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Incorporation of Thermal Hydraulic Models for Thermal Power Dispatch into a BWR Power Plant Simulator

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Incorporation of Thermal Hydraulic Models for Thermal Power Dispatch into a BWR Power Plant Simulator

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ACRONYMS

BOP	balance of plant
BWR	boiling water reactor
DI	deionized
DHL	delivery heat loop
DOE	Department of Energy
DRTS	digital real time simulator
DSL	delivery steam line
FDR HTR	feed water heater
HP	high pressure
HSI	human/system interface
HSSL	Human System Simulation Laboratory
HTSE	high-temperature steam electrolysis
INL	Idaho National Laboratory
LP	low pressure
LWR	light-water reactor
MOV	motor operated valve
MSR	moisture separator reheater
MSH	min steam header
MSIV	main steam isolation valve
NPP	nuclear power plant
NPS	national pipe standard
PFD	process-flow diagram
PORV	pressure operated relief valve
PWR	pressurized water reactor
P&ID	piping and instrumentation diagram
TBV	turbine bypass valve
TCV	turbine control valve
TPD	thermal power dispatch
U.S.	United States (of America)
XSL	extraction steam line
tpd	tonnes per day

Incorporation of Thermal Hydraulic Models for Thermal Power Dispatch into a BWR Power Plant Simulator

1. INTRODUCTION

1.1 Overview

This report describes the development, modeling, and results of a full-scope generic boiling water reactor (GBWR) power plant simulator that incorporates coupled electrical and thermal power dispatch to an industrial process located approximately one kilometer from the nuclear power plant. The simulator is a commercial BWR simulator that has been modified to include thermal power dispatch (TPD) as described in past milestone reports [1, 2]. The commercial BWR 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 GBWR 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 complement to worked performed earlier this year that focused on the generic PWR (GPWR) simulator [3,4].

The modifications and simulations discussed in this report were performed by GSE Systems, Inc. and the University of Florida under contract with INL. The operational results from two versions of the modified simulator are discussed in this report. As noted in previous work, the heat transport fluid for thermal power dispatch may be either superheated steam or a synthetic oil [4]. The thermal power dispatch (TPD) system extracts heat or steam from the secondary system of the nuclear plant and delivers that thermal power to an industrial user located approximately one kilometer from the nuclear plant. These simulators provide tools to study the feasibility of coupling existing nuclear reactors to industrial processes. The focus of this work is industrial processes that require large amounts of electric power and relatively lower amounts of thermal power, such as high temperature electrolysis (HTE) for hydrogen production. For that application, the ratio of electric power and thermal power that is needed is approximately four to one.

Previous milestones have simulated thermal power dispatch using a full-scope generic pressurized water reactor (GPWR) simulator at levels of 5%, 15%, and 50% thermal power delivery using either oil or steam as the heat transfer medium [3,4]. The thermal power dispatch system design employed in the GBWR by GSE Systems closely follows the steam and oil designs used for 15% thermal power dispatch in the GPWR [3]. The focus of this work will be on the differences in operation of a BWR and how the thermal power dispatch integration and control affects a BWR system compared to a PWR system.

1.2 Design Considerations

Simplified diagrams of the GBWR simulator modified to enable thermal power dispatch (TPD), (hereafter referred to as the TPD-GBWR simulator) are shown in Figure 1. Panel A depicts the overview for the design using synthetic oil as the heat transfer fluid, and Panel B depicts the system design using steam. The industrial heat user, in this case a high temperature electrolysis (HTE) plant that produces hydrogen and oxygen from de-ionized or demineralized water, 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-GBWR 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 the synthetic oil version of the TPD-GBWR (Figure 1, Panel A), a second loop contains the synthetic oil, denoted the delivery heat loop (DHL), which transports the heated oil to the hydrogen plant, where a second set of heat exchangers uses the heated oil to generate steam for hydrogen production. Condensed water from the extraction heat exchangers is returned to the main condenser of the nuclear power plant, as shown in Panel A of Figure 1. For the second design, the extraction steam has the same connection points to the nuclear plant as in the first design with synthetic oil. The key difference is that the extraction heat exchanger uses heat in the extraction steam to boil deionized or demineralized water to make steam to send to the hydrogen production plant, as shown in Panel B of Figure 1.

