INL/RPT-23-74666
Revision 0

## Light Water Reactor Sustainability Program

# Impacts of Extracting 30% of Reactor Power from a Pressurized Water Reactor

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# Impacts of Extracting 30% of Reactor Power from a Pressurized Water Reactor

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# SUMMARY

This report summarizes key impacts of 30% thermal power extraction on a generic Westinghouse 4-loop PWR. Full details of the PEPSE modeling and impacts, including plant transients, hazards, and core reactivity impacts can be found in [1]. Reactor response to load rejection or other transient events would need to be assessed for acceptability through further core and plant response analysis.

High-pressure/low-pressure turbine and moisture separator reheater performance is very similar to the performance under a 75% power case; this operating profile is expected to be maintainable for long durations.

Condenser operating conditions are expected to continue to meet operation requirements while evacuation capacity will not be impacted.

There are minimal impacts on the power train pumps and replacement is not anticipated.

It is not expected that feedwater heater tube degradation or nozzle wear will be an issue. Heater shell wear patterns could be affected, resulting in increased degradation. Tube side pressure drop for the thermal extraction case is not expected to appreciably impact reliable operation of the heaters. Drain inlet mass fluxes remain bounded by industry guidance. However, mass flux parameters for specific heaters were shown to exceed guidelines and could result in increased wear rates. Operating temperatures and pressures decreased for all feedwater heaters (FWHs), increasing design margin. Volumetric flow through all drain coolers is also expected to decrease, resulting in increased margin for tube vibration parameters.

Analysis of the extraction steam (ES) system shows that overall, ES line pressure drops increase due to higher flow velocities. The increased flow velocities should be included in the individual station Flow Accelerated Corrosion program to ensure that any potential degradation is properly monitored and addressed. Expansion joint liner thickness requirements also increased. Replacement of expansion joints may be needed to ensure requirements are met with thermal extraction conditions. As a result of pressures and temperatures mostly decreasing with thermal extraction, operating condition margins largely improved for valves and expansion joints in the ES system.

Heater drain tanks are expected to operate normally. FWH drain control valves (DCVs) will require greater flow passing capability. Therefore, station specific review is required. It is expected that station specific review will find replacement of the FWH 2 and 3 DCVs necessary due to significant increase in required valve CV when operating with 30% thermal extraction.

The conclusions above establish that 30% thermal extraction can be performed safely without major plant equipment replacement. Minor upgrades and increased maintenance may be required for specific plant components (e.g., expansion joints and DCVs).

The results described herein are based on a generic reference plant and PEPSE model. Plant-specific evaluation of core/plant response and equipment would be required for any station considering a modification of this type. The results of a site-specific evaluation may differ from this generic PEPSE model analysis and equipment assessment based on plant/equipment design, operation, and age.

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# ACRONYMS

| | |
|---|---|
| BEA | Battelle Energy Alliance, LLC |
| DCV | drain control valve |
| DOE | Department of Energy |
| ES | extraction steam |
| FWH | feedwater heater |
| HEI | Heat Exchange Institute |
| HPT | high-pressure turbines |
| HX | heat exchanger |
| INL | Idaho National Laboratory |
| LPT | low-pressure turbines |
| MS | main steam |
| MSDT | moisture separator drain tank |
| MSR | moisture separator reheater |
| PEPSE | Performance Evaluation of Power System Efficiencies |
| PWR | pressurized water reactor |
| RTDS | real-time digital simulator |
| VWO | Valves Wide Open |

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# Impacts of Extracting 30% of Reactor Power from a Pressurized Water Reactor

