

Light Water Reactor Sustainability Program

Preconceptual Designs of Coupled Power Delivery between a 4-Loop PWR and 100-500 MW_e HTSE Plants



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Preconceptual Designs of Coupled Power Delivery between a 4-Loop PWR and 100-500 MW_e HTSE Plants

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NOTE:

The body of this report and Appendices A through J are based primarily on report SL-016181, Revision 1, "Nuclear Power Plant Pre-Conceptual Design Support for Large-Scale Hydrogen Production Facility," November 2022, Sargent & Lundy report to the LWRS Program. Appendix K is based on Report WNA-DS-05327-GEN, Rev. 0, "500 MWe Hydrogen Production Facility Control System Implementation for High Temperature Electrolysis for a Pressurized Water Reactor", April 2023, Westinghouse report to the LWRS Program.

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ABSTRACT

This study develops a preconceptual design for the integration between a large-scale high temperature electrolysis facility and a nuclear power plant (NPP). Two hydrogen facility sizes are considered: 100 MW_{nom} and 500 MW_{nom}, where the subscript “nom” refers to the nominal size of the high temperature electrolysis facility (HTEF). Both steam supply designs use cold reheat steam extraction from the turbine system as a heat source. A brief comparison is also included for steam supply from main steam. A reboiler inside the protected area of the power plant transfers steam heat to the demineralized water supply for the HTEF. After the heat transfer, the extracted steam condenses and returns to the condenser while the process steam routes out of the protected area to the HTEF. Electrical power is tapped off from the high-voltage side of the generator step-up (GSU) transformer, where it is then transported via a 345-kV transmission line to the HTEF. Circuit breakers and disconnects are located at both ends of the transmission line. Step-down transformers and miscellaneous switchgear/buses are located at the end of the transmission line inside the HTEF boundary.

Computer modeling was performed for the thermal and electrical designs. The steady-state parameters for thermal extraction from the turbine cycle were determined using PEPSE, which is a software program for analyzing the steady-state thermal cycle performance of electric generating plants. These parameters were used to inform transients and size equipment in combination with Applied Flow Technology (AFT) Arrow and AFT Fathom modeling for steam and water piping, respectively. Electrical transients were analyzed using PSCAD software. An electrical transient analyzer program (ETAP) model was used to evaluate power flow and short circuit, which enabled the sizing of transformers and protective equipment.

A cost estimate was developed for both integration designs for plant separation distances of 250 m and 500 m. From these estimates, the modifications for thermal and electrical interfacing of a first-of-a-kind nuclear-integrated hydrogen facility are anticipated to cost between \$60–250/kW_{nom}. On a thermal power basis, the thermal power has an estimated cost of approximately \$8/MWh_{th} (megawatt-hours of thermal energy) for a 500 MW_{nom} HTEF located 500 m away from the NPP. That value decreases to approximately \$7.5/MWh_{th} for a 250 m separation distance between the HTEF and the NPP. This value is lower than previous estimates of the cost of heat extracted from NPPs primarily because in this work the steam is extracted from cold reheat instead of from the main steam line, which reduces the cost of the dispatched steam by approximately \$3.5/MWh_{th}.

Nuclear steam extraction can provide a profit avenue for many plants and is not restricted to hydrogen production. Ammonia production, oil refining, and paper production, among other industrial processes all require thermal energy, which can be provided by NPPs. Future work should look further at the details of thermal extraction for a variety of use cases. This can include increased levels of extraction and multiple simultaneous users. Additionally, site-specific studies should be performed to develop industry experience and improve cost accuracy.

EXECUTIVE SUMMARY

Background

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. Policy and economic incentives to reduce fossil fuel consumption has led to a steady build out of intermittent wind and solar energy, resulting in excess clean generation during some daily hours and deficits of clean energy during other hours. Additional sources of clean energy storage or energy generation flexibility are needed to balance daily, weekly, and monthly supply and demand of clean energy. The overlapping impact of the dominant clean generating sources (variable renewables and baseload nuclear power) exacerbates this challenge during daily supply and demand cycles.

Nuclear power has significant near-term potential to change its longstanding operational model by shifting generation output away from electrical generation when renewable generation can meet grid demand. During these times, nuclear facilities can flexibly produce real-time usable or storable clean energy to assist in decarbonizing not only the power grid but also industry and transportation. Specifically, producing hydrogen by water electrolysis has the potential to favorably influence all these sectors as a storage medium and energy carrier for excess variable carbon-free generation.

Selection of the Hydrogen Production Technology

Promising technologies to produce clean hydrogen from water can be divided into electrochemical and electrothermal processes. Leading electrochemical processes include alkaline, proton exchange membrane (PEM), and solid oxide electrolysis cell (SOEC) systems. Leading thermochemical processes include the sodium-oxygen-hydrogen (Na-O-H) cycle, copper-chlorine (Cu-Cl) cycle, and sulfur-iodine (S-I) cycle. Thermochemical cycles typically have high operating temperatures and require heat input at temperatures well above the operating temperature of pressurized water reactors (PWRs), so very high-temperature reactors (VHTRs) with outlet temperatures hotter than 650°C are preferred.

Solid oxide cell electrolysis (SOEC) systems, also known as high-temperature steam electrolysis (HTSE) systems, use high temperature rather than precious metal catalysts to split water molecules. HTSE technology is less mature than alkaline and PEM technologies; however, multiple companies have announced facilities that can produce HTSE systems at scales greater than 500 MW_{DC}/yr (direct current megawatts per year). HTSE systems need power in the forms of DC electrical power and heat at approximately 150°C (302°F) to produce saturated steam. Using nuclear heat to generate steam for the HTSE process increases the efficiency of the process. The specific electric and thermal energy requirements for HTSE have been reported as 36.8 kWh_e/kg-H₂ and 6.4 kWh_{th}/kg-H₂, respectively, as shown in Table S-1. The projected electric-specific energy consumption is well aligned with a value of 37.7 kWh/kg-H₂ measured at Idaho National Laboratory (INL) using a 100 kW Bloom Energy SOEC system. Similar to PEM systems, HTSE systems show promising capabilities to flex their power consumption and hydrogen production over a time scale of seconds to minutes to allow coupled nuclear plants flexibility in dispatching power either to the power grid or to hydrogen production.

In comparing the merits of using PWRs to provide power for leading electrochemical water-splitting technologies, it is helpful to compare the power requirements in terms of thermal power. Approximating the conversion efficiency of converting nuclear heat to electrical power by a PWR to be 33%, specific thermal energy requirements of alkaline, PEM, and HTSE systems are estimated to be 164–230, 158, and 118 kWh_{th}/kg-H₂. The benefit of integrating HTSE hydrogen production with nuclear power is apparent. Compared to PEM electrolysis, HTSE systems using nuclear power can produce 33% more hydrogen for the same nuclear thermal power. The final column of Table 1 indicates potential benefits of using heat from high temperature reactors for hydrogen production. Additional details can be found in Section 1.2.2. For HTSE, the improvements in hydrogen production efficiency are caused exclusively by the higher efficiency of converting nuclear heat to electricity.

Table S-1. Efficiencies of leading hydrogen production technologies for the near-term time horizon.

| Hydrogen production technology | Electricity input | Thermal power input | PWR input thermal power ($\eta_{th \rightarrow e} \approx 0.33$) | VHTR input thermal power ($\eta_{th \rightarrow e} \approx 0.46$) |
|--------------------------------|-------------------------------------|--------------------------------------|--|---|
| | kWh _e /kg-H ₂ | kWh _{th} /kg-H ₂ | kWh _{th} /kg-H ₂ | kWh _{th} /kg-H ₂ |
| Alkaline (near-term) | 54–70 | 0 | 164–230 | 117–165 |
| PEM (near-term) | 52 | 0 | 158 | 113 |
| HTSE (near-term) | 37 | 6 | 118 | 86 |
| Na-O-H cycle ^a | 20 | 40 | 141 ^b | 83 |
| Hybrid S-I cycle ^a | 17 | 53 | Not applicable | 91 |

a Future projection for mid-term time horizon.

b Assumes advanced high temperature heat pump with coefficient of performance equal to 2 that operates between 290°C and ~500°C.

Selection of a Representative Nuclear Power Plant

As of the end of 2022, 68 of the 92 commercially operable U.S. nuclear power plant (NPP) units were PWRs. With such a significant portion of the NPP fleet employing this type of design, it is an appropriate choice for use as the representative reference plant for the preconceptual design. Additionally, the use of nonradioactive steam in the secondary system of a PWR makes PWRs the logical choice for an initial feasibility study. It is noted that a boiling water reactor (BWR) will require additional design considerations due to radioactive steam in the secondary system. Therefore, BWRs are not considered in this feasibility study but may be evaluated in future work.

The most common type of PWR in the U.S. is a Westinghouse 4-loop PWR, of which there are 26 units operating as of the end of 2022. Westinghouse also designed 2-loop and 3-loop PWRs, of which there are 5 units and 15 units operating, respectively, for a total of 46 operating Westinghouse PWRs. Thus, Westinghouse PWRs represent 75% of all operating PWRs in the U.S. ($46/68 = 75\%$). The fundamental designs of Westinghouse PWRs are sufficiently similar, such that a 4-Loop PWR is representative of 2-loop and 3-loop PWRs if the different reactor scales are properly accounted for. Considering that 4-loop Westinghouse PWRs are the most common type, this model has been selected for this study.

Summary of the High-Level Integration Design

This report is based primarily on a preconceptual design report prepared by Sargent & Lundy (S&L) [19] with input from INL. The 4-Loop PWR is assumed to have a generating capacity of approximately 1,200 megawatts electric (MW_e). Steam is extracted from the PWR using one or more new connections in the crossunder (cold reheat) piping between the high-pressure (HP) turbine and the moisture separator reheaters (MSRs). A brief comparison is also included for steam supply from main steam. This report considers two large-scale hydrogen production facilities, with nominal ratings of 100 MW_{nom} and 500 MW_{nom}, respectively. Detailed information for both designs is in the preconceptual design report prepared by S&L [19]. Table S-2 provides the specific parameters for both designs. The nominal rating corresponds to the DC power input of the HTEF at full hydrogen production. A 100 MW_{nom} high-temperature electrolysis facility (HTEF) is expected to produce as much as 55-58 tonnes of hydrogen per day, depending upon the configuration.

The exact amount of heat required by the HTEF to generate steam for hydrogen production depends on heat recuperation and other design choices within the plant. For the purposes of this study, typical heat input requirements are assumed without performing detailed heat integration designs that depend upon a specific HTEF configuration, which is vendor dependent. Steam delivered to the HTEF is required to be at least 150°C (302°F) and 50 pounds per square inch gauge (psig). Analyses performed for this study achieved these requirements, as

summarized in Table S-2. Hydraulic analyses were performed to size the piping and auxiliary equipment required to meet thermal extraction demands for the HTEF. For purposes of the preconceptual design, minor additional thermal extraction is needed to cover various thermal losses, inefficiencies, and design margins typically associated with the sizing of piping, pumps, heat exchangers, valves, etc. As noted above, the thermal power required for hydrogen production in an HTEF is approximately 20% of the nominal power. Based on these considerations, the thermal power requirement of the 100 MW_{nom} HTEF is taken to be 25 MW_{th} and that of the 500 MW_{nom} HTEF is taken to be 105 MW_{th}. Both hydrogen facilities are assumed to be located outside of the protected area but inside the owner-controlled area (OCA). Designs are prepared for distances of 250 m and 500 m between the PWR and both HTEFs. Product hydrogen is transported a safe distance away (e.g., 1+ km) for high-pressure compression and storage.

Within the PWR, piping is installed to route the high-temperature steam from the crossunder piping to a steam reboiler that creates steam in a tertiary loop fed from a deionized or demineralized water source. This steam is provided to the HTEF for use in the HTE process. Condensed drain flow on the secondary side of the steam reboiler is directed to a location within the secondary loop of the plant to minimize thermal losses.

The revenue meter for the NPP is assumed to be at a high-voltage switchyard, adjacent to the NPP protected area. Net metering of the HTEF may be required for cases where the revenue meter is located at the generator terminals or in the Turbine Building. Electrical energy, in the form of alternating-current (AC) power, is diverted from the output of the main generator to the HTEF, where most of the required power is converted to rectified DC power.

The electrical loads required for hydrogen production were 105 MW_e and 500 MW_e for the 100 MW_{nom} and 500 MW_{nom}, respectively. As with thermal power, electrical losses and inefficiencies must be considered to supply adequate power to the facility. Additional electrical power needs to be supplied to the hydrogen facility to support plant auxiliaries and other ancillary loads. The total apparent electric power rating for these two facilities comes to 140 megavolts ampere (MVA) and 600 MVA, respectively.