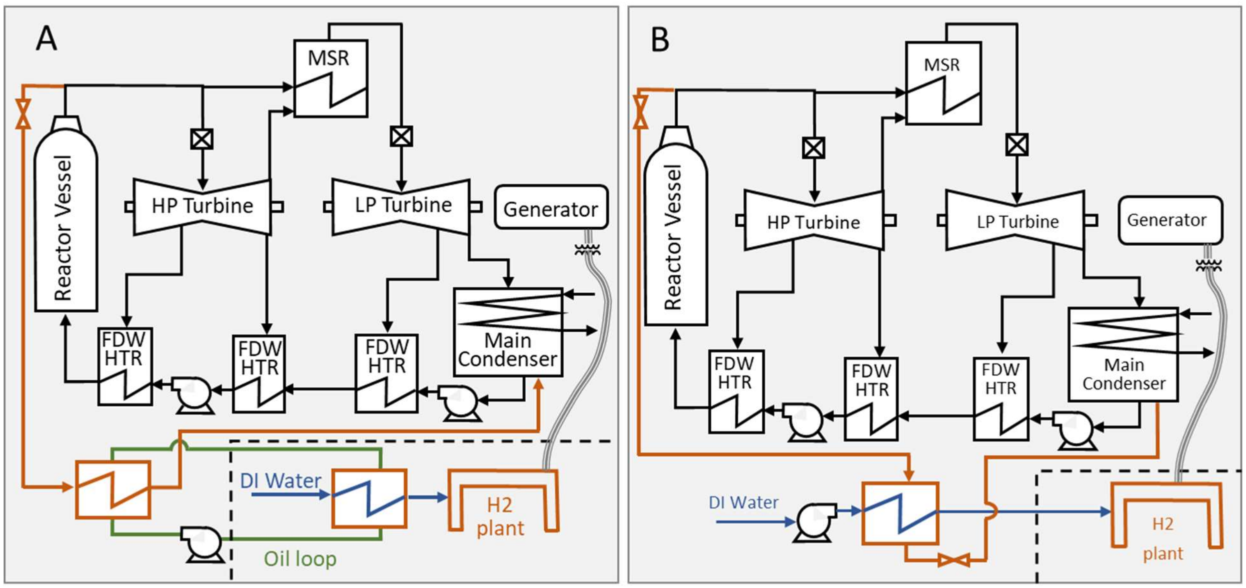

Figure 1. Simplified diagram of the Thermal Power Dispatch GBWR (TPD-GBWR) Simulator. Panel A: configuration for Versions #1 and #2. Panel B: configuration for Versions #3 and #4. The dashed line indicates the boundary of the NPP.

The design requirements ensure multiple purposes are accomplished, including 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 of the BWR is maintained at or near the 100% steady power condition while the steam is maneuvered to allow for thermal and electrical power dispatch to the coupled industrial process.

Table 1 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 1. 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 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 the modifications made for the synthetic oil version of the TPD-GBWR simulator, and Section 3 presents the modifications made for the corresponding steam version. Section 4 discusses the results and discussion from the simulations. Section 5 summarizes the conclusions from the work.

2. THERMAL POWER DISPATCH (TPD) SYSTEM MODELS USING OIL AS THE HEAT TRANSFER FLUID

2.1 Overview

The GBWR simulator is based on hundreds of FORTRAN source code files that invokes various programs used by GSE Systems, Inc [5 5]. These include RELAP5-HD, a modified version of RELAP5-3D for real-time simulation as well as JADE, a GSE owned software for generating thermodynamic and logical flowsheets and source codes. The GBWR is based on a General Electric Type 5 boiling water reactor with Mark II containment. The total steam flow rate is 10.57 MPPH with a 100% turbine power output of approximately 854 MWe.

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

The GBWR simulator works uses a graphical user interface (GUI) with screen drawings that are used to modify the underlying model. Within the GBWR simulator, the tpe1 drawing contains the components the connection between the extraction steam line (XSL) and the main steam line. Figure 2 shows the new tpe1 drawing in the oil version of the TPD-GBWR. The entire reactor and turbine system is modeled using RELAP5-HD in the GBWR, so this tpe1 drawing is added using JADE to interface with the RELAP model of the primary system. This design is based on the design used for the TPD-GPWR with necessary modifications to match the differences in operating parameters. This model has two heat exchangers which are connected to the delivery heat loop (DHL). The first heat exchanger is a condenser for the steam, and the second heat exchanger is a subcooling heat exchanger that increases enthalpy that can be removed from the reactor side of the heat transfer system. Pressure reliefs and high-level drains needed for the initial analysis are included in the drawing and model.