## 1. INTRODUCTION

The United States and countries around the world are seeking to reduce dependence on fossil fuels to achieve climate goals and ensure national energy security. Nuclear power has significant near-term potential to support these objectives by transitioning to flexible plant operation and generation. In this paradigm, during times when renewable generation can meet grid demand, nuclear facilities can flexibly dispatch thermal power (heat) to assist in decarbonizing industry and transportation. As part of the Department of Energy's (DOE's) effort in researching thermal power dispatch systems and related flexible plant operations, a plan was made to develop a conceptual design for extracting 30% of the reactor power from a pressurized water reactor (PWR) and publish that design in a milestone report prepared by Idaho National Laboratory (INL). A second thrust of that effort was to evaluate the impacts of extracting 30% of the reactor power on the overall efficiency of the PWR, as well as impacts on the feedwater heater temperature and corresponding turbine performance. As the work progressed, it became apparent that both objectives could be accomplished with a single report. A report documenting both the thermal power dispatch design and its impacts on a 4-loop Westinghouse PWR was prepared by Sargent and Lundy (Chicago, Illinois) and submitted to the DOE's Light Water Reactor Sustainability program in June 2023 as SL-017758 "Heat Balance Model Analysis and Equipment Assessment for 30% Thermal Extraction from a Nuclear Power Plant" [1].

This report summarizes key impacts on PWR performance from that report to fulfill project planning requirements. The full details of the design and operating impacts can be found in Fidlow et al.'s 2023 report [1].

## 2. MODEL DESIGN

### 2.1 Reference Plant

The reference plant modeled for this report is based on 4-loop Westinghouse PWR design. In a PWR, high-pressure water passes through the reactor core, where it is heated by thermal energy created by nuclear fission. This primary water flows through a steam generator, where it boils feedwater in the secondary plant cycle to create steam. This steam then drives a series of turbines that rotate, generating electricity in the process. This secondary steam is separated from primary loop coolant by the steam generator; therefore, it is not radioactive. As a large portion of the U.S. commercial nuclear power plant fleet were designed as Westinghouse 4-loop PWRs, this design was selected to be applicable to the greatest number of existing nuclear plants.

The reactor modeled in this report has a thermal power rating of 3,650 MWt, with a plant generating capacity of approximately 1,225 MWe. Additional details regarding the selected Westinghouse 4-loop PWR can be found in Westover et al.'s 2023 report [2]. A thermal extraction case of 30% (~1,095 MWt) thermal extraction was considered in this report with respect to a baseline case with no thermal extraction.

### 2.2 Affected Equipment

This report is primarily focused on the impacts of large-volume thermal extraction on the plant secondary cycle. Equipment is assessed to determine which specific components will require additional maintenance or replacement for 30% thermal extraction. The equipment that was assessed includes:

- High-pressure turbines (HPTs)
- Low-pressure turbines (LPTs)

- Condensers
- Pumps
- Moisture separator reheaters (MSRs)
- Feedwater heaters (FWHs)
- Extraction steam
- Feedwater heater drains
- MSR drains.

The assessment identified the limiting equipment issues for a typical PWR to be the nozzle velocities in the FWHs and the pressure drop in the FWH drain control valves (DCVs). This report focuses primarily on those issues. The full details of the assessment can be found in Fidlow et al.'s 2023 report [1].

## 2.3 Thermal Power Extraction

Previous work has assessed the impacts of steam extraction up to 105 MWt (~3%) on the nuclear plant [2]. At this comparatively small volume of extraction, cold reheat (downstream of the high-pressure turbine) was deemed optimal from a nuclear plant efficiency standpoint. However, as higher steam volumes are extracted from the cold reheat, turbine shaft imbalance, blade loading, and thrust may cause the turbines to deviate from intended design. Therefore, cold reheat steam extraction is not recommended for higher power levels and not evaluated in this report. Additionally, higher quality and pressure of the main steam enables lower extraction volumes for the same thermal power, as well as smaller piping. As a result of these factors, the preferred location for 30% steam extraction is main steam (as opposed to cold reheat), upstream of the high-pressure turbine. Main Steam extraction is shown in Figure 1.