Table S-2. HTEF parameters by plant size.

| Parameter | Unit | HTEF Size | |
|--|------------------|-----------------------|-----------------------|
| | | 100 MW _{nom} | 500 MW _{nom} |
| Hydrogen Production Capacity ^a | U.S. tons/day | 55–58 | 275–290 |
| H ₂ Plant Electric Load MW _e | MW _e | 105 | 500 |
| H ₂ Plant Auxiliary Loads + Margin | MW _e | 22 | 50 |
| Power Factor | — | 0.92 | 0.92 |
| Total Electrical Power Requirements | MVA | 140 | 600 |
| H ₂ Plant Thermal Load | MW _{th} | 20 | 100 |
| Plant Thermal Losses + Margin | MW _{th} | 5 | 5 |
| Total Thermal Power Requirements | MW _{th} | 25 | 105 |
| Steam Input Temperature ^b | °F | >300 (333) | >300 (333) |
| Steam Input Pressure ^b | psig | >50 (59.3) | >50 (59.3) |
| Separation Distance from PWR | m | 250 & 500 m | 250 & 500 m |

a Conservative production capacities are shown based on 2022 values. Technology improvements over the next few years are expected to improve the yields of these plants to approximately 60 and 300 U.S. tons/day, respectively.

b Parameters in parenthesis indicate actual design values.

Summary of the Estimated Integration Costs

An overview of the direct, indirect, and contingency costs for the 100 MW_{nom} and 500 MW_{nom} facilities are provided below in Table S-3. The analysis assumes annual inflation of 2% but neglects financing and tax costs. The estimate for the integration of the NPP hydrogen steam supply equipment and associated electrical infrastructure for the 100 MW_{nom} design totals close to \$246/kW_{nom}, while the 500-MW_{nom} integration modifications are estimated to cost \$78/kW_{nom}. Based on these estimates, **the standardized cost of the 500 MW_{nom} design is approximately one-third of the 100 MW_{nom} design.** This reduction can be explained by the consolidation of equipment under the larger design, reducing material and labor costs with respect to production capacity. Changing the number of piping trains, power lines, or integration equipment (mechanical and electrical) for these designs will alter the capital cost of these modifications accordingly. One potential cost-reduction strategy is to decrease separation distance between the NPP and HTEF. This adjustment would decrease the length of piping and power lines, which would have subsequent benefits, including reduced excavation and foundation costs, better efficiency (reduced thermal and electrical losses), and potential utilization of smaller, less expensive equipment. Reducing thermal and electrical separation by 50%, from 500 m to 250 m, is assumed to be physically feasible for some plants (additional hazard analysis and licensing evaluation is necessary to assess overall regulatory compliance but is not considered within this study). Table S-3 shows an approximately 20% reduction in integration cost across both designs by reducing plant separation. Additional cost details can be found in Table 13 in the body of the report. The contingency budgets listed in Table S-3 are relatively large and approximately equal to the direct costs. Large contingency budgets are appropriate for first-of-a-kind installations. The contingency funds can likely be decreased by 50% or more for subsequent installations that follow similar engineering designs.

Table S-3. Installation cost summary for integration of nuclear and hydrogen plant (2022 U.S. dollars).

| Parameter | 100 MW _{nom} | | 500 MW _{nom} | |
|--|-----------------------|------------------|-----------------------|------------------|
| | 500 m separation | 250 m separation | 500 m separation | 250 m separation |
| Total Capital Investment (Direct and Indirect Costs) | | | | |
| Direct cost (\$MM) ^a | 7.42 | 5.42 | 13.1 | 10.2 |
| Indirect cost (\$MM) ^b | 8.98 | 7.15 | 13.07 | 10.22 |
| Contingency (\$MM) | 8.20 | 6.20 | 13.2 | 10.2 |
| Total capital investment (\$MM) | 24.6 | 19.0 | 39.0 | 30.6 |
| Operating Costs and Considerations | | | | |
| NPP power reduction (MW _e) | 5.3 | 5.3 | 22.47 | 22.47 |
| Annual cost of NPP power reduction (\$MM) ^c | 1.45 | 1.45 | 6.16 | 6.16 |
| 20 Year lifetime operating cost (\$MM) | 24.1 | 24.1 | 102.3 | 102.3 |
| Total Costs and Considerations | | | | |
| 20 Year lifetime total cost (\$MM) | 48.7 | 43.7 | 141.3 | 132.9 |
| Ratio lifetime capital to operating costs | 102% | 79% | 38% | 30% |
| Standardized (std.) Costs | | | | |
| Std. steam cost per unit delivered heat (\$/MWh _{th}) | 13.9 | 12.3 | 8.06 | 7.58 |
| Std. steam cost from Ref. [2] (\$/MWh _{th}) | 11.6 | | | |
| Std. steam cost per nominal HTEF size (\$/kW _{nom}) | 204 | 150 | 70.0 | 53.4 |
| Std. electric cost per nominal HTEF size (\$/kW _{nom}) | 42.1 | 37.9 | 8.62 | 7.73 |
| Std. total cost per nominal HTEF size (\$/kW _{nom}) | 246 | 190 | 78.1 | 61.2 |

a Direct costs include labor, materials, subcontracts, construction equipment, and process equipment.

b Indirect costs include additional labor, site overheads, other construction costs and project indirects.

c Assumes an electricity sales price of \$30/MWh.

It is helpful to compare the cost estimates in Table S-3 with assumptions that have been made in previous analyses with estimated costs for hydrogen production, assuming a similar production configuration in which an HTEF is coupled to a PWR. In the study by Wendt, Knighton, and Boardman, [2], it was assumed that a 1,000 MW_{nom} HTEF was coupled to an NPP at a distance of 1 km. The direct capital cost of the steam delivery system from the NPP was estimated to be \$41.1 million, which is in very good agreement with the estimated cost presented in Table S-3, after accounting for differences in scale and assumed steam delivery distance. Importantly, however, as shown in Table S-3, operating costs dominate the total costs for HTEFs that are 500 MW_{nom} and larger.

The dominating operating cost is the loss of PWR electric power output due to thermal power dispatch to the HTEF. As indicated in Table S-3, the PWR electric power output decreases by 5.3 MW_e and 22.4 MW_e, respectively, for the 100-MW_{nom} and 500-MW_{nom} HTEF cases. These values are lower than estimated in the previous hydrogen production cost study [2] because extracting steam from cold reheat in the PWR has less impact on electric power production than removing steam from the main steam line, as assumed in the previous work. The previous work assumed that reduction in electric power production was equal to the thermal power delivery to the HTEF divided by the thermal-to-electric conversion efficiency of the PWR, which would have corresponded to 8.5 MW_e for the 100 MW_{nom} HTEF case and 35.7 MW_e for 500 MW_{nom} HTEF case, respectively. Importantly, as summarized in Appendix C, a PEPSE analysis was conducted for a case in which steam was extracted from the main steam line. As noted in Table C-2, extracting 105 MW_{th} from the main steam line caused the generator output to decrease by 37.9 MW. This result indicates extracting steam from the main steam line causes an additional loss of 15.4 MW from the generator, compared to extracting the needed steam from cold reheat. **Extracting steam from the cold reheat reduces the operating costs of the thermal power dispatch system by approximately 40%, compared to extracting steam from the main steam line. The lowest standardized (Std.) cost of steam supply is associated with the 500 MW_{nom} HTEF case and is 7.58 \$/MWh_{th}, which exhibits a marked improvement compared with the estimate of 11.6 \$/MWh_{th} from [2].** For comparison, an abbreviated cost estimate was performed for a case in which steam is provided to the HTEF using an electric boiler. Additional details of the electric boiler analysis can be found in Table 14. **The estimated standardized cost of steam from an electric boiler was estimated to be greater than \$25/MWh_{th}.** As noted above, costs estimated in this study are for a first-of-a-kind installation with large contingency budgets. **Subsequent installations with similar designs may have substantially lower costs if contingency costs can be avoided.**

ACRONYMS

| | |
|--------------|---|
| 10 CFR 50.59 | Code of Federal Regulations |
| AACE | Association for the Advancement of Cost Engineering |
| AC | alternating-current |
| AFT | applied flow technology |
| ASME | American Society of Mechanical Engineers |
| AVR | automatic voltage regulator |
| BES | bulk electric system |
| BIL | bipartisan Infrastructure Law |
| BWR | boiling water reactor |
| CDF | Core Damage Frequency |
| CM | construction management |
| CT | current-transformers |
| DAR | Design Attribute Review |
| DOE | U.S. Department of Energy |
| DOWG | Design Oversight Working Group |
| EPCM | engineer, procure, construction management |
| ETAP | electrical transient analyzer program |
| FAC | flow-accelerated corrosion |
| FCV | flow control valve |
| FPOG | Flexible Plant Operations and Generation |
| H3RG | Hydrogen Regulatory Research Review Group |
| HTE | High-Temperature Steam Electrolysis |
| G&A | general and administrative |
| GSU | generator step-up |
| HMI | human-machine interface |
| HP | high-pressure |
| HSS | hydrogen steam supply |
| I&C | Instrumentation and Controls |
| INPO | The Institute of Nuclear Power Operations |
| LAR | License Amendment Request |
| LCOE | levelized cost of energy |
| LCOH | levelized cost of hydrogen |
| LERF | Large Early Release Frequency |

| | |
|-------------------|---|
| LP | low-pressure |
| LTE | low-temperature electrolysis |
| LWR | Light Water Reactor |
| LWRS | Light Water Reactor Sustainability |
| NPP | nuclear power plant |
| MOD | manually operated disconnect |
| MSR | moisture separator reheaters |
| MWh _{th} | megawatt-hours of thermal energy |
| NERC | North American Electric Reliability Corporation |
| NPSH | net positive suction head |
| NSIAC | Nuclear Strategic Issues Advisory Committee |
| OCA | owner-controlled area |
| OEM | original equipment manufacturers |
| OPGW | optical ground wire |
| P&ID | process and instrumentation diagram |
| PRA | Probabilistic Risk Assessment |
| PT | potential transformers |
| PWR | Pressurized Water Reactor |
| RO | reverse osmosis |
| SCWR | super critical water reactors |
| SDP | standard design process |
| SPV | single-point vulnerability |
| SOEC | Solid Oxide Electrolysis Cell |
| Std | standardized |
| STD | standard pipe size |
| TB | Turbine Building |
| TNV | thermoneutral voltage |
| USNRC | U.S. Nuclear Regulatory Commission |
| UFSAR | Updated Final Safety Analysis Report |
| VAR | Volt-Amps Reactive |

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Preconceptual Designs of Coupled Power Delivery between a 4-Loop PWR and 100-500 MW_e HTSE Plants

1. INTRODUCTION

1.1 Why Nuclear Generated Hydrogen?

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. Policy and economic incentives to reduce fossil fuel consumption has led to a steady build-out of intermittent wind and solar energy, resulting in excess clean generation during some daily hours and deficits of clean energy during other hours. Additional sources of clean energy storage or energy production flexibility are needed to balance daily, weekly, and monthly supply and demand of clean energy. The overlapping impact of the dominant clean generating sources (intermittent renewables and baseload nuclear power) exacerbates this challenge during daily supply and demand cycles.

Nuclear power has significant near-term potential to change its longstanding operational model by shifting generation output away from electrical generation when renewable generation can meet grid demand. During these times, nuclear facilities can flexibly produce real-time usable or storable clean energy to assist in decarbonizing not only the power grid but also industry and transportation. Specifically, producing hydrogen by water electrolysis has the potential to favorably influence all these sectors as a storage medium and energy carrier for excess intermittent carbon-free generation.

The 2022 Bipartisan Infrastructure Law (BIL), officially known as the Infrastructure Investment and Jobs Act (IIJA) [1], provides up to \$8 billion to help establish Regional Clean Hydrogen Hubs over the next 5–6 years. This bill is key to addressing several barriers for many nuclear reactors to implement hydrogen production.

To qualify as clean hydrogen (H₂), the life-cycle emissions of carbon dioxide (CO₂) of the H₂ produced must be less than 2 kg-CO₂e per kg-H₂ [a]. At least one of these hubs must use nuclear energy for some fraction of the hydrogen produced in a given region. The federal cost share of up to 50% of the total project costs (up to \$1.25 billion) should make it possible to realize a favorable return on investment for first-of-a-kind demonstration projects.