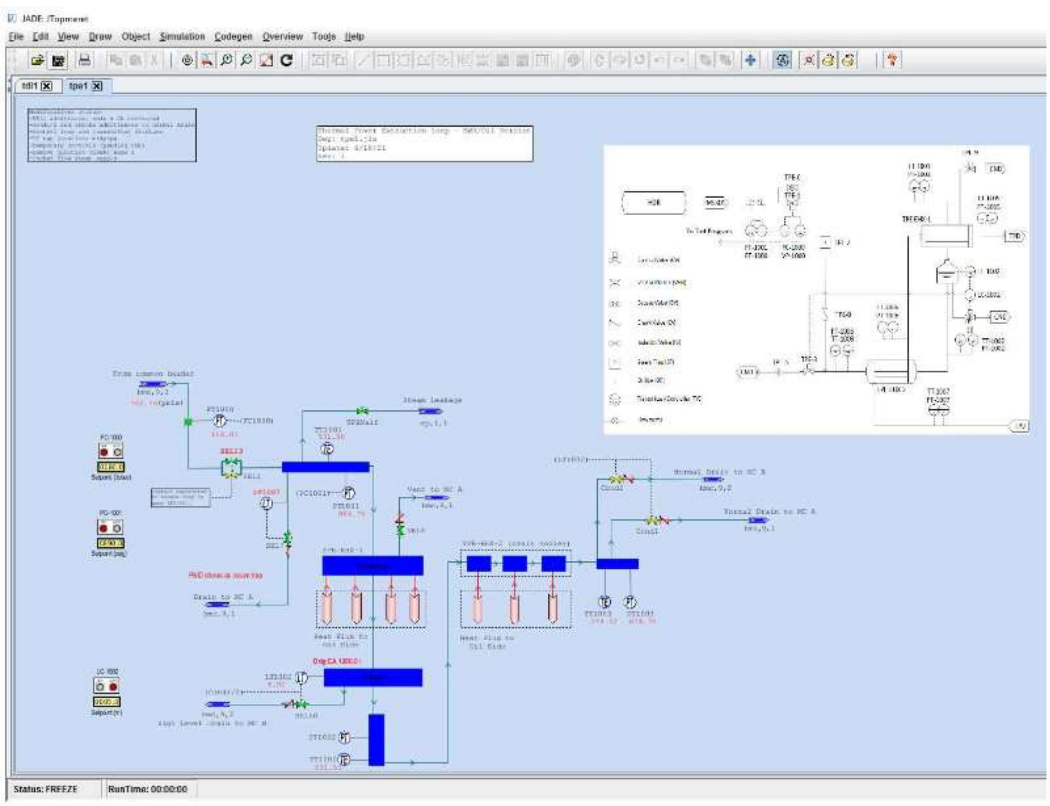

Figure 2. Screenshot of the extraction steam line (XSL) components included in the tpe1 drawing of the TPD-GBWR.

The steam flow rate is controlled by a new pressure controller, which assists in maintaining a stable pressure in the main steam header. This is different than the current version of the TPD-GPWR, which uses a flow controller in the XSL. In BWR operation, the reactor power is changed by increasing or decreasing the flow of water through the BWR core. The feedwater is boiled in the reactor pressure vessel and directed to the main steam header. The reactor (steam) pressure is controlled by the steam turbine which modulates governor valves to maintain constant reactor pressure. In this design, turbine power follows reactor power, which is different from a PWR in which the reactor power follows the turbine power. Therefore, controlling the TPD system for a BWR requires a different approach than for a PWR. Since BWR reactors are maintained by holding the steam pressure constant, it makes sense to control flow in the XSL to maintain steam pressure in the main steam line and reactor pressure vessel. These controls must be modulated because simply opening the steam extraction valve to the XSL system could cause the turbine system to automatically respond and decrease turbine power.

Figure 3 shows the piping system model for the delivery heat loop (DHL) in JTopmeret™ for the oil version of the TPD-GBWR. This version of the DHL is 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. This is based on the previous version of the TPD-GPWR [3]. This approach does 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 thermal power dispatch power changes; however, it provides a preliminary look at the transient effects that the TPD system has on the BWR plant. 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.

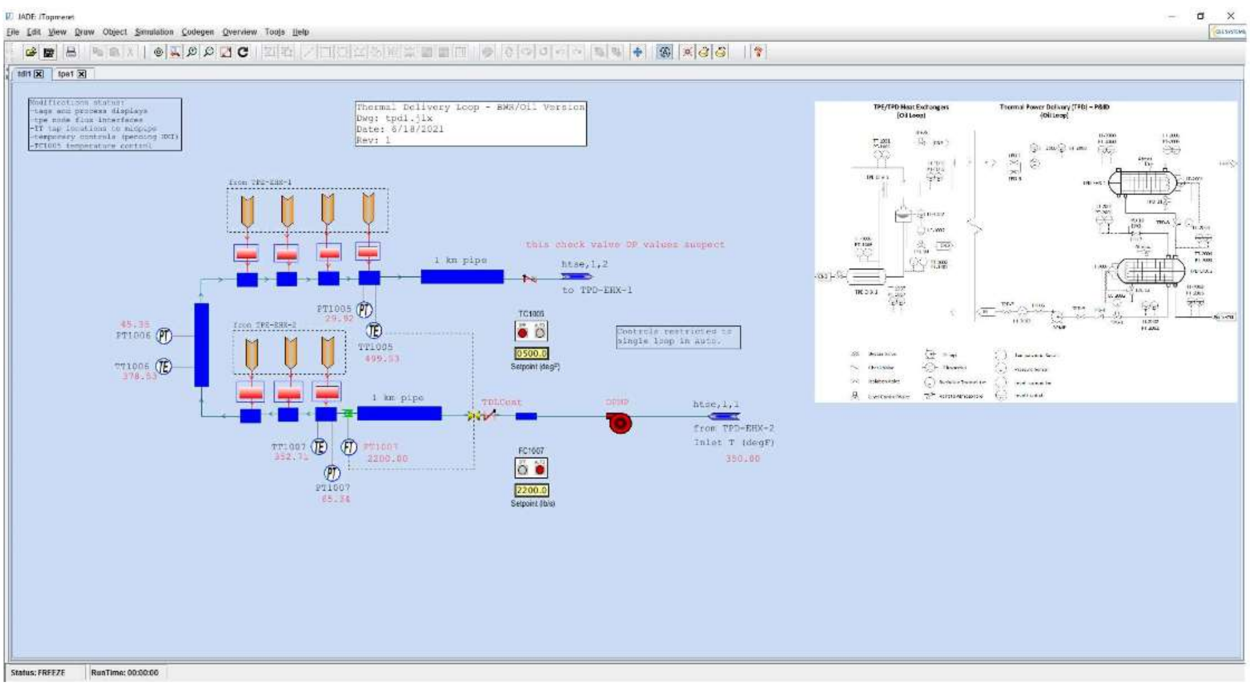

Figure 3. Screenshot of the delivery heat loop (DHL) piping system drawing of the TPD-GBWR simulator that uses oil as the heat transfer fluid.