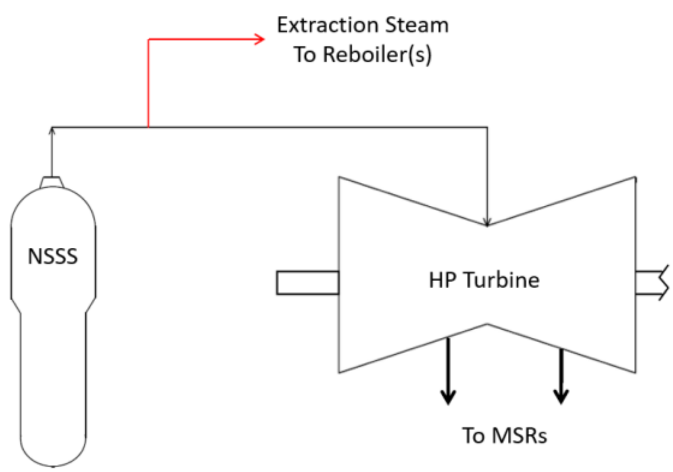


Figure 1. Main steam extraction.

Following extraction, this steam would pass through a heat exchanger(s) in the Protected Area, where it would boil demineralized feedwater that would be sent outside the plant boundary. The plant steam would condense in the heat exchanger before returning to the main condenser. Process steam would be piped to the desired use case. This could include hydrogen production (via high-temperature steam electrolysis), thermal storage, and district heating, among other applications. The supply and return locations of nuclear steam/condensate is illustrated in Figure 2.

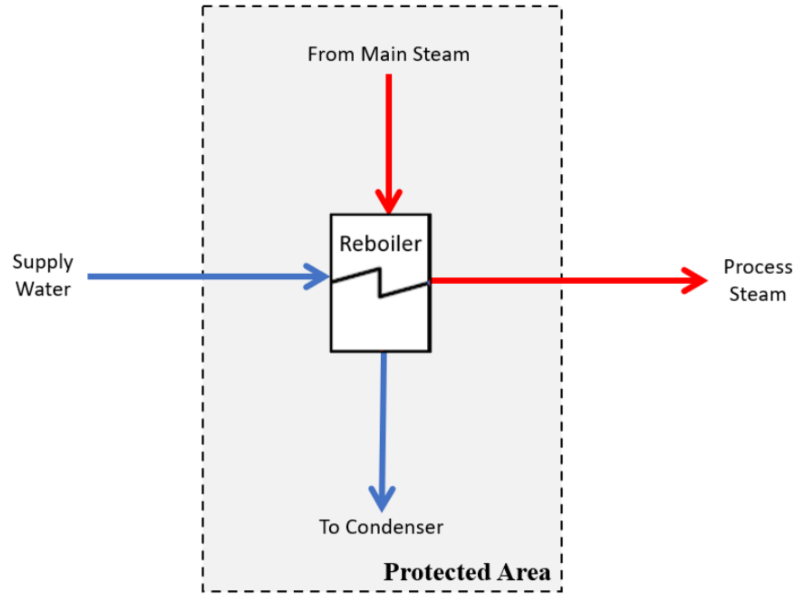


Figure 2. Working fluid supply and return locations.

## 2.4 PEPSE Heat Balance Model

A generic Performance Evaluation of Power System Efficiencies (PEPSE) heat balance model of the reference plant is used as the starting point of this evaluation [3]. This model is modified through the addition of splitters, mixers, and stream components to assess the impacts of 30% thermal extraction on the nuclear power cycle main steam system. A heat exchanger component is used to model the steam reboiler thermal performance. The extracted steam is condensed and subcooled before it is returned to the power cycle. A pump component is used to model system pressure increase from a demineralized water supply tank to the reboiler. The amount of thermal energy extracted is calculated within PEPSE using operational variables. The amount of thermal energy extracted is controlled by changing the flow fraction out of the main steam splitter supplying the reboiler.

The PEPSE model is based on the following assumptions:

1. The temperature of the condensed and subcooled extraction steam is assumed to be 120°F before it is returned to condenser
2. The discharge pressure for the water supply pump is assumed to be 650 psia
3. The heat exchanger pressure drop is assumed to be 50 psid
4. Pressure and temperature losses to the environment are included in the new associated steam components based on the assumed inputs in Table 1.