Technical and economic assessments of hydrogen production by nuclear power plants (NPPs) indicate that light water reactors (LWRs) will be able to feasibly produce clean hydrogen through water-splitting electrolysis for an nth-of-a-kind nuclear hydrogen plant. This is based on a hydrogen plant that is integrated with an existing NPP when the price of electrolysis units is consistent with an established supply chain of materials and fabrication year-over-year. The BIL also intentionally includes \$1 billion to help raise the technology and commercial-scale manufacturing readiness of electrolysis. The assumption is that several large-scale demonstration projects and the required manufacturing industries will make it possible to expand the leading projects at nth-of-a-kind economics.

The technology readiness levels of water-splitting electrolysis systems have dramatically increased in recent years [2] as the global interest increases in clean hydrogen production and decarbonization of transportation, industry, and other sectors. Electrolyzed hydrogen produced by renewables and low-temperature electrolysis (LTE) is already emerging as a near-term clean, stored energy carrier.

a CO₂e refers to a unit of greenhouse gas reductions equivalent to the impact of CO₂. As a reference, the conventional process of producing hydrogen by steam methane reforming emits 7-10 kg CO₂ per kg H₂ produced depending on the process design and accounting for life-cycle emissions associated with NG production.

1.2 Why Integrate Light Water Reactors with High-Temperature Steam Electrolysis (HTSE) Plants?

Promising technologies to produce clean hydrogen from water can be divided into electrochemical and electrothermal processes. Leading electrochemical processes include alkaline, proton exchange membrane (PEM) and solid oxide electrolysis, while leading electrothermal processes include the sodium-oxygen-hydrogen (Na-O-H) cycle, copper-chlorine (Cu-Cl) cycle, and sulfur-iodine (S-I) cycle.

1.2.1 Electrochemical Low-Temperature Electrolysis

Alkaline electrolysis is the most mature water-splitting process technology with multiple 100+ MW systems installed and operating. It has a relatively low capital cost but current designs also have relatively low efficiency with system-specific energy consumption for hydrogen production in the range of 54–70 kWh/kg-H₂ [3]. PEM electrolysis is a less mature technology but is already available at MW and tens of MW scale. PEM electrolysis systems use rare and precious metal catalysts to achieve a system-specific energy consumption that is anticipated to reach 52 kWh/kg-H₂ by around 2025 [4]. This projected specific energy consumption is slightly better than systems today achieve, as reported by a Nel Hydrogen 1.25 MW PEM system, which recently began producing hydrogen at the Nine Mile Point Nuclear Plant owned by Constellation Energy. The scale of electrochemical water-splitting systems is typically reported on a DC power input basis. For example, a 1.25 MW PEM system operating under normal conditions consumes 1.25 MW of DC power. Constellation Energy reported that the PEM system at the Nine Mile Point Nuclear Plant produced 560 kg/hr, corresponding to a specific energy consumption of 53.6 kWh/kg-H₂ [5]. An advantage of PEM electrolysis is that the systems are capable of rapid dynamic operation between approximately 20–100% of their rated capacities.

1.2.2 Electrochemical High-Temperature Electrolysis

Solid oxide cell electrolysis (SOEC) systems, also known as HTSE systems, use high temperature rather than precious metal catalysts to split water molecules. HTSE technology is less mature than alkaline and PEM technologies; however, multiple companies have announced facilities that can produce HTSE systems at scales greater than 500 MW_{DC} per year [6,7]. HTSE systems need power in three forms: (1) DC electrical power, (2) heat at approximately 150°C to produce saturated steam, and (3) heat at approximately 800°C for process topping heat. The ratios of the required power inputs depend upon specific operating conditions. In a typical operating condition, 75-78% of the input power is needed as DC electrical power, 16–19% of the input power is needed to produce steam at approximately 150°C, and 5–8% of the input power is needed for high-temperature topping heat. Typically, the high-temperature topping heat is produced using electrical heaters so that the ratio of the required electric power to thermal power is between four and five. This ratio of electric-to-thermal power can be achieved from a PWR by extracting slightly less than 10% of the steam from the primary steam supply loop and using heat from this steam to provide the heat needed by the HTSE plant through appropriate heat exchangers. Using nuclear heat to generate steam for the HTSE process increases the efficiency of the process (Figure 1 and Figure 2). The specific electric and thermal energy requirements for HTSE have been reported as 36.8 kWh/kg-H₂ and 6.4 kWh_{th}/kg-H₂, respectively [8]. The projected electric-specific energy consumption is well aligned with a value of 37.7 kWh/kg-H₂, which was measured at Idaho National Laboratory using a 100 kW Bloom Energy SOEC system [9]. The thermal specific energy consumption of 6.4 kWh_{th}/kg-H₂ is readily determined from the heat of vaporization of water and by accounting for engineering losses in large-scale systems. Similar to PEM systems, HTSE systems show promising capabilities to flex their power consumption and hydrogen production over a time scale of seconds to minutes to allow coupled nuclear plants flexibility in dispatching power to either the power grid or to hydrogen production.

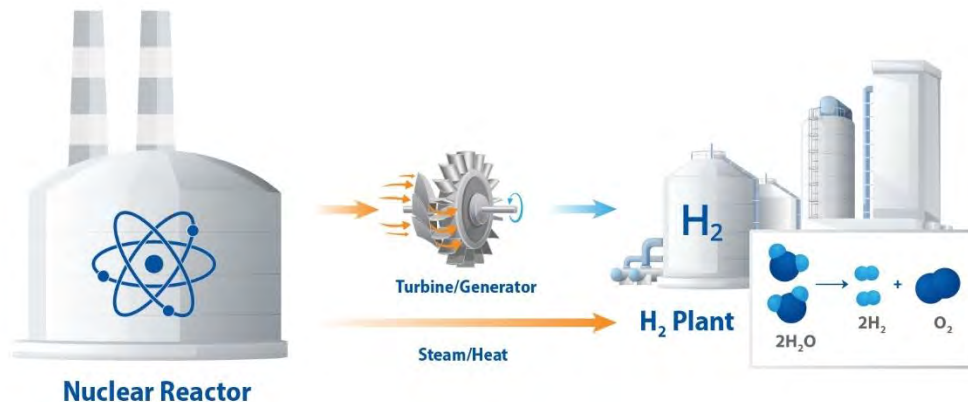


Figure 1. Graphical representation of heat and electricity flowing from a nuclear reactor to an HTEF.

In comparing the merits of using PWRs to provide power for leading electrochemical water-splitting technologies, it is helpful to compare the power requirements in terms of thermal power. Approximating the conversion efficiency of converting nuclear heat to electrical power ($\eta_{th \rightarrow e}$) by a PWR to be 33%, specific thermal energy requirements of alkaline, PEM, and HTSE systems are estimated to be 164–230, 158, and 118 kWh_{th}/kg-H₂, as summarized in Table 1. The benefit of integrating HTSE hydrogen production with nuclear power is apparent. Compared to PEM electrolysis, each kg of hydrogen can be produced using 33% less thermal power $(156-118)/118 = 33\%$.

Table 1 also includes a column assuming the electricity is provided by a very high-temperature reactor (VHTRs) that can achieve a thermal power to electricity conversion efficiency ($\eta_{th \rightarrow e}$) of approximately 46%. It has been noted that heat from VHTRs can be used to increase the efficiency of HTSE processes because 5–8% of the input power is needed for high-temperature topping heat. In practical applications, however, there are several factors that will likely negate the potential increase in efficiency from utilizing high-temperature heat. First, assuming a VHTR can convert thermal power to electricity with an efficiency of 46%, the potential increase in efficiency that could be gained by using high-temperature heat inside the HTSE facility (HTEF) instead of electrical heaters would be limited to 1/46% of 5–8% or approximately 3%. Second, transferring high-temperature gas from the VHTR in the HTEF and using heat from the gas in the HTEF would have unavoidable thermal losses that would further limit the potential increase in system efficiency to less than 1–2%. The reason for the high thermal losses is that the high-temperature topping heat is needed locally within the hot boxes that contain the solid

Table 1. Efficiencies of leading hydrogen production technologies for the near-term time horizon.

| Hydrogen production technology | Electricity input | Thermal power input | PWR input thermal power ($\eta_{th \rightarrow e} \approx 0.33$) | VHTR input thermal power ($\eta_{th \rightarrow e} \approx 0.46$) |
|--------------------------------|-------------------------------------|--------------------------------------|--|---|
| | kWh _e /kg-H ₂ | kWh _{th} /kg-H ₂ | kWh _{th} /kg-H ₂ | kWh _{th} /kg-H ₂ |
| Alkaline (near-term) | 54–70 | 0 | 164–230 | 117–165 |
| PEM (near-term) | 52 | 0 | 158 | 113 |
| HTSE (near-term) | 37 | 6 | 118 | 80 |
| Na-O-H cycle ^a | 20 | 40 | 141 ^b | 83 |
| Hybrid S-I cycle ^a | 17 | 53 | Not applicable | 91 |

^a Future projection for mid-term time horizon.

^b Assumes advanced high temperature heat pump with coefficient of performance equal to 2 that operates between 290°C and ~500°C.

oxide electrochemical cells. These hot boxes contain between 100 kW_{DC} and 1 MW_{DC} of cells and contain heat recuperators, such that in current designs, relatively low-temperature steam and gases enter and exit the hot boxes. Using high-temperature gas to provide the topping heat in the hot boxes would require additional high-temperature piping to transfer the high-temperature gas into and out of the hot boxes as well as additional heat exchangers inside and outside the hot boxes. These additional high-temperature pipes and heat exchangers would substantially increase the system complexity, footprint, capital expense, and thermal losses.

Figure 2 shows an example cell voltage and current relationships of low and high-temperature electrolysis systems and illustrates an additional factor that limits the practicality of using high-temperature topping heat from a VHTR to increase the efficiency of an HTEF. HTSE systems operate along the solid red line shown in Figure 2, while low-temperature alkaline and PEM electrolysis facilities operate along the solid blue line. LTE systems must operate at cell voltages that are greater than the water thermoneutral voltage (TNV) because that is the minimum voltage required to split water molecules. High-temperature electrolysis systems can operate at either above or below the steam TNV, although there are strong motivating factors to operate near the steam TNV. Operating at cell voltages below the steam TNV allows thermal power (heat) to replace some of the electrical power in the water-splitting reaction; however, electric current and hydrogen production rates decrease as the cell voltage decreases. Hydrogen production costs increase as the hydrogen production rate decreases because the specific capital equipment cost increases. Operating at cell voltages above the steam TNV produces Ohmic heating that offsets the high-temperature topping heat that must be provided to the solid oxide cells during hydrogen production.

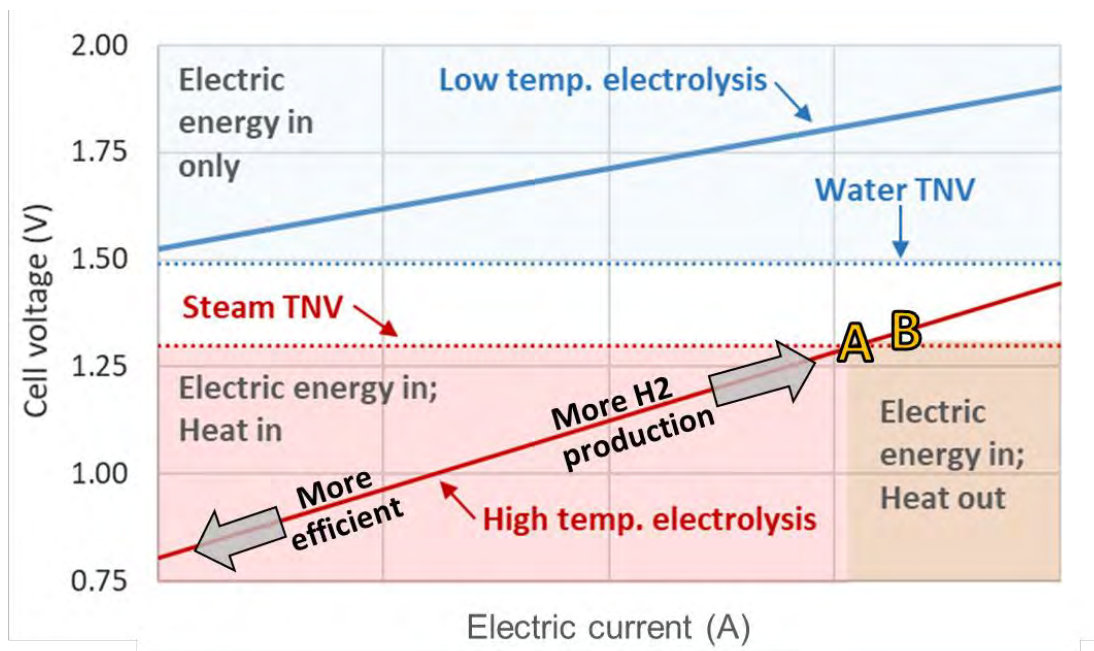


Figure 2. Cell voltage and current relationship for low and high-temperature electrolysis.