The DHL contains two options for flow control, a flow controller and a temperature controller. This approach matches that of the current version of the TPD-GPWR in which the oil flow rate is controlled to maintain a set temperature as the steam extraction flow rate increases. This control scheme eliminates potential pressure instability issues in the extraction steam loop (XSL) and main steam line. When the TPD system is not operating but is expected to operate in the near future, it is beneficial to keep the lines heated and partially pressurized. This condition is referred to as Hot Standby mode, and in this mode, the steam pressure is significantly lower in the XSL than in the main steam line because the low heat transfer across the extraction heat exchangers lowers the thermal equilibrium of the steam. During the transition to full TPD, the pressure in the delivery heat loop (DHL) decreases dramatically if the oil flow rate is not controlled to ramp with the steam extraction flow rate. The pressure slowly recovers as the heat transfer stabilizes during the transition. 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. Sudden depressurization of the DHL system during power transitions is avoided by using the temperature after the first heat exchanger as the control variable for the oil flow rate. This approach improves the control scheme allowing the pressure to be maintained at a relatively high level during transitions from Hot Standby to TPD operating mode.

3. THERMAL POWER DISPATCH (TPD) SYSTEM MODELS WITH STEAM DELIVERY

Figure 4 shows the new tpe3 drawing added to the TPD-GBWR version that has a delivery steam line (DSL). Both systems are included in a single drawing because the main fluid is water in both systems. This model interfaces with the GBWR in the same way as the version that uses synthetic oil as the heat transfer medium in a delivery heat loop (DHL). The design is based on the TPD-GPWR with necessary modifications to match the differences in operating parameters. The design basis for the steam-to-steam heat transfer system in a PWR is discussed in a previous report [3]. Three separate heat exchangers, including a preheater, a reboiler, and a superheater, are used to generate steam from demineralized water for hydrogen production. The main difference in this work compared the TPD-GPWR is the design of the reboiler. In this model, a natural circulation thermosyphon reboiler is used, while a kettle type reboiler is used in the TPD-GPWR [3]. Pressure relief valves and high-level drains needed are included in the drawing and model.