Table 1. PEPSE model input assumptions.

| Description | Units | 30% Extraction |
|---|---|---|
| Main steam extraction differential pressure (DP) | Pounds/in.$^2$ differential (psid) | 80 |
| Main steam extraction heat loss | British thermal units/hour (BTU/hr) | 210,000 |
| Process steam extraction DP | psid | 100 |
| Process steam extraction heat loss | BTU/ht | 2,230,000 |

# 3. 30% REACTOR POWER EXTRACTION RESULTS

## 3.1 Thermal Analysis

The full analysis results are in Fidlow et al.'s 2023 report [1]. This report summarizes general impacts on the plant and specific impacts to the FWHs, which are expected to be the limiting equipment. PEPSE computer program was utilized to determine the performance of the entire turbine cycle including prediction of the gross generator output. Modifying the generic PEPSE model, plant impact was assessed for 30% thermal extraction, as shown in Table 2. The PEPSE diagrams are provided in Fidlow et al.'s 2023 report [1] and a summary diagram is included in the Appendix A of this report. Important changes to note are the 25–30% changes in the flows and pressure drops through the turbines and the 27.6°F decrease in the final FWH temperature.

Table 2. General impacts for 30% reactor thermal power extraction.

| Description | Units | 0% Extraction | 30% Extraction | Difference |
|---|---|---|---|---|
| Generator electric power | Mwe | 1,228.0 | 844.6 | -31.2% |
| Thermal power extracted | MWt | 0 | 1,095 | — |
| % of main steam (MS) flow | % | 0 | 21.9 | — |
| MS flow from steam generator | lbm/hr | 16,037,390 | 15,436,290 | -4% |
| HPT inlet flow | lbm/hr | 15,218,400 | 11,272,260 | -26% |
| HPT 1st stage pressure | psia | 651.5 | 487.5 | -25% |
| Moisture separate reheater (MSR) inlet pressure | psia | 190.3 | 140.2 | -26% |
| LPT inlet flow | lbm/hr | 3,673,069 | 2,677,248 | -27% |
| LPT inlet pressure | psia | 175.5 | 129.3 | -26% |
| Condenser duty | BTU/hr | 8.21E+09 | 5.78E+09 | -30% |
| Condensate pump flow | lbm/hr | 11,334,490 | 11,723,820 | 3% |
| Heater drain pump flow | lbm/hr | 4,732,792 | 3,742,365 | -21% |
| FWH pump flow | lbm/hr | 16,067,280 | 15,466,190 | -4% |
| Final FWH temperature | °F | 440.9 | 413.3 | -27.6 |
| Cascading drain flow to condenser | lbm/hr | 817,619 | 745,815 | -9% |
| Cogen heat exchanger (HX) inlet mass flow | lbm/hr | — | 3,376,114 | — |
| Cogen HX inlet pressure | psia | — | 817,3 | — |
| Cogen HX inlet temperature | °F | — | 520.7 | — |
| Cogen HX outlet pressure | psia | — | 120.0 | — |

## 3.2 Turbine Impacts

The representative turbine cycle performance is modeled in a PEPSE model, which contains cases benchmarked to the turbine vendor's thermal kit. Cases at Valves Wide Open (VWO), rated thermal power (100%), and 75% power are provided. As shown in Table 2, the main turbine is expected to experience a reduction in mass flow rate of at least 25% when operating in the 30% thermal extraction case. HPT flows are expected to reduce by a similar amount on either side of the HPT flow path. Therefore, additional stress due to turbine imbalance is not expected. The 30% thermal power extraction case trends very closely with the 75% power case provided by the turbine vendor, as shown in the entropy-enthalpy chart in Figure 3. The LPT in the 30% thermal power extraction case also trends closely with the 75% power case provided by the turbine vendor. Based on the review of PEPSE heat balance conditions, the high-pressure and LPTs are expected to operate within design for the 30% thermal extraction case. However, final acceptability of operation under this condition must be confirmed with the turbine original equipment manufacturer on a plant-specific basis.