The point marked “A” in Figure 2, which corresponds to operation at the steam TNV, is the point at which 5-8% topping heat is required, as listed in Table 1. At a cell voltage and electric current slightly higher than point “A,” the Ohmic heating exactly matches the required topping heat, such that inline topping heaters or heat exchangers are not required. This point is marked “B” in Figure 2. As noted above, increasing the cell voltage and electric current potentially decreases hydrogen production costs even though cell efficiency is slightly lower because the system capital equipment expense decreases. A primary objective of HTSE system manufacturers and the U.S. Department of Energy (DOE) is to

increase the durability of solid oxide electrolysis cells, so that they can sustain higher current densities and hydrogen production rates. Using high-temperature heat from a VHTR to increase the efficiency of an HTEF is counter to present-day goals of HTSE system manufacturers and DOE. The HTEF thermal power input value for HTSE systems in the final column of Table 1 assumes heat from a VHTR is only used to produce electricity and steam at approximately 150°C for the HTSE process (the cycle topping heat is provided using electricity). A further point regarding the information in Table 1 is that the improved efficiency of the thermal-to-electric power conversion efficiency of the VHTR is not the driving parameter for decreasing the cost of hydrogen production. As discussed in the study by Wendt, Knighton, and Boardman [2], the cost of hydrogen is affected predominantly by the cost of electricity, so NPPs that produce electricity at the lowest cost are favored to produce low-cost hydrogen, regardless of their thermal-to-electric power conversion efficiency.

1.2.3 Thermochemical Cycle Technologies

As noted, thermochemical processes are also promising options for hydrogen production; although, their technological maturity is much lower. Thermochemical cycles typically have operating temperatures and require heat input at temperatures well above the operating temperature of PWRs. Therefore, VHTRs with outlet temperatures hotter than 650°C are preferred [10]. Of the thermochemical cycles, the Na-O-H [11] and Cu-Cl [12,13] cycles have the potential to operate at the lowest temperature—approximately 500°C—while the S-I cycle operates at approximately 800°C [14,15]. Due to their moderate operating temperatures and power requirements, the Na-O-H and Cu-Cl cycles are compatible with receiving heat and electricity from super critical water reactors (SCWRs) for hydrogen production. Coupling these cycles to PWRs would require a chemical heat pump to upgrade the temperature of the steam, which decreases the efficiency of the process [16].

For the Na-O-H chemical process, initial studies show that the ideal exergy efficiency of the cycle is 82%, making it a potential candidate for H₂ production [11, 17]. The HTEF thermal power input value for the Na-O-H cycle in the final column of Table 1 assumes that high-temperature heat from a VHTR is used in the thermochemical Na-O-H cycle, and therefore, the anticipated high-temperature thermal input power requirements of HTSE and Na-O-H technologies are approximately equal at 80 kWh_{th}/kg-H₂. It must be noted, however, that Na-O-H cycle technology is not yet mature, and its projected overall system efficiency has relatively high uncertainty. The coupled SCWR Cu-Cl hybrid cycle has been studied extensively in Canada and has been shown to have exergy efficiency of 27.8% [12]. The hybrid S-I cycle has also been studied extensively and has a reported exergy efficiency of 35% [18,14,15].

1.3 Why Select a 4-Loop Westinghouse PWR as a Reference Plant to Integrate with HTSE?

Development of a preconceptual design must begin by establishing a reference plant to describe the proposed modifications, analyze the impacts, and approximate assigned costs. Individual sites can then compare the attributes of the reference plant to their specific plant to adjust the modifications described or scale the associated costs appropriately.

A Westinghouse 4-loop PWR has been selected for this study. Westinghouse PWRs represent 75% of all operating PWRs in the U.S. (46/68 = 75%). A 4-Loop PWR is representative of typical Westinghouse PWRs.

As of the end of 2022, 68 of the 92 commercially operable U.S. NPP units were PWRs. In a PWR, high-pressure (HP) water passes through the reactor core, where it is heated by thermal energy created by nuclear fission. This “primary” water flows to a heat exchanger (called a steam generator), where it boils feedwater in the “secondary” plant cycle to create steam. This steam then drives a series of turbines, which turn a generator to create electricity. This secondary turbine cycle steam is not radioactive due to being separated from the reactor coolant within the steam generators. With such a significant portion of the NPP fleet employing this type of design, it is an appropriate choice for use as the representative reference plant for the preconceptual design. Additionally, the use of nonradioactive steam makes a PWR the logical choice for an initial feasibility study. It is noted that a BWR will require additional design considerations due to radioactive steam.

The most common type of PWR is a Westinghouse 4-loop PWR, of which there are 26 units operating as of the end of 2022. Westinghouse also designed 2-loop and 3-loop PWRs, of which there are 5 units and 15 units operating, respectively, for a total of 46 operating Westinghouse PWRs. Thus, Westinghouse PWRs represent 75% of all operating PWRs in the U.S. ($46/68 = 75\%$). A 2-loop plant has two steam generators and reactor coolant pumps, while 3-loop and 4-loop plants have correspondingly increased numbers of steam generators and reactor coolant pumps. Due to the increased numbers of loops, 3-loop and 4-loop plants have higher thermal outputs than 2-loop plants. The rated thermal outputs of 2-loop, 3-loop, and 4-loop PWRs are approximately 1800, 2700, and 3500 MW_{th}, respectively. The fundamental designs of the plants are sufficiently similar that a 4-loop PWR is representative of 2-loop and 3-loop PWRs if the different reactor scales are properly accounted for. Considering that the 4-loop Westinghouse PWRs are the most common type and that they are representative of 75% of operating PWRs in the U.S., a 4-loop Westinghouse PWR has been selected for this study.

1.4 High-Level Design Parameters

The body of this report and Appendices A through J are based primarily on a preconceptual design report prepared by S&L with input from INL [19]. Appendix K contains recommendations for the control system implementation and is based on a report by Westinghouse [20]. The plant is assumed to have a generating capacity of approximately 1200 megawatts electric (MW_e), which is also reasonable for this design. Steam is extracted from the PWR using one or more new connections in the crossunder (cold reheat) piping between the HP turbine and the MSRs, as shown in Figure 3. This report considers two large-scale hydrogen production facilities with nominal ratings of 100 MW_{nom} and 500 MW_{nom}, respectively. Detailed information for both designs is located in the preconceptual design report prepared by S&L [19]. Table 2 provides the specific parameters for both designs. The nominal rating corresponds to the DC power input of HTEF at full hydrogen production. A 100 MW_{nom} HTEF is expected to produce as much as 55–58 MTs of hydrogen per day, depending upon the configuration.

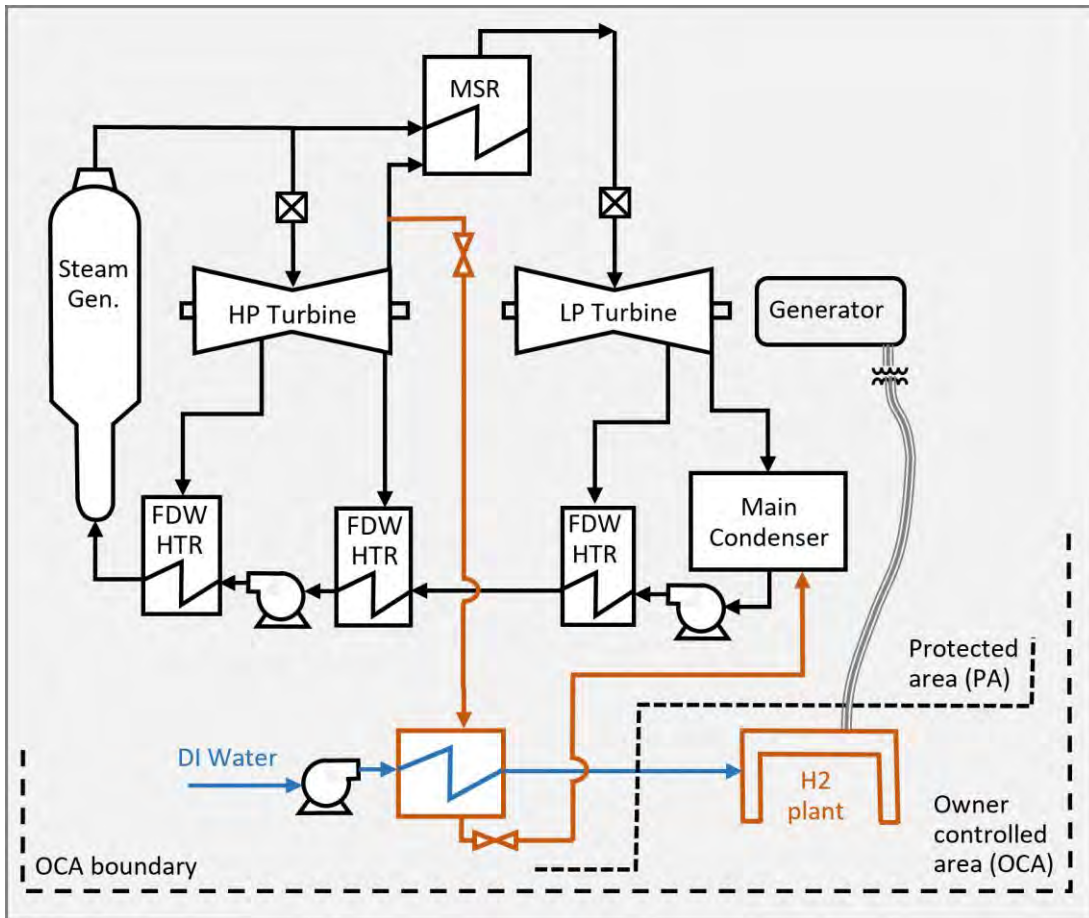


Figure 3. Steam extraction from cold reheat piping downstream of the HP turbine.

The exact amount of heat required by the HTEF to generate steam for hydrogen production depends on heat recuperation and other design choices within the plant. For this study, typical heat input requirements are assumed without performing detailed heat integration designs that depend upon the specific HTEF configuration, which is vendor dependent. Steam delivered to the HTEF is required at temperature of at least 300°F and pressure of at least 50 pounds per square inch gauge (psig). Analyses performed for this study achieved these requirements, as summarized in Table 2. The final steam conditions supplied to the HTEF are approximately 333°F and 74 pounds per square inch absolute (psia). Hydraulic analyses were performed to size the piping and auxiliary equipment required to meet thermal extraction demands for the HTEF. For the preconceptual design, minor additional thermal extraction is needed to cover various thermal losses, inefficiencies, and design margins typically associated with the sizing of piping, pumps, heat exchangers, valves, etc. As noted, the thermal power required for hydrogen production in an HTEF is approximately 20% of the nominal power. Based on these considerations, the thermal power requirement of the 100 MW_{nom} HTEF is taken to be 25 MW_{th}, and that of the 500 MW_{nom} HTEF is taken to be 105 MW_{th}. Both hydrogen facilities are assumed to be located outside of the protected area but inside the owner-controlled area (OCA), as indicated in Figure 3. Designs are prepared for distances of 250 m and 500 m between the PWR and the HTEFs. Product hydrogen is transported a safe distance away, such as 1 km, for high-pressure compression and storage.

Table 2. HTEF parameters by plant size.

| Parameter | Unit | HTEF Size | |
|--|------------------|-----------------------|-----------------------|
| | | 100 MW _{nom} | 500 MW _{nom} |
| Hydrogen Production Capacity ^a | U.S. tons/day | 55-58 | 275-290 |
| H ₂ Plant Electric Load MW _e | MW _e | 105 | 500 |
| H ₂ Plant Auxiliary Loads + Margin | MW _e | 22 | 50 |
| Power Factor | — | 0.92 | 0.92 |
| Total Electrical Power Requirements | MVA | 140 | 600 |
| H ₂ Plant Thermal Load | MW _{th} | 20 | 100 |
| Plant Thermal Losses + Margin | MW _{th} | 5 | 5 |
| Total Thermal Power Requirements | MW _{th} | 25 | 105 |
| Steam Input Temperature ^b | °F | >300 (333) | >300 (333) |
| Steam Input Pressure ² | psig | >50 (59.3) | >50 (59.3) |
| Separation Distance from PWR | m | 250 & 500 m | 250 & 500 m |

1 Conservative production capacities are shown based on 2022 values. Technology improvements over the next few years are expected to improve the yields of these plants to approximately 60 and 300 U.S. tons/day, respectively.