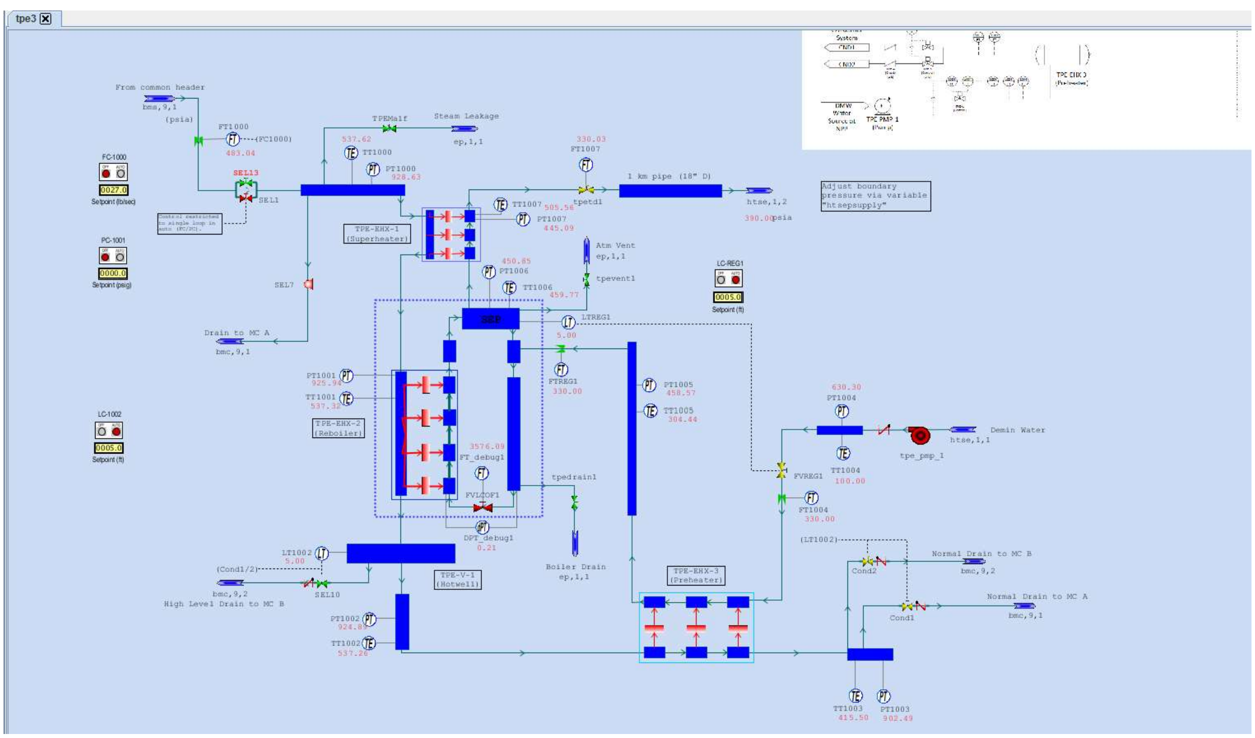

Figure 4. Screenshot of the extraction steam line (XSL) and delivery steam line (DSL) components included in the tpe3 drawing of GBWR.

The version of the TPD-GBWR with a steam delivery line (DHL) has the same pressure-based steam flow control in the XSL as the version that uses synthetic oil as the heat transfer medium. Flow of demineralized water and steam to the hydrogen production plant is controlled by a level controller in the reboiler separator, which is consistent with the control scheme used in the TPD-GPWR [3].

4. THERMAL POWER DISPATCH (TPD) SIMULATIONS

This section explains the operating and transition modes for the TPD-GBWR simulator that employs synthetic oil as the heat delivery fluid. The primary operating thermal power dispatch 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 Thermal Power Dispatch (TPD) operating modes 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 power requirement to maintain the TPD in Hot Standby mode is expected to be less than 3% of the maximum TPD amount, so infrequent transition from Cold Shutdown (0% TPD) to Hot Standby operating mode does not represent a significant challenge to NPP operations.

Initial conditions are established in the simulator that correspond to each primary operating mode, so that test procedures involve transitioning from one operating mode to another to understand how both the operator and the plant respond to the operational changes. Each operating mode refers to 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 Simulator Results for Transitioning between Hot Standby and Thermal Power Dispatch Using Oil as the Heat Transfer Fluid

Simulations were performed for Thermal Power Dispatch (TPD) up to 15% of the maximum rated reactor power using the oil version of the TPD-GBWR at a ramp rate of 10 lbs/s. Results from benchmark RELAP5-3D simulations have been presented in a prior report [3] and are not repeated here. Figure 5 shows the flow in the main steam line, the steam flow to turbine, the steam flow to XSL, and the turbine electric power for the transition from Hot Standby to TPD and back to Hot Standby mode. The trends in the steam flow rates behave as expected. As steam flow increases in the XSL, flow through the turbine and feedwater heater systems decrease, which causes the feedwater temperature entering the reactor to decrease. At constant flow rate, the reactor power in a BWR increases as the feedwater temperature decreases because the lower reactor void fraction increases neutron moderation. As Figure 6 shows, as flow in the XSL increases, feedwater temperature decreases from 423 °F to 409 °F, and the reactor power increases from 100% to nearly 102%. The decrease in reactor void, main steam pressure and reactor dome pressure are all shown in Figure 7.

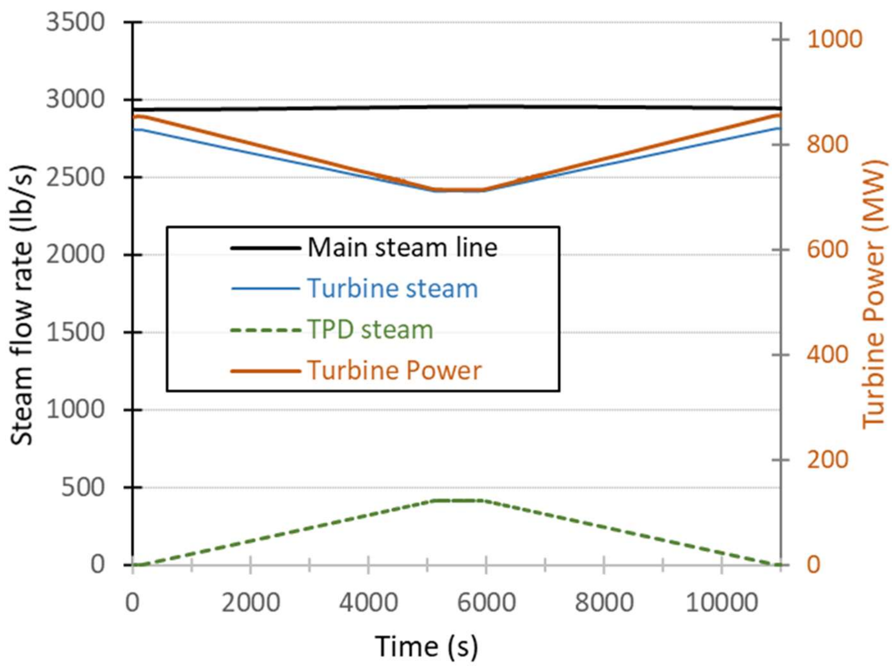

Figure 5. Steam flow rates and turbine electric power for the transition to 15% TPD using oil as the heat transfer fluid.