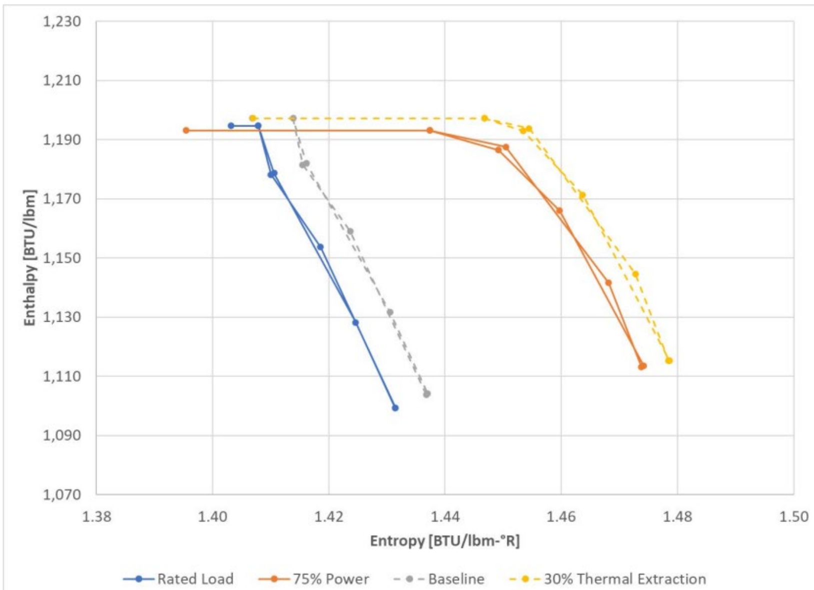


Figure 3. Enthalpy-entropy chart for the high-pressure turbine.

## 3.3 Feedwater Heater Steam Inlet Nozzle Velocities

The condensate (CD) and feedwater systems deliver feedwater (condensed steam) to the steam generators. The CD system first directs flow through three parallel trains of low-pressure FWHs (the first point external drain cooler and the first through the fourth point heaters). Flow then passes through two parallel trains of low-pressure FWHs (the fifth point external drain cooler, and fifth and sixth point heaters) to the turbine driven feed pumps. Feedwater flow then continues through two parallel high-pressure FWHs (seventh point heaters) to the steam generators. The FWHs receive extraction steam flow and moisture separator reheater drain flow from the turbine system. The FWH channel end nozzle velocities under 30% thermal power extraction slightly exceed the Heat Exchange Institute (HEI) guidelines as tabulated in [1]. However, changes from 0% thermal power extraction are small, so feedwater nozzle wear is not expected to increase significantly. Similarly, the tube velocities remain within or only marginally exceed HEI guidelines, so no issues are expected in the tubes.

Steam inlet nozzle velocities for 30% thermal power extract increase for all FWHs and exceed the HEI guideline for the second, third, and fourth point heaters, as shown in Table 3 [4]. Shell wear rates will likely slightly increase and should be considered during regular future inspections. Based on the past experience with the power uprate projects, which similarly increased flow velocities, no FWH replacement is expected unless the existing FWH are in poor condition. Drain outlet velocities decrease for the thermal extraction case; therefore, HEI guidelines are not challenged, and wear rates may decrease.

Table 3. Steam inlet nozzle velocities

| FWH | HEI limit | 0% Extraction | 30% Extraction | Difference |
|---|---|---|---|---|
| 1st point | 215 | 137 | 181 | 32.6% |
| 2nd point | 195 | 148 | 206 | 38.9% |
| 3rd point | 179 | 179 | 249 | 39.1% |
| 4th point | 167 | 156 | 214 | 37.5% |
| 5th point | 156 | 101 | 115 | 37.2 |
| 6th point | 150 | 103 | 139 | 19.8% |
| 7th point | 146 | 80 | 123 | 5.4% |

## 3.4 Extraction Steam

To maximize steam cycle efficiency, the extraction steam (ES) system diverts steam taken from the turbine to the FWHs. As shown in the PEPSE modeling diagram in Appendix A, there are three stages of extraction from the HPT and four stages of extraction from each LPT. The ES is used to heat the feedwater in seven separate FWH stages. There are three trains for the first through the fourth point low-pressure FWHs, two trains for the fifth and sixth point low-pressure FWHs, and two trains for the seventh point high-pressure feedwater heater.