2 Parameters in parenthesis indicate actual design values.

Within the PWR, piping is installed to route the high-temperature steam from the crossunder piping to a steam reboiler that creates steam in a tertiary loop fed from a deionized or demineralized water source. This steam is then provided to the HTEF for use in the HTE process. Condensed drain flow on the secondary side of the steam reboiler is directed to a location within the secondary loop of the plant to minimize thermal losses.

The revenue meter for the NPP is assumed to be at a high-voltage switchyard, adjacent to the NPP protected area. Net metering of the HTEF may be required for cases where the revenue meter is located at the generator terminals or in the Turbine Building. It is also assumed there will not be any safety-related or Class I seismic equipment inside the Turbine Building.

Transmission system voltages vary throughout the country based on utility standard practices, system loading, and area geography. Typical interconnection voltages for commercial NPPs range from 230-500 kV. It is assumed for this report that the transmission system interconnection voltage for the reference plant is 345 kV. Electrical energy, in the form of alternating-current (AC) power, is diverted from the output of the main generator to the HTEF, where a majority of the required power is converted to rectified DC power.

The DC electrical loads required for hydrogen production were 100 MW_e and 500 MW_e for the 100 MW_{nom} and 500 MW_{nom}, respectively. As with thermal power, electrical losses and inefficiencies must be considered to supply adequate power to the facility. Additional electrical power needs to be supplied to the hydrogen facility to support plant auxiliaries and other ancillary loads. For the 100 MW_{nom} facility, a power factor of 0.92 was used in combination with 10% additional power (11 MW_e) for auxiliary power and 10% additional power (11 MW_e) for the margin. The 500 MW_{nom} facility used the same power factor and percent auxiliary power, but no margin (margin is covered by the increased auxiliary power). The total apparent electric power rating for these two facilities comes to 140 megavolts ampere (MVA) and 600 MVA, respectively.

2. 100 MW_{nom} HTEF DESIGN AND EQUIPMENT

2.1 Design

2.1.1 Description of Modification

Process steam from the plant's main steam system is extracted through one or more new connections in the crossunder (cold reheat) piping between the HP turbine and the moisture separator reheaters (MSRs). This insulated carbon steel steam piping includes manual isolation at the tap location(s) and an air-operated flow control valve (FCV) before the piping routes out of the Turbine Building to the hydrogen steam supply (HSS) steam reboiler. Station instrument air is used for the actuation of this control valve. During a turbine trip, air supply to this valve would stop, causing this valve to close, isolating the steam line. The process and instrumentation diagram (P&ID) provided in Appendix A shows the arrangement of steam extraction for the cycle. HSS equipment, located in an outdoor area adjacent to the TB within the protected area, is comprised of a steam reboiler, steam drum, drain receiver, drain cooler, reboiler feed pump, and demineralized water storage tank, reboiler feed level control valve, relief valve(s), and isolation valves. A potential layout of the HSS equipment is included in Appendix B. Station instrument air is routed from an available header in the TB to supply the control valve.

A H₂ interface control panel, located in the Main Control Room, provides operational control of the mechanical and electrical equipment that dispatches steam and power to the HTEF. See Section 2.1.4 for details, including the interface with the Main Control Room. The H₂ interface control panel also houses the protective relay components. On the plant secondary side of the reboiler, stainless steel drain piping is routed from the steam reboiler, to the drain receiver, the drain cooler, and finally to the main condenser in the TB. An air-operated level control valve is in the piping at the condenser, with tie-ins to the station instrument air system and control signal cables, which are routed from the reboiler drain receiver. A reverse osmosis (RO) system located within the HTEF boundary is required to generate the supply flow of demineralized water to the steam reboiler. High-density polyethylene (HDPE) piping is direct-buried at a suitable depth and routed from the RO system at the H₂ facility to the demineralized water storage tank within the Protected Area of the NPP. Stainless steel piping is routed from the tank to the suction of the reboiler feed pump. From the discharge side of the feed pump, stainless steel piping connects to the drain cooler, which is followed by the steam drum and then the steam reboiler. The drain cooler serves to preheat reboiler feedwater for hydrogen production and cool reboiler drain water headed to the condensers. The rate of demineralized water, which is fed to the drain cooler, is operated by a level control valve using station instrument air. Control signals are received from the water level transmitter within the steam drum. Insulation and heat tracing are added to exposed piping and outdoor equipment as needed.

Insulated carbon steel process steam piping from the reboiler is provided with a self-contained backpressure regulating valve before it is routed through the protected area boundary to the HTEF. Drains and steam traps are provided to remove condensed water from the line. Reboiler chemistry is maintained through provision of a blowdown connection that can be routed to a station drain. The ability to sample the reboiler blowdown enables plant personnel to ensure radioactivity has not inadvertently contaminated the flow of steam to the HTEF. The 345-kV transmission line (H₂ feeder) for the H₂ plant is tapped to the line between the NPP's generator step-up (GSU) transformer high-voltage bushing and the switchyard. The transmission line has two manually operated disconnect (MOD) switches and a 345-kV circuit breaker at the beginning of the line. The H₂ feeder is 0.5 km long, with the revenue meter at the beginning of the line. Located at the end of the line, inside of the HTEF boundary, are two 345-kV disconnect switches, a 345-kV circuit breaker, and a three-winding step-down transformer to convert the power down from 345 kV to 13.8 kV. Medium-voltage power cables are routed from the step-down transformer to two medium-voltage switchgears inside the HTEF. These cables and switchgear are to be provided as part of the H₂ facility design. The transmission line to the HTEF is protected by redundant microprocessor-based line-current differential (87L) relays. Each pair of relays communicates via fiber optic cables over the transmission line. The NPP's existing GSU transformer differential relays will cover the new high-voltage breaker at the H₂ feeder within their zone of protection. Interface with the existing plant tripping scheme of the existing GSU transformer differential relays is required to be able to trip the high-voltage breaker to the HTEF.

A conceptual site plan showing the thermal and electrical interface between the plants is provided in Appendix B.

2.1.2 Mechanical Design

2.1.2.1 Selection of NPP Steam Dispatch Location

The heat balance diagrams included in Appendix B illustrate the expected plant operating conditions when considering station operation without thermal extraction and station operation with the thermal extraction specified in Table 3. The modeling accounts for 1750 ft (approximately 530 m) of piping, with multiple fittings to allow a connection from the NPP to the HTEF. The heat balance model also accounts for heat loss through insulated outdoor piping.

The preferred location of extraction is cold reheat (i.e., downstream of the HP turbine exhaust and upstream of the MSRs). This steam extraction location provides sufficient thermal energy to heat up cold water to the targeted steam conditions while minimizing the impact to both station efficiency and transient operation (i.e., loss of supply steam to the HTEF). Steam extraction at this location also reduces the steam supply temperature experienced by the reboiler, limiting necessary design considerations for that component. Additional rationale for locating the steam dispatch location at the cold reheat is provided in Appendix C.

Table 3. Summary of important system parameters for 25-MW_{th} extraction.

| Parameter | Unit | Extraction Level | | Δ |
|--|------------------|--------------------|---------------------|----------------------|
| | | 0 MW _{th} | 25 MW _{th} | |
| Reactor Thermal Power | MW _{th} | 3659 | 3659 | — |
| Generator Output | MW _e | 1239.6 | 1234.3 | -5.3 MW _e |
| Main Steam Flow | Mlb/hr | 16.28 | 16.28 | 0.00% |
| Cold Reheat Flow | Mlb/hr | 12.73 | 12.72 | -0.05% |
| 25 MW _{th} Thermal Extraction Flow | lb/hr | 0 | 85,238 | — |
| Extracted Steam Fraction of Cold Reheat Flow | % | 0 | 0.67 | 0.67% |
| Remaining Steam to MSRs | Mlb/hr | 12.73 | 12.64 | -0.67% |
| Hot Reheat Flow | Mlb/hr | 11.26 | 11.17 | -0.76% |
| Heater Drain Forward Temperature | °F | 339.7 | 339.0 | -0.7°F |
| HP FWH Cascading Drain Flow | Mlb/hr | 1.39 | 1.39 | -0.23% |
| LP FWH Cascading Drain Flow | Mlb/hr | 2.42 | 2.41 | -0.41% |
| Heater Drain Tank Pressure | psia | 185.5 | 184.0 | -1.5 psi |

NOTE: Cascading drain conditions are averaged. Individual feedwater heater drain lines may have higher variations in conditions. Changes from 0 MW_{th} to 25 MW_{th} were calculated in Microsoft Excel. There may be slight differences due to truncation of values when entering the values in the table.

2.1.2.2 Selection of NPP Drain Return Location

The preferred location selected to return the condensed drain flow is at the main condenser. Returning to the main condenser allows sufficient energy removal from the cycle steam, while minimizing the amount of steam diversion and resulting impact to the NPP. Returning to other locations at higher temperatures (e.g., heater drain tank or a location in the feedwater system) would drive up the required mass flow of the diverted steam to achieve the required thermal extraction level and would result in further impacts to the NPP.

2.1.2.3 Thermal Analysis

A PEPSE Heat Balance model of a reference Westinghouse 4-loop PWR NPP was used to determine the impact on the station when considering various levels of thermal extraction. As previously discussed, the preferred location for steam extraction is cold reheat, and the preferred location for subcooled water return is the main condenser. The targeted steam conditions at HTEF are 300°F and 50 psig. Appendix C provides heat balance drawings, which shows the impact to the NPP when considering 25-MW_{th} power extraction. Table C-1 provides the station impact to significant parameters throughout the power cycle, considering 25-MW_{th} power extraction.

2.1.2.4 Impact on Plant Hazards

Not included in this report. See Reference [18].

2.1.2.5 Evaluation of Plant Transients

Introduction of the HTEF to the existing NPP could cause operational transients that would need to be addressed. Specifically, the startup or shutdown of the HTEF needs to be evaluated to ensure there are no adverse effects on the operation of the existing NPP. Plant response to various electrical transients and faulted conditions is described below. PEPSE Heat Balance diagrams (shown in Appendix C) are developed to evaluate the impact of extracting steam from the nuclear power cycle to supply thermal energy to a reboiler unit used to preheat the process steam for H₂ production. Table 3 provides a summary

of the important parameters for the 25-MW_{th} extraction. Note that only parameters exhibiting some degree of change are shown; other values, such as most system temperatures, show virtually no change (see Appendix C).

Table 3 shows the 25-MW_{th} extraction from cold reheat requires 85,238 lb/hr of steam, which corresponds to approximately 0.67% of total cold reheat flow. Startup of the HTEF requires opening of the steam extraction line from cold reheat to the reboiler unit. This operation diverts a very small portion, approximately 0.67%, of the total cold reheat flow and reduces the hot reheat flow to the low-pressure turbines by approximately 0.76%. These changes are not expected to cause any significant burden on the existing plant operation. Note that the main steam flow conditions remain virtually unchanged, and, therefore, the turbine control valve position remains unchanged. The only other important change is the slight reduction of the main generator output, approximately 5.3 MW_e, but this change represents only approximately 0.4% of the total generator output.

It is also noted that the extraction of steam from the cycles, as described in this report, is operationally similar to a low-pressure turbine bypass. Plants are typically designed with approximately 25% or more turbine bypass capability, and plant transients are already analyzed with turbine bypass that is much greater than the level of steam extraction described.

Similarly, for the shutdown of the H₂ production facility, the changes are insignificant and should not cause any significant burden on the existing plant operation.

2.1.2.6 Impact on Core Reactivity

The impact on core reactivity associated with extracting steam from the secondary cycle must be assessed for any plant-specific modification as described within this report. However, based on the scale of thermal power extraction considered for this preconceptual design (<1% of secondary mass flow), it is expected that there will be a minimal impact on reactivity for the conditions analyzed within this design report.

2.1.3 Electrical Design

The HTEF requires 105 MW_e power for the electrolysis process and approximately 11 MW_e for auxiliary loads. Using a power factor of 0.92 for H₂ plant processes and a 10% margin, the total power required by the HTEF is 140 MVA. Spacing between the electrolyzers and NPP equipment is approximately 0.5 km; therefore, power is supplied from the NPP via a 345-kV transmission line spanning the plant separation.

2.1.3.1 Selection of NPP Electrical Dispatch Location

The electrical physical layout diagram in Fig. B-7 illustrates the preferred electrical system tie-in point, which is the high-voltage side of the NPP main GSU transformer. The electrical feed to the HTEF consists of a high-voltage circuit breaker, two MOD switches, and a 0.5-km high-voltage transmission line. For a total apparent power rating of 140 MVA, the current rating of the high-voltage equipment must be in the range of approximately 162–350 A when considering a nominal transmission system voltage in the range of 230–500 kV. This is well within the typical rating of available high-voltage electrical equipment. The short circuit rating of the high-voltage circuit breaker should be selected to match the design ratings of the existing electrical switchyard.