Maintaining the reactor power constant at 100% of rated power output while increasing flow in the XSL would require decreasing the feed water flow, which would further decrease the turbine power production. It is important to note that as steam flow in the XSL increases, the percent decrease in turbine power generation is slightly stronger than the percent decrease in steam flow in the turbine system, so the efficiency of the turbine system is slightly derated during TPD operation. A similar decrease in plant efficiency with increasing thermal power dispatch was also observed in the TPD-GPWR simulator [3], although a direct comparison is difficult because in simulations that were performed recently using the TPD-GPWR simulator, the main steam flow rate decreased as steam flow increased in the XSL. For there to be a direct comparison between the impacts of TPD on BWR and PWR plant operations, it will be necessary to decrease the steam flow in the BWR as steam flow increases in the XSL to maintain the reactor at 100% thermal power. Such a simulation could be the focus of future simulations.

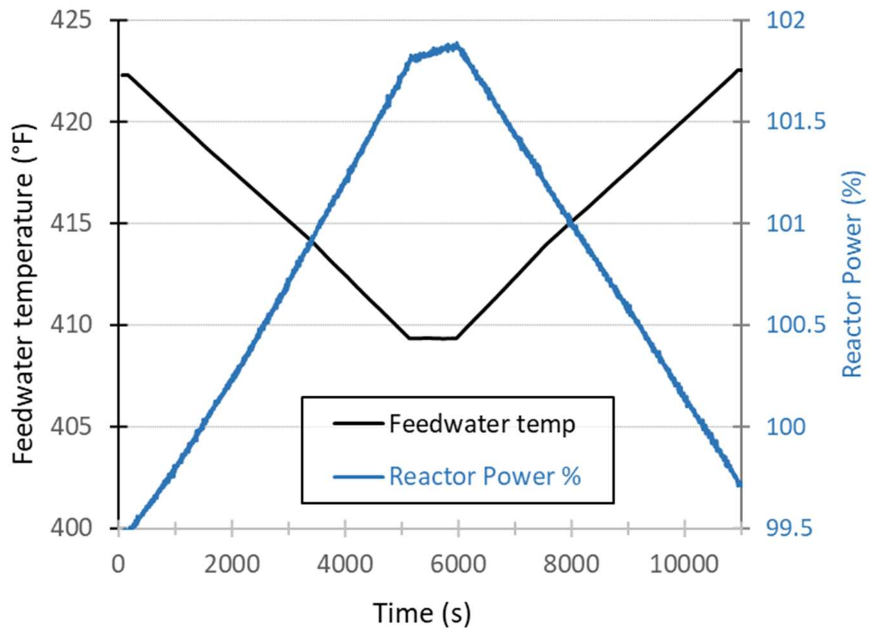

Figure 6. Feed water temperature and reactor power during the transition to 15% TPD using oil as the heat transfer fluid.

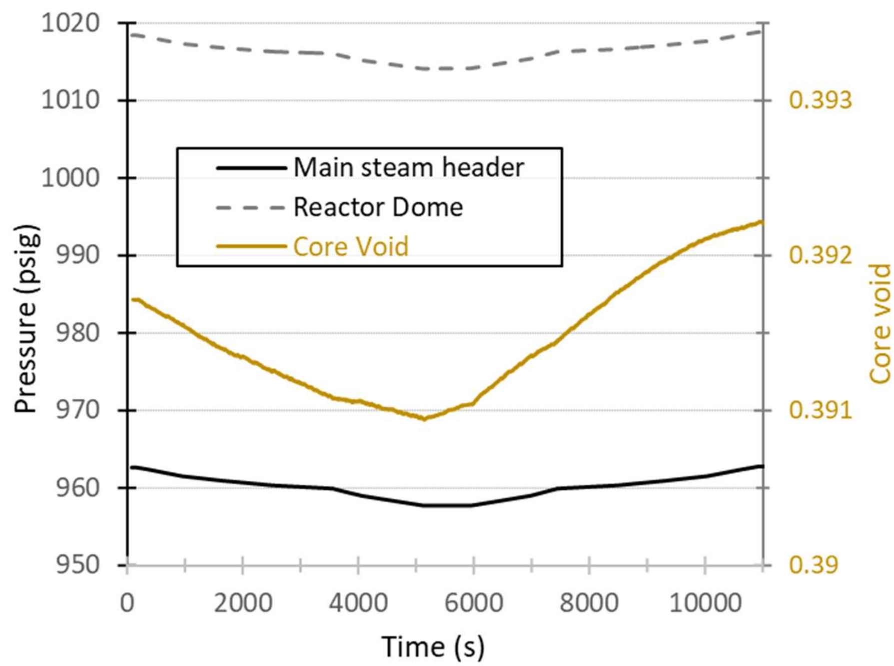

Figure 7. Reactor core void fraction and the reactor and steam header pressures during the transition to 15% TPD using oil as the heat transfer fluid.