### 3.4.1 Expansion Joint Liner Thickness

Based on PEPSE modeling, margins for design pressures and temperatures will largely improve for relevant valves and expansion joints in the FWH stages; however, the required expansion joint liner thickness increases, as indicated in Table 4. Liner thickness requirements increase for the thermal extraction case. Existing expansion joints will need to be evaluated on a plant-specific basis and may need to be replaced to ensure they meet new liner thickness requirements.

Table 4. Expansion joint liner thickness.

| LPT FWH Stage | Required Liner Thickness (in.) | | Difference |
|---|---|---|---|
| | 0% | 30% | |
| 4th | 0.137 | 0.160 | 17.2% |
| 3rd | 0.138 | 0.163 | 17.9% |
| 2nd | 0.156 | 0.184 | 17.8% |
| 1st | 0.149 | 0.172 | 15.1% |

### 3.4.2 Heater Drain System

There are seven stages of feedwater heating for normal operations. Two parallel trains (“A” and “B” trains), each consisting of FWH 5, 6, and 7 are available for normal operation. Drains cascade back to the heater drain tank starting at FWH 7. Flow for each train passes through the FWH 5 external drain coolers before entering the heat drain tank Emergency drains to the condenser are available for FWHs 5, 6, and 7.

Three parallel FWH drain trains (“A” train, “B” train, and “C” train), each consisting of a FWH 1, 2, 3, and 4, are available for normal operation. Drains cascade from FWH 4 to the flash tanks through FWHs 3 and 2. FWH 1 drain to the flash tanks as well. Each flash tank drains to the condenser via the FWH 1 external drain coolers. Emergency drains to the condenser are available for FWHs 4, 3, and 2, as well as the flash tanks.

Four MSR drain trains (“A” train, “B” train, “C” train, and “D” train), each consisting of a moisture separator drain tank (MSDT), the first stage reheater drain tank (RH1DT), and a second stage reheater drain tank (RH2DT) are available for normal operation as well. The MSDT drains are directed to the heater drain tank. The first and second stage reheater drains are directed to FWHs 5 and 7, respectively. Emergency drain lines to the condenser are available for each of the drain lines.

Based on PEPSE modeling, all drains experience a decrease in flow, so no issues are expected in the drains. The pressure drops across the valves are the minimum of the allowable pressure drop due to choked flow and the available pressure drop from valve inlet to outlet based on flow conditions and frictional losses. All DCVs experience choked flow conditions except the MSDT. With respect to valve capacity, a decrease in valve pressure loss is non-conservative; therefore, nearly all valves see a non-conservative reduction in allowable pressure loss. In most cases, the reduction in allowable pressure drop is significant, with FWH 2 normal drains seeing a greater than 80% reduction in pressure drop available.

As shown in Table 5, the required $C_v$ capacities for all FWH normal drain valves increase for 30% thermal power extraction. The $C_v$ of a control valve measures its flow capacity at full open condition relative to the pressure drop across the valve and is defined as the volume of water flowing through the open valve that causes a pressure drop of 1 psi. FWHs 2 and 3 show significant increase in required flow capacity, with FWH 2 requiring approximately double the baseline capacity. It is expected that a station specific review of these FWHs would result in requiring valve replacement prior to 30% thermal extraction operation. Additional equipment changes are not expected, but station specific review is required. Flash tank and the various MSR drain tanks all see reduced capacity requirements and are not shown in Table 5.

Table 5. Drain valve required $C_v$ capacities [5].

| Description | Cv | | Difference |
|---|---|---|---|
| | 0% | 30% | |
| Flash tank normal | 1019 | 892 | -12.5% |
| FWH 2 normal | 796 | 1,595 | 100.5% |
| FWH 3 normal | 271 | 367 | 35.8% |
| FWH 4 normal | 74 | 84 | 13.1% |
| FWH 6 normal | 245 | 248 | 0.9% |
| FWH 7 normal | 150 | 155 | 3.2% |

# 4. CONCLUSIONS AND FUTURE WORK

This report summarizes key impacts of 30% thermal power extraction on a generic Westinghouse 4-loop PWR. Full details of the PEPSE modeling and impacts, including plant transients, hazards, and core reactivity impacts can be found in [1]. Reactor response to load rejection or other transient events would need to be assessed for acceptability through further core and plant response analysis.