An alternative option for the electrical system tie-in location is the generator isolated phase (isophase) bus. This may be advantageous for NPPs with insufficient space between the GSU transformer and transmission line dead-end structure to tap the high-voltage transmission line. The major drawbacks of connecting to the isolated phase bus are the relatively high cost of tapping the isophase bus, high short-circuit levels, and losses associated with transmitting electrical power 0.5 km at the generator voltage level. The short circuit levels at the outlet of the NPP isophase bus are typically more than 100 kA, which necessitates a specially designed generator circuit breaker for sufficient short circuit protection and isolation of the H₂ plant feed from the NPP. Further, it is not practical to extend the isophase bus 0.5 km to the HTEF. Limiting the available fault current to safe levels for transmission of electrical power via overhead lines or underground cable would require current-limiting reactors or a transformer connected between the isophase bus and the feeder to the HTEF, which leads to additional capital costs and electrical losses. Based on the challenges associated with the electrical tie-in at the isophase bus, this option is not investigated further in this report.

2.1.3.2 Electrical Design and Equipment within NPP Boundary

The 345-kV transmission line will be tapped to the line between the NPP GSU transformer's high-voltage bushing and the switchyard. The H₂ transmission line routes over a transmission tower to a 345-kV circuit breaker and its two MOD switches for line protection and maintenance. Potential transformers will be installed between the MOD switch and the high-voltage breaker for the new line's revenue meters. This equipment will be in the NPP protected area or yard area, depending on available space in the protected area. For a plant separation distance of 500 m, the H₂ transmission line will be routed over six more transmission towers to reach the H₂ plant area. The line then terminates at a 345-kV circuit breaker and associated disconnect switches and a three-winding, step-down transformer to step the power down from 345 kV to 13.8 kV inside the HTEF boundary. These components should be incorporated into the HTEF design and are outside the scope of this report. The two non-segregated buses or cables that connect the two secondary windings to two medium-voltage switchgears inside the HTEF also are part of the H₂ plant design and outside the scope of this report. See Fig. B-7 for the H₂ transmission line electrical physical layout. The three-winding step-down transformer is rated for 345 kV-delta/13.8 kV-wye/13.8 kV-wye, 84/112/140MVA ONAN/ONAF/ONAF, 9.5% nominal impedance H-X, H-Y. The 13.8-kV windings are resistance-grounded. Revenue meters are installed in different locations depending on the NPP. Some NPPs locate revenue meters inside the Turbine Building, outside after the GSU transformer or out in the switchyard. Therefore, the NPP and associated grid operators should have discussions early in the process to review their agreement in relation to the location of the connecting point of the H₂ feeder and the issues that can affect the location of the H₂ feed connecting point in relation to the meters such as GSU transformer power losses.

2.1.3.3 Transmission Line Control and Protection

The control and indication of the H₂ power line can be performed locally at the equipment or from the Main Control Room for the high-voltage circuit breaker. Also, the control and indication for the reboiler pump and control and position indication of the steam admission valve associated with the steam line can be performed from the Main Control Room. The two manually operated 345-kV disconnect switches will only have indications in the Main Control Room. It is assumed that the revenue meters for the new H₂ transmission line will be located outdoors close to their associated 345-kV breaker. Protective relays associated with the new high-voltage circuit breaker to protect the H₂ power line will be located in NPP Relay Room and utilize plant DC power sources. The transmission line protective relays at the end of the line will be located within the HTEF boundary. Coordination between the NPP and HTEF electrical equipment will be required.

2.1.3.4 Power Requirements for Hydrogen Steam Supply Equipment

HSS equipment located in the protected area requires 480 VAC and 125 VDC to operate the reboiler feed pump and any required auxiliary loads. The power will be supplied from a 480-VAC load center and 125-VDC distribution panel in the Turbine Building.

2.1.3.5 Switchyard Arrangement and Offsite Power

The switchyard breaker alignment is not affected by the addition of the new high-voltage line to the H₂ plant, as the new line is protected by a new high-voltage circuit breaker downstream of the tap point, as shown in electrical single-line diagram (Appendix H). The new H₂ power line has no impact on the switchyard voltage, breaker alignment, generator automatic voltage regulator (AVR) loading, or the status of offsite power voltage regulating devices. The H₂ production facility is physically and electrically separated from the offsite power circuits. Therefore, there is no impact to offsite power sources or plant safety loads, which are normally powered from offsite power sources.

2.1.3.6 Electrical Short Circuit and Load Flow/Voltage Drop Analysis

An electrical transient analyzer program (ETAP) electrical power system model was prepared to evaluate the power flow and short circuit impacts of the HTEF electrical tie-in (Appendix H). The model was developed based on typical electrical parameters for an NPP main power circuit. The ETAP model consists of the following components:

- Thevenin equivalent source representation of the high-voltage transmission system
- NPP synchronous generator
- NPP main GSU transformer
- 0.5-km high-voltage transmission line to the HTEF
- HTEF step-down transformer
- Two medium-voltage switchgear buses for the HTEF
- Lumped loads to represent the loading at the HTEF.

The step-down transformer supplying the HTEF is specified as a three-winding unit to supply 105 MW_e to the H₂ plant plus additional capacity for auxiliary loads. The application of a three-winding transformer enables the use of standard 3000A, 15-kV-class switchgear. Note that use of a two-winding transformer would be limited to a maximum apparent power supply rating of approximately 70 MVA at 13.8 kV ($3000\text{A} \times 13.8\text{kV} \times \sqrt{3} = 71.7\text{ MVA}$). A short circuit analysis was performed in ETAP to determine estimated equipment short circuit ratings and to aid in sizing the HTEF step-down transformer. The H₂ plant step-down transformer was modeled as an 84/112/140MVA ONAN/ONAF/OFAF three-winding transformer. The high-voltage winding is connected in delta and the medium-voltage windings connected in wye. The short circuit analysis model shows that a 9.5% nominal impedance between the H-X and H-Y windings (with $\pm 7.5\%$ tolerance) on the 42 MVA self-cooled base of the secondary windings allows for the use of 40-kA medium-voltage switchgear at the H₂ plant. The ETAP model shows that adding the hydrogen plant has a negligible impact on the existing NPP equipment. The hydrogen plant loads are primarily rectifiers supplying direct current to the electrolyzers (approximately 80% of total load). Diode-based rectifiers permit current to flow only in one direction and, therefore, do not supply short circuit current back to the power system. The only sources of short circuit current in the HTEF are motor loads in the auxiliary system. The amount of short circuit current supplied by the motor loads is negligible in comparison with the short circuit current supplied by the high-voltage transmission system and NPP generator. The ETAP model shows the HTEF contributes less than 0.1 kA of short circuit current at 345 kV when compared to approximately 38 kA from the system and approximately 7 kA from the NPP.

The ETAP model was also used to perform a load flow and voltage drop analysis to evaluate the sizing of the electrical equipment, including the HTEF step-down transformer. The load flow analysis shows the 140 MVA top rating of the H₂ plant step-down transformer is sufficient to carry the full load of the HTEF. The thermal load and voltage drop across the 0.5-km high-voltage transmission line is not significant. A typical transmission conductor size, such as a 795 kcmil Drake ACSR or higher, based on common transmission practices in the area is recommended.

The voltage drop analysis performed with the ETAP model shows that the hydrogen plant step-down transformer does not require an on-load tap changer if the transmission voltage is maintained within approximately a $\pm 2.5\%$ bandwidth. Per NUC-001, this applies to NPPs that operate per a voltage schedule and to NPPs that require strict voltage regulation for offsite power (assuming the offsite power source is supplied from the same location in the transmission system). In this case, a standard de-energized tap changer (with taps at $\pm 5\%$, $\pm 2.5\%$, and 0%) on the high-voltage winding provides flexibility to adjust the high-voltage winding voltage based on the target transmission system operating voltage. An on-load tap changer on the HTEF step-down transformer would provide additional flexibility for locations where the transmission system operating voltage may vary over a wider range and for locations where the hydrogen facility may operate while the NPP is in a refueling outage.

2.1.3.7 Protective Relaying Design

The electrical tie-in of the HTEF has a non-negligible impact on the NPP protective relaying scheme. The relay protection single-line diagram in Appendix H shows the conceptual protective relaying scheme design. In this design, the existing main GSU transformer differential protection scheme is restrained from operating for a fault on the high-voltage transmission line by summing a set of bushing current-transformers (CTs) from the new high-voltage circuit breaker with the existing switchyard CTs. This arrangement turns the transmission line to the NPP into a three-terminal line. Note that this requires careful evaluation of the existing CTs and relaying scheme to ensure that the new CTs on the high-voltage circuit breaker are properly matched (including CT ratio and accuracy class) and the scheme will function properly. In some instances, it may be required to upgrade the existing transformer or line protection package to a microprocessor-based relaying scheme to mitigate mismatch between the existing and new CTs. Additionally, the trip output of the existing line and GSU transformer protection scheme should be tied into the trip circuit of the new high-voltage circuit breaker protecting the line to the HTEF.

The high-voltage transmission line to the HTEF is protected by redundant microprocessor-based line-current differential (87L) relays. This scheme requires four redundant line-current differential relays, two on each end of the transmission line. Each pair of relays communicates via fiber optic over the transmission line optical ground wire (OPGW). High-speed protection is required per North American Electric Reliability Corporation (NERC) protection requirements for bulk electric system (BES) elements and to ensure the NPP generator remains stable should a fault occur on the transmission line. To ensure the stability of the NPP generator during fault clearing, the total clearing time of the line protection package needs to be less than the critical clearing time identified in the transient stability analysis. Additionally, breaker failure protection must be implemented so that the switchyard breakers or the generator circuit breaker (if the NPP is equipped with a generator circuit breaker) trip in the event of a failure of the new high-voltage circuit breaker.

The step-down transformer to the HTEF is protected by redundant transformer differential relays (87T). Overcurrent relays (50/51) are employed on the low-voltage windings for overload protection and backup overcurrent fault protection. The redundant transformer differential relays (87T) and the overcurrent relays are located inside the HTEF.

It is important to note that with this arrangement of the protection scheme, the only additional exposure for the NPP generator for a single failure is the very short length of conductor bus from the electrical tap point to the new high-voltage breaker. The length of this bus should be as short as practical to minimize additional exposure. There is no impact on the reliability of the offsite power circuits. Table 4 shows the required trip logic for different fault locations following the electrical tie-in of the hydrogen plant.

Table 4. Electrical fault condition trip logic.

| Fault Location | Initial Trip Device | H ₂ Breaker Failure Trip Device |
|---|--|--|
| Existing high-voltage line and line tap to new high-voltage circuit breaker | Existing high-voltage switchyard circuit breakers Generator circuit breaker (if equipped) New high-voltage circuit breaker | None |
| New high-voltage line to HTEF | New high-voltage circuit breaker New high-voltage step-down transformer circuit breaker | Existing high-voltage switchyard circuit breakers Generator circuit breaker (if equipped) |
| HTEF transformer | New high-voltage step-down transformer circuit breaker inside the HTEF | New high-voltage circuit breaker |

2.1.3.8 Electrical Transient Analysis

An electrical transient analysis was performed to evaluate the impacts of a trip of the hydrogen plant load on the existing NPP generator using PSCAD software. The ETAP model is described in Section 2.1.3.6 on the electrical short circuit and load flow/voltage drop analysis. The model consists of the following components:

- A representation of the surrounding high-voltage transmission system, including dynamic boundary bus source to capture governor response to a loss of large load in the area
- The NPP synchronous generator, including the AVR and governor control models
- The NPP main GSU transformer
- The 0.5-km high-voltage transmission line to the HTEF
- The HTEF step-down transformer
- Lumped loads to represent the loading at the HTEF.