There are multiple options that can be pursued to mitigate the effects of TPD on BWR and PWR operations. The most promising option is to mitigate the decrease in feedwater temperature that causes the reactor power to increase. One way to do that would be 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 thermal power dispatch (TPD) above 15%. Another option is to extract steam from the high pressure or low pressure 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 the decrease in turbine performance or lifetime.

4.2 Simulator Results for Transitioning between Hot Standby and Thermal Power Dispatch with Steam Delivery

Simulations were also performed for Thermal Power Dispatch (TPD) up to 15% of the maximum rated reactor power using the steam version of the TPD-GBWR. Results from benchmark RELAP5-3D simulations have been presented in a prior report [4]. The operating and tests modes established for the TPD-GBWR simulator with a delivery steam line (DSL) are the same as for the simulator with an oil delivery heat loop (DHL) and include Cold Shutdown, Hot Standby, and Thermal Power Dispatch (TPD). Figure 8 shows the flow in the main steam line, the steam flow to turbine, the steam flow to XSL, and the turbine electric power for the transition from Hot Standby to TPD and back to Hot Standby operating mode. The results are nearly identical to those obtained using the oil version of the TPD-GBWR simulator. The nearly identical results are expected because both system designs operate in similar ways with similar impacts on the BWR system. Similarly, at TPD increases, the feedwater temperature decreases resulting in a reactor power increase as shown in Figure 9. Notably, in the steam version of the TPD-GBWR, the reactor void fraction behaves more steadily with a more defined steady state achieved during TPD operations than for the TPD system that uses oil as a heat transfer fluid. This can be seen by comparing Figures 7 and 10. Because steady state is achieved more easily using steam as the heat transfer media, the simulations using the delivery steam line employed a ramp rate of 20 lbs/s, which is two times faster than the ramp rate for the simulations that usee oil as the heat transfer media.

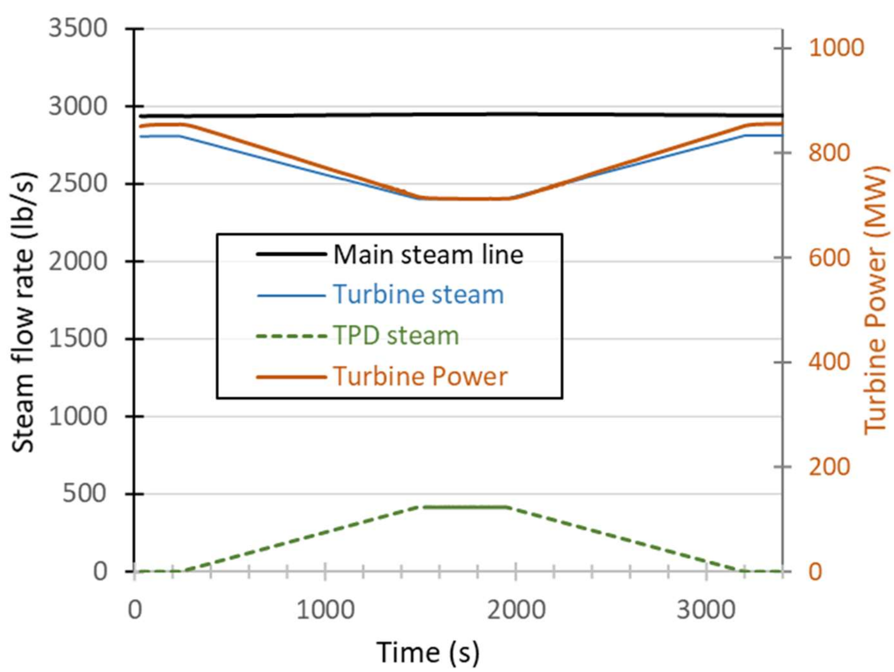

Figure 8. Steam flow rates and turbine power for the transition to 15% TPD with steam delivery.

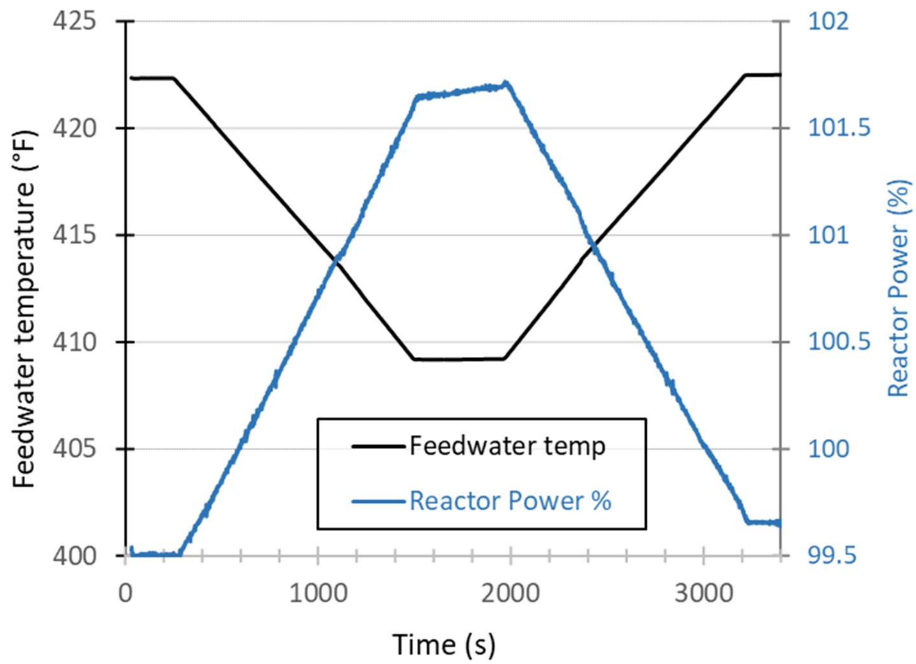

Figure 9. Feedwater temperature and reactor power for the transition to 15% TPD with steam delivery.