High-pressure/low-pressure turbine and moisture separator reheater performance is very similar to the performance under a 75% power case; this operating profile is expected to be maintainable for long durations.

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Analysis of the ES system shows that overall, ES line pressure drops increase due to higher flow velocities. The increased flow velocities should be included in the individual station Flow Accelerated Corrosion program to ensure that any potential degradation is properly monitored and addressed. Expansion joint liner thickness requirements also increased. Replacement of expansion joints may be needed to ensure requirements are met with thermal extraction conditions. As a result of pressures and temperatures mostly decreasing with thermal extraction, operating condition margins largely improved for valves and expansion joints in the ES system.

Heater drain tanks are expected to operate normally. FWH DCVs will require greater flow passing capability. Therefore, station specific review is required. It is expected that station specific review will find replacement of the FWH 2 and 3 DCVs necessary due to significant increase in required valve CV when operating with 30% thermal extraction.

The conclusions above establish that 30% thermal extraction can be performed safely without major plant equipment replacement. Minor upgrades and increased maintenance may be required for specific plant components (e.g., expansion joints and DCVs).

The results described herein are based on a generic reference plant and PEPSE model. Plant-specific evaluation of core/plant response and equipment would be required for any station considering a modification of this type. The results of a site-specific evaluation may differ from this generic PEPSE model analysis and equipment assessment based on plant/equipment design, operation, and age.

Future work will develop detailed PEPSE heat balance models and evaluate plant impacts for 50% and 70% reactor thermal power extraction.

# 5. REFERENCES


[1] Fidlow, H. R., H. Gaudin, J. Miller, G. Neimark, and N. Richards (2023) "Heat Balance Model Analysis and Equipment Assessment for 30% Thermal Extraction from a Nuclear Power Plant." SL-017758 Sargent and Lundy, Chicago, Illinois.