The PSCAD model was used to simulate a trip of the hydrogen plant load under both faulted and unfaulted conditions. It is conservatively assumed that during the event, the turbine mechanical power will not ramp down in response to the transient but rather remain constant. Therefore, upon the trip of the HTEF, the excess power from the NPP generator is injected into the transmission system. The model shows that for a 105- MW_e electrical load with 10% auxiliary power and margin, the NPP generator remains stable for both faulted and unfaulted trips of the HTEF. During an unfaulted trip of the line, the generator exhibits a slight increase in mechanical speed (<0.02%), which is followed by damped oscillations. The mechanical transient decays within 10 seconds. After the hydrogen facility load is tripped, there is a slight increase in grid voltage (<0.5%) due to the loss of load. The generator excitation system responds to reduce the field current and return the grid voltage back to the pre-trip value. For a faulted trip of the HTEF load, the simulations show that a three-phase fault on the high-voltage transmission line must be cleared within 0.2 seconds to ensure the generator remains stable. For a three-phase fault on the high-voltage transmission line, cleared in 0.2 seconds, the generator mechanical

speed increases by approximately 2% during the fault. After the fault is cleared, there are several oscillations in the generator speed, as the mechanical transient decays within 10 seconds. The generator excitation system responds by increasing the field current during the fault and subsequent voltage recovery. After the voltage recovers, the excitation system restabilizes within several seconds. Note that the generator response during a faulted trip of the high-voltage transmission line is comparable to the response expected for a fault on any other transmission line connected to the high-voltage switchyard.

Additional sensitivity analysis was performed to determine the maximum amount of power that could be transmitted radially from the NPP to the nearby HTEF without impacting the stability of the NPP generator during a loss of load. The additional runs show that the H₂ plant load can be increased up to the maximum output power rating of the generator without causing the generator to become unstable following a trip of the high-voltage transmission line feeding the hydrogen facility, either with or without a fault. Note that this model is based on typical plant and transmission system data, which may not be representative of the available capacity for all plants. To lessen the impact on the grid during a high-voltage line trip for larger loads (near the rating of the generator), the H₂ plant loads may be accommodated by using redundant transmission lines and step-down transformers to distribute the load across multiple circuits. Note that redundant lines should not have a common failure mode such as utilizing multi-circuit transmission towers.

2.1.3.9 Bulk Electric System Regulatory Impacts

The high-voltage transmission line supplying the HTEF is classified as a BES element because the line is connected to a radial system with a generator that has a gross individual nameplate rating greater than 25 MVA and a voltage of 100 kV or above. Note that the BES classification includes only the high-voltage transmission line and excludes the step-down transformer supplying the HTEF. The BES classification subjects the transmission line and connected facilities (e.g., circuit breakers, disconnect switches, instrument transformers, and protective relays) to compliance with NERC Reliability Standards. Table 5 provides a summary of the applicable reliability standards. Note that the NPP is already subjected to the following standards.

Table 5. Applicable NERC Reliability Standards.

| Number | Title | Description |
|---------|---|---|
| CIP-014 | Physical Security | Physical security of the line and switchyard must be maintained to mitigate a physical attack that could result in instability of the nuclear facility. |
| FAC-001 | Facility Interconnection Requirements | The reliability impacts of the interconnection of the facility must be studied to ensure no negative impacts on the generator. |
| FAC-008 | Facility Ratings | The high-voltage transmission facility ratings and rating methodology must be documented and maintained. |
| MOD-032 | Data for Power System Modeling and Analysis | Steady-state, dynamic and short-circuit modeling data must be maintained and communicated with the transmission owner. |
| PRC-005 | Transmission and Generation Protection System Maintenance and Testing | A protection system maintenance and testing program shall be maintained. |
| PRC-023 | Transmission Relay Loadability | The protective relay settings shall be reviewed to ensure they do not affect line loadability. |
| PRC-027 | Coordination of Protections Systems for Performance During Faults | The transmission line protection shall be coordinated with the generator and transmission owner. A baseline short-circuit study shall be maintained. |
| TPL-001 | Transmission System Planning Performance Requirements | The relay protection systems shall be redundant such that failure of a single relay system does not impact the generator. |

2.1.4 Instrumentation and Controls Design

2.1.4.1 Operator Control Capabilities

As described in Section 4.1, the NPP supplies two principal components for the HTE process: (1) cold reheat steam from the HP turbine exhaust and (2) 345-kV electrical power. NPPs are usually loaded to 100% capacity; hence, the steam and electrical supplies to the HTEF are expected to contribute to this total. As with any plant system, it will be important for the NPP Control Room operators to have indications of the HTEF supply parameters and system conditions. This information is needed to effectively evaluate HTEF contributions to overall NPP operation and take any necessary actions. Actions that the operators may need to take include the ability to start and stop steam supply and electrical power to the HTEF. Additional guidance for the implementation of the control system can be found in Appendix K.

To facilitate HTEF operation, a dedicated set of operator controls with remote human-machine interface (HMI) will be provided. The HMI will allow for control, indication, and alarm of the H₂ power line and steam supply. These controls will be electrically and functionally isolated from NPP controls, but the remote HMI will be collocated in the NPP Main Control Room. Existing plant fiber optic infrastructure will be used to communicate between the HMI and equipment associated with H₂ power line and steam supply. This permits the status of the HTE process parameters to be available to NPP Control Room operators to evaluate the impact of HTEF loading on NPP operation. It also allows necessary on and off control for operators to enable or isolate the HTEF supply steam and electrical power. Additional indication and controls will be provided locally to the HSS equipment.

The operator should be trained in operating the power and steam supplies from the NPP to the HTEF using the new standalone HMI. A special procedure should be prepared for this operation.

2.1.4.2 Available Process Parameters for Monitoring

The following process parameters are expected to be available to allow plant personnel to monitor performance of the thermal and electrical extraction systems:

- Electrical power consumption on the plant computer logging system
- Steam flow diverted from the plant on the plant computer system (for plant performance engineer)
- HSS equipment trouble alarm in Main Control Room
- Hydrogen plant trip or fire alarm in Main Control Room.

2.1.4.3 Response to Faulted Conditions

An understanding of how the plant and equipment will respond to postulated faulted conditions is critical when moving forward with a design change to plant equipment. The following is a summary of potential failure modes of the installed thermal and electrical extraction components and a brief description of the plant and operations response to ensure that the plant can be maintained in a safe condition:

- Extraction Steam leak to reboiler—Response depends on the severity and location of leak. If possible, extraction steam line is isolated through manual or remote closure of the steam admission valve to the reboiler. Without extraction steam supply, H₂ plant shutdown would occur. If isolation is not possible, manual trip of the NPP would occur, similar to the response to an unisolable MS line leak.
- Process Steam leak to HTEF—Leak can be isolated through manual closure of process steam supply valve leaving the reboiler. H₂ plant shutdown would occur. The NPP turbine generator would pick up load, and the grid would absorb the additional load.
- Reboiler drain valve fails closed—This should not occur since the valve is set to fail open. However, if this event were to occur, reboiler drain level would rise in the reboiler. Either the extraction steam supply valve would close on high-high level or an emergency dump valve would open to the lower level.
- Reboiler Drain valve fails open—Level in the reboiler would drop and potentially steam would be passed to the condenser. A level-to-valve position automatic comparison could be implemented to close the steam admission valve.
- Extraction Steam supply valve fails open—This should not occur since the valve is set to fail closed. However, if this event were to occur, the design pressure of both sides of the reboiler are equal to or greater than the steam conditions. The amount of condensation would be controlled by the demand from the HTEF. The condensate level would be controlled by the condensate drain valves. With normal operation of the reboiler feed supply, the plant would continue to operate normally.

- Extraction steam supply valve fails closed—The reboiler level would fall; the condensate drain line would control the level by closing down. Process steam to the HTEF would cease flowing, and the H₂ plant would shut down. The closure of the steam line would divert the steam flow to the turbine. The turbine steam admission valve would either slightly close or the generator would produce more power, which would be absorbed by the grid.
- Rapid trip of HTEF—Steam demand from the NPP to the HTEF would cease, the level on the hydrogen-side of the reboiler would increase, and the supply water admission valve would close in response. This would remove cooling from the plant-side of the reboiler and steam condensation would decrease. The condensate drain valve would close down to maintain the level until it completely closed. The steam that would have gone to the reboiler would be available to the low-pressure turbines. Either the turbine admission valve would throttle down or more power would be supplied to the grid.
- Short in high-voltage line—Overcurrent protection, as discussed in this report, would trip the hydrogen plant, and the balance of the transient would be like the rapid trip of the hydrogen plant.
- Open in high-voltage line—An open in the high-voltage line would trip the HTEF, and the NPP would respond in the same manner as a rapid trip of the HTEF.

2.1.4.4 Design Attribute Review

A strategic plan called “Delivering the Nuclear Promise: Advancing Safety, Reliability and Economic Performance,” was developed to ensure the financial viability of the commercial nuclear power industry through a partnership of U.S. nuclear utilities. The Nuclear Strategic Issues Advisory Committee (NSIAC) created a series of initiatives related to the Delivering the Nuclear Promise plan. One of the initiatives was the development of a standard process to streamline design changes for plants through adopting a standardized process, applying a graded approach to modifications, and alleviating some of the administrative burden associated with the existing processes.

The Design Oversight Working Group (DOWG) developed industry procedure IP-ENG-001, “Standard Design Process” [21], which was subsequently adopted by the industry because of this initiative. Consistent with its stated goals, the procedure provides a graded approach for selecting from multiple types of engineering changes (e.g., commercial, equivalent, and design change), which streamlines the modification process. When performing an engineering change in accordance with IP-ENG-001, the responsible engineer completes the Design Attribute Review (DAR), which is a series of questions that aids in the identification of impacted disciplines, stakeholders, and programs. As part of the preconceptual design, a sample DAR has been completed [Appendix J]. While this effort must be performed on a plant and design-specific basis when performing a similar modification, the information is provided as an example to guide the process. Key design attributes to consider are discussed below.

2.1.4.5 Electrical

This conceptual design covers the installation of 0.5 km of 345-kV transmission line between the GSU transformer and the HTEF. A 345-kV high-voltage circuit breaker and two associated disconnect switches, potential transformers (PTs), and transmission line tower will be installed in the plant protected area or the yard area, depending on available space around the GSU transformer. Step-down transformer 345-13.8 kV with two disconnect switches will be installed at the end of the transmission line in the HTEF.

- The control/indications of the 345-kV circuit breaker and indication only for the breaker-associated disconnect switches for the H₂ transmission line are from the Main Control Room. All the required protective relays for the H₂ power line are located in the plant Relay Room. The local control and monitoring for the electrical equipment associated with the H₂ steam line, such as a water pump, are from the Main Control Room. A standalone HMI for control and indications of the H₂ power line and steam supply is available in the Main Control Room, using existing fiber optic infrastructure in the plant to communicate between the HMI and equipment associated with H₂ power line/steam line.
- CTs at the H₂ feeder high-voltage circuit breaker will be brought back into the existing GSU transformer differential relays to cover the new high-voltage breaker within their zone of protection. Interface with the existing plant tripping scheme of the existing GSU transformer differential relays is required.
- Low-voltage AC power (480 VAC) is supplied from the plant AC auxiliary power system to HSS equipment for the reboiler feed pump. Also, 125 VDC is supplied from the plant for the high-voltage breaker control and protective relay circuits.
- The installation of a new power line to supply power to the HTEF has no effect on the switchyard voltage, breaker alignment, generator AVR loading, or status of offsite power voltage regulating devices.
- All added electrical equipment and the towers for the transmission line are connected to the station's grounding.
- The added power cables (480 VAC and 125 VDC) and CT cables in the TB should meet plant design and materials requirements. The added cables require evaluation against the plant's fire requirements or raceway capacity.
- The load flow analysis demonstrates the change in the switchyard voltage due to the addition of the 105-MW_e electrical load plus auxiliaries is negligible. As such, there is no impact to generator volt-amperes reactive (VAR) loading, which is controlled based on switchyard voltage.
- The switchyard breaker alignment is not impacted by the addition of the new high-voltage line to the hydrogen plant as the new high-voltage line is protected by a new high-voltage circuit breaker downstream of the tap point. The only additional exposure for the NPP generator and switchyard breakers to trip for a single failure is for a fault on the very short length of the conductor bus from the electrical tap point to the new high-voltage breaker. The length of this bus work is designed as short as practical to minimize the additional exposure.
- Generator electrical characteristics are a function of the synchronous machine design and construction and are not impacted by the addition of the hydrogen production facility. The impact is comparable to the addition of a new line or load fed directly from the transmission switchyard.

- The hydrogen production facility is physically and electrically separated from the offsite power feed. Therefore, there is no impact to offsite power loading for the post-trip scenario.
- The load flow analysis demonstrates the change in the switchyard voltage from the addition of the 105-MW_e electrical load plus auxiliaries is negligible. Therefore, the status of offsite power voltage regulating devices is not impacted.

2.1.4.6 Instrumentation and Controls (I&C)

The use of digital controls is an integral component of the proposed coupling of an HTEF to an NPP. Standard Design Process (SDP) IP-ENG-001 directs that any NPP modification that involves digital equipment must assign a digital engineer in accordance with Nuclear Industry Standard Process NISP-EN-04, Standard Digital Engineering Process. This procedure supplements the SDP by addressing additional engineering activities applicable to modifications involving programmable electronic equipment.