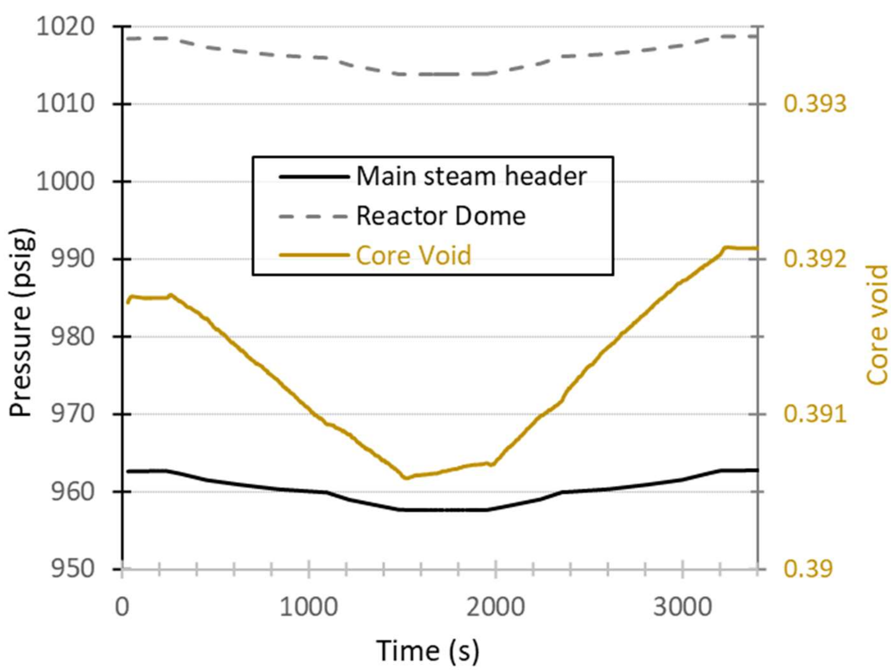

Figure 10. Reactor core void fraction and the reactor and steam header pressures during the transition to 15% TPD with steam delivery.

5. CONCLUSIONS AND RECOMMENDATIONS

This report has described thermal-hydraulic modeling to support development of a generic full-scope BWR plant simulator that includes thermal power dispatch, referred to as the Thermal Power Dispatch

GBWR (TPD-GBWR) simulator. The TPD-GBWR 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 electrolysis (HTE) 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 steam systems at the BWR and the hydrogen plant. Operational results from two versions of the modified simulator have been presented. The first version uses synthetic oil as the heat transfer fluid in a closed delivery heat loop (DHL) that generates steam at the hydrogen plant. The second version uses steam as the heat transfer fluid in a delivery steam line (DSL) to provide steam to the hydrogen plant. For both versions, the estimated thermal power delivery distance is approximately one kilometer. The amount of thermal power dispatched in the simulators is 15% of the total reactor thermal power such that the simulators provide a tool to study the feasibility of coupling a BWR to industrial processes that benefit from a combination electrical and thermal power dispatch.

The baseline operation of the TPD-GBWR simulators has three basic operating modes:

A. Cold Shutdown – the TPD systems have zero flow and are at ambient temperature;

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

C. Thermal power dispatch (TPD) – the TPD systems are operating to provide the desired thermal power to the coupled 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 dispatch while also maintaining the BWR at near full thermal power operation. Simulations results show that this can be readily accomplished, although additional work is needed in order to adjust the flow rate of the coolant in the reactor core to prevent overpowering the reactor during the transition. The designs of the system that use synthetic oil and steam as the heat transfer fluid have been modeled using various modeling software tools, including RELAP5-3D, and have been discussed in previous reports. The designs implemented in the TPD-GBWR are consistent with designs implemented and discussed in the TPD-GPWR for PWR simulation.

The worked performed for this milestone was performed by GSE Systems Inc. and the University of Florida under contract with INL. The GBWR simulator and its modifications have been delivered to INL per the deliverables of the work contract. All deliverables of the work contract have been met. Work will continue on the TPD-GBWR in conjunction with continuing work on the TPD-GPWR to improve the system designs and incorporate improved control and safety systems as well as additional systems to prevent any impact that TPD operation could have on the nuclear power plant.

6. ACKNOWLEDGEMENTS

We acknowledge GSE Systems for the support and work provided on the GBWR with the assistance of the University of Florida.

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