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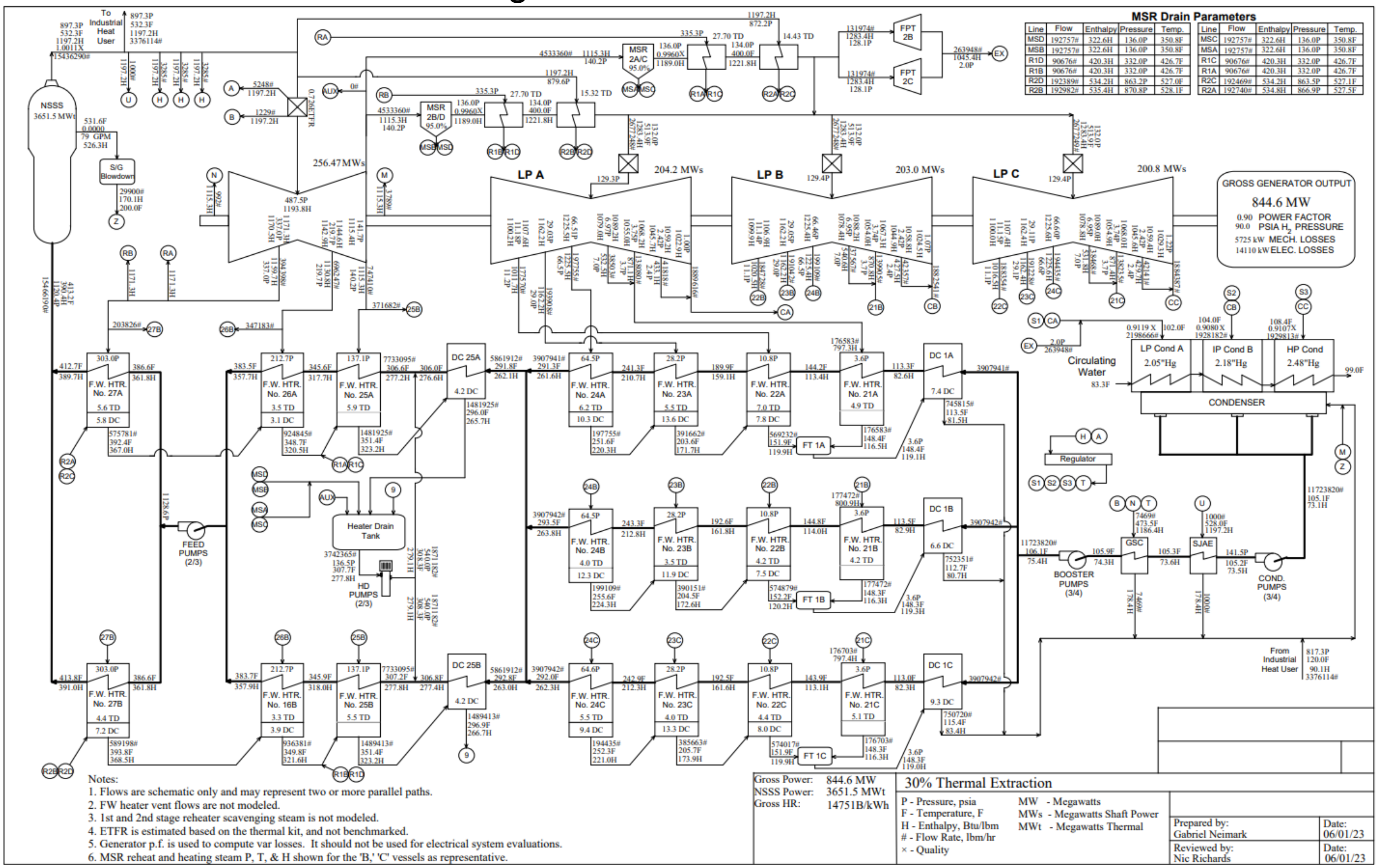
# APPENDIX A

## PEPSE Modeling For 30% Thermal Power Extraction




**MSR Drain Parameters**

| Line | Flow | Enthalpy | Pressure | Temp. | Line | Flow | Enthalpy | Pressure | Temp. |
|---|---|---|---|---|---|---|---|---|---|
| MSD | 192757# | 322.6H | 136.0P | 350.8F | MSC | 192757# | 322.6H | 136.0P | 350.8F |
| MSB | 192757# | 322.6H | 136.0P | 350.8F | MSA | 192757# | 322.6H | 136.0P | 350.8F |
| R1D | 90676# | 420.3H | 332.0P | 426.7F | R1C | 90676# | 420.3H | 332.0P | 426.7F |
| R1B | 90676# | 420.3H | 332.0P | 426.7F | R1A | 90676# | 420.3H | 332.0P | 426.7F |
| R2D | 192389# | 534.2H | 863.2P | 527.0F | R2C | 192469# | 534.2H | 863.5P | 527.1F |
| R2B | 192982# | 535.4H | 870.8P | 528.1F | R2A | 192740# | 534.8H | 866.9P | 527.5F |

Notes:
1. Flows are schematic only and may represent two or more parallel paths.
2. FW heater vent flows are not modeled.
3. 1st and 2nd stage reheater scavenging steam is not modeled.
4. ETFR is estimated based on the thermal kit, and not benchmarked.
5. Generator p.f. is used to compute var losses. It should not be used for electrical system evaluations.
6. MSR reheat and heating steam P, T, & H shown for the 'B,' 'C' vessels as representative.

Gross Power: 844.6 MW
NSSS Power: 3651.5 MWt
Gross HR: 14751B/kWh

30% Thermal Extraction

P - Pressure, psia
F - Temperature, F
H - Enthalpy, Btu/lbm
# - Flow Rate, lbm/hr
× - Quality

MW - Megawatts
MWs - Megawatts Shaft Power
MWt - Megawatts Thermal

Prepared by: Gabriel Neimark — Date: 06/01/23
Reviewed by: Nic Richards — Date: 06/01/23