect the existing Updated Final Safety Analysis Report (UFSAR) Design Basis Accidents (DBA) analyses (specifically, any effects on the step load decrease transient);
5	The TDP system will be designed to allow switching at least 90% of power delivery from the hydrogen plant to the electric grid in less than 10 minutes, such that the hydrogen plant can act as a dispatchable load. The integrated system shall be capable of cycling power to and from the hydrogen plant at least two times in each 24 hours.

Design decisions that follow from the design requirements include:

1. The TDP system will extract steam from the main steam header (MSH) downstream of the main steam isolation valve (MSIV) so that the extraction point will be outside containment but prior to the turbine throttle and governor valves to provide steam with the highest possible temperature (decision to meet Requirement #1);
2. Isolation flow control valves (FCVs) will be installed in the XSL that will be operable from the main control room to allow NPP operators to immediately stop the flow at any time (decision to meet Requirement #2);
3. Reactor controls will be modified such that the reactor remains between 98 and 100% thermal power while steam flow is increased or decreased in the XSL, preferably without the use of control rods or adjustments to boron concentration in the reactor coolant (decision to meet Requirement #3);
4. Steam flow rate in the XSL is preferred as a control variable because thermal power extraction is directly proportional to steam flow rate (this decision facilitates Requirements #2 and #3);

5. Reactor controls will be modified such that the control rods will not move during normal operations at 100% reactor power (2900 MWth) due to the operation of the TDP system (decision to meet Requirements #1 and #4);
6. Steam in the XSL will be fully condensed to liquid water in the extraction heat exchangers;
7. Condensate from the XSL will be returned to the condenser. Future work will explore returning condensate, which has a temperature of approximately 193°C (380°F), to the feedwater heater system to increase efficiency;
8. A closed-loop DSL is used to transport heat to the hydrogen plant to maintain as much flexibility as possible.