- A goal of the proposed design is to minimize the modification of existing digital controls, or the addition of new digital components, to the NPP. This is accomplished through use of a dedicated set of operator controls and remote HMI. The DAR process will identify and document the appropriate design inputs and bounding technical requirements. A determination must be made to classify the digital controls components to determine whether the requirements of NISP-EN-04 apply.
- For digital controls subject to meeting these requirements, additional engineering activities are needed to demonstrate compliance. These additional activities are described and explained in Electric Power Research Institute (EPRI) 3002011816, Digital Engineering Guide.
- Adopting nuclear cybersecurity rules for those components installed at the HTEF may impose additional costly and unnecessary requirements. Commercial cybersecurity may be used in lieu of nuclear cybersecurity depending on component locations, digitalization of vendor-procured instrumentation and controls (I&C), and impacts on plant safety, among other considerations. Site-specific reviews should be conducted to determine whether hydrogen projects demand nuclear cybersecurity requirements.

2.1.4.7 Mechanical

This modification includes a range of new mechanical components that will be added to the plant, including manual valves, check and relief valves, control valves, a heat exchanger (reboiler), a pump, a tank, and steam traps. Inclusion of these components involves hydraulic considerations such as pump sizing, available net positive suction head (NPSH), fluid velocity, pressure drop, American Society of Mechanical Engineers (ASME) code requirements, and system design conditions (temperature and pressure).

- Detailed design of the discharge piping for the reboiler feed pump should consider the potential for vibration. Use of industry best practices, such as short vent/drain cantilevers and 2-1 socket weld profiles, should limit the potential for piping vibration susceptibility. Post-modification testing will validate the adequacy of the design.
- Steam piping and drain piping installed by this modification requires analysis to evaluate expected primary and secondary pipe stress. Provisions for thermal flexibility (expansion loops) will be required in the steam piping routed to the HTEF. Nozzle reaction loads require evaluation to vendor-supplied nozzle allowables.
- Pipe support design will be informed by pipe reaction loads output from stress analyses.
- Depending on the local climate, freeze protection may be required for demineralized water piping when above ground and for the demineralized water storage.

- Piping installed by this modification includes saturated steam and saturated water and, therefore, should be evaluated for inclusion in the plant flow-accelerated corrosion (FAC) program. Portions of the drains piping from the reboiler to the condenser could include two-phase flow and should be evaluated for potential erosion concerns.
- The reboiler will require pressure relief. Considerations include relieving pressure setpoint, relieving capacity, and code requirements.
- Air-operated valves included in this modification are expected to use the plant instrument air system. This impact requires evaluation to ensure that the system maintains adequate positive operating margin.
- Based on site-specific analysis results, impacts on reactivity will require assessment due to potential changes in final feedwater temperature and expected transient associated with a fault at the H₂ facility or control failure of the steam/drains piping flow. No significant impacts are anticipated based on the thermal analysis and transient discussions previously provided.
- Water/steam hammer effects should be considered for system transients and for system startup (e.g., introducing steam into a cold pipe). It is noted that adequate steam pipe drainage is critical with such a long run of outdoor steam pipe. Several drain pots may be needed along the pipe route and at low points to avoid water slug accumulation that could cause water/steam hammer.
- Provision for venting and draining piping and equipment will be required.
- The design should include the ability to sample the dispatched steam (or at a minimum the reboiler blowdown) to ensure that the steam flowing to the HTEF does not include radiological contamination.
- A new condenser connection will be added with this modification. Protection of condenser internals (e.g., tube impingement) should be considered when choosing the connection location, baffle, or sparger design, etc. Impacts to nozzle loading on the condenser walls need to be evaluated.

2.1.4.8 Structural

- Pipe supports are required for steam and drain piping, including pipe supports to route steam piping 0.5 km to the HTEF.
- Foundation designs are required for HSS equipment, transformers, disconnect switches, circuit breakers, etc.
- The addition of the demineralized water tank should be evaluated as a potential flood source.

2.1.4.9 Programs

- The piping added to the MS and Secondary Drains system will need to be evaluated against FAC program criteria.
- The fire protection program should consider the impact of new cables and conduits on combustible loading. Additionally, the location of the HSS equipment will require review for accessibility by the fire brigade.
- The heat exchanger (steam reboiler), relief valves, check valves, and air-operated valves will need to be added to the FAC and fire brigade program criteria.
- The welding required by the modification should be reviewed by the material compatibility and welding programs.
- The NERC program should review the impacts of the modification. The protective relays of the H₂ transmission line will interface with the plant existing generator and GSU transformer differential relays to cover the new high-voltage breaker within their zone of protection.

2.1.4.10 Stakeholders

- Since the PRA model is affected by the modification, PRA is required as a stakeholder
- System Engineering, Operations, Training, and Maintenance groups are required as stakeholders due to the new equipment added to the plant
- The high-voltage aspects of the modification require Industrial Safety and Transmission as stakeholders
- Site-specific design may include transmitting information to the plant computer
- Security will be required as a stakeholder for the modification due to the installation of HSS equipment within the protected area. These items affect line-of-sight and lighting in the area.

It should be noted that routing the 12-in. steam piping from within the station protected area to the HTEF does not meet the definition of a three-dimensional pathway as defined in NEI 09-05 [21] and, therefore, does not require a physical barrier or intrusion detection. Site-specific security input will be used in the design of pipe routing through protected area fencing.

Site security may also take actions to accommodate the additional personnel and vehicles needed onsite if the HTEF happens to be located within the OCA.

The DAR provided in Appendix J and summarized above has not identified any concerns or obstacles beyond what would be expected for a typical nuclear modification of this magnitude. One key area of note, however, is the consideration of impacts on Security as a stakeholder routing electrical and mechanical commodities across the protected area boundary is not typical of general plant modifications.

2.1.4.11 Considerations of Alternate Designs

Not included in this report. See Ref. [19].

2.1.5 Additional Design Options and Considerations

2.1.5.1 Additional Circuit Breaker

An alternative option for H₂ line protection and the minimization of a single-point vulnerability (SPV) is the installation of two 345-kV circuit breakers in series to protect the hydrogen power line. This design prevents a generator trip; if one of the 345-kV breakers fails to trip and clears the line fault, the second breaker can trip before the generator protection trips. This option depends on the protection philosophy of the NPP and available land.

2.1.5.2 Shell and Tube Reboiler Option

The design presented in this section uses a welded plate and frame heat exchanger as the extraction steam reboiler. Other heat exchangers may also be used at the discretion of the plant. Discussions with different heat exchanger vendors have revealed that a kettle-style shell and tube reboiler may provide an alternate design solution. The kettle-style design simplifies the HSS arrangement by removing the need for an external steam drum, at the expense of a larger physical footprint when compared to the welded plate and frame heat exchanger with a steam drum. The cost of this option is comparable to the welded plate and frame design; therefore, the option should be considered during detailed design.

In Section 3.1.5.2, a kettle-style shell and tube reboiler is used to illustrate the feasibility of the design implemented within the 500-MW_{nom} preconceptual design. The contrasting complexity and size of these designs are illustrated through the respective P&IDs and physical reboiler arrangements (Appendix A).

2.1.5.3 Chrome-Moly or Stainless Steel Steam Piping to H₂ Facility

In this section, carbon steel piping is used to provide reboiler steam to the HTEF (refer to Section 2.2.2). Extended use of carbon steel under expected conditions may increase refurbishment or

replacement frequency and could require the installation of a filter before the SOECs to avoid rust contamination. To reduce contaminants, alternative piping materials may be used. Both chrome-moly and stainless-steel piping are reasonable choices, which would reduce corrosive wear at the expense of higher material and labor costs. All piping selections in the plant protected area should follow nuclear piping codes and standards.

2.1.5.4 Net Metering in Place of 100-MW_{nom} Electrical Dispatch

Net metering uses several revenue meters in the power plant to measure power delivered in different areas and on separate transmission lines. An NPP can use net metering to supply energy to the HTEF behind the meter, avoiding the restrictions of a poorly placed revenue meter that would require power is supplied to the grid before it reaches the HTEF.

NPP revenue meters are installed in different locations depending on the plant. They can be located inside TBs, on the high-voltage side of the GSU transformer, or out in the switchyard. The power line for the hydrogen facility supply should be tied in behind the NPP's revenue meters. If a plant's revenue meters are located inside the TB or immediately after the GSU transformer, net metering should be considered.

The NPP and associated grid operators should have discussions early in the process to reach agreement regarding the tie-in location of the connecting point of the H₂ feeder. NPPs should consider net metering if they have limitations connecting the hydrogen feeder before the plant existing revenue meter.

2.1.5.5 Decreased Separation Between NPP and HTEF

The 500-m separation selected for this design was based on a generic PRA, assuming a large hydrogen detonation from a production facility approximately five times larger than this 100-MW_{nom} design (see Ref [19] Section 3.3.2). There is a strong likelihood that relocating the 100-MW_{nom} HTEF adjacent to the NPP would be safe and would adhere to regulatory requirements, with the further addition of barriers or protective measures as needed. Decreasing the separation between the NPP and HTEF provides one cost-saving strategy since thermal piping and electrical transmission costs are reduced. Based on expected spacing of components within the protected area boundary and the HTEF boundary, the minimum separation distance is anticipated to be approximately 250 m.

Section 4.3 illustrates the cost difference between this reduced separation option and the original 500-m spacing. Note, the location of the HTEF is highly dependent on available land and on the location of plant equipment, including the switchyard. Section 5.3 discusses siting limitations for the hydrogen production facility.

Detailed cost breakdowns for the integrating a PWR with a 100 MW_{nom} HTEF with standoff distances of 250 m and 500 m can be found [19; Attachment L]. Appendix I provides a detailed cost breakdown for 500 MW_{nom} HTEF option located 500 m from the NPP. Appendix B illustrates potential site arrangements for these options.

2.2 Major Equipment Required for Preconceptual Design

Equipment sizing is presented in the following sections based on the thermal and electrical analyses discussed in Section 2.1.2 and Section 2.1.3, along with analyses included in Appendices C through G. As a site-specific project moves into the detailed design phase, the considerations for final pipe sizing and location of major equipment would be evaluated with a focus on constructability and overall integration cost.

Further design optimization related to the delivered temperature and pressure of the steam extracted from the NPP can be performed based on the site-specific requirements to enable the least cost of the NPP auxiliary equipment and connection commodities. Additionally, site-specific research into the location of the hydrogen plant with respect to the NPP may provide avenues for cost optimization through the reduction of electrical transmission, steam piping, and demineralized water commodities. Continued optimization of this preconceptual design could drive further cost reductions.

2.2.1 Reboiler Sizing

Performance parameters for the steam reboiler are determined using the PEPSE analysis provided in Appendix C. Sizing information for input to reboiler vendors is provided considering 25-MW_{th} thermal power extraction in Table 6. Note that the parameters in Table 6 are at the connections to/from the reboiler.

Table 6. Reboiler sizing parameters for 25-MW_{th} power extraction.

| Connection Location | Mass Flow Rate | | Temperature | | Pressure | |
|--|----------------|--------|-------------|----|-----------|------|
| | | | | | | |
| Steam Supply from Cold Reheat | 85,238 | lbm/hr | 364 | °F | 161 | psia |
| Drain to Main Condenser | 85,238 | lbm/hr | 120 | °F | by Vendor | |
| Demineralized Water Supply | 73,777 | lbm/hr | 60 | °F | 140 | psia |
| Steam Supply to H ₂ Production Facility | 73,777 | lbm/hr | 350 | °F | 120 | psia |

2.2.2 Piping and Reboiler Feed Pump Sizing Summary

Adding the hydrogen production facility to the existing NPP requires sizing of the various pipelines, which is performed based on the 25-MW_{th} thermal extraction. Steam pipe sizes are determined in Appendix D and Appendix E. Water pipe sizes are determined in Appendix F and Appendix G. Additionally, the reboiler feed pump is sized, and the reboiler drain control valve conditions are determined.

The results of pipe sizing are summarized as follows:

- Extraction steam piping to the H₂ plant steam reboiler (Appendix D)
Pipe size of 10-in., standard thickness (STD) schedule carbon steel, 240-ft long was modeled, resulting in a maximum steam velocity of ~120 ft per second (ft/sec). Design pressure of 250 psig and design temperature of 400°F were selected to envelop the steam conditions.
- Process steam piping to the HTEF (Appendix E)
Pipe size of 12-in., STD schedule carbon steel, 1750-ft long was modeled from the steam boiler to the H₂ plant, resulting in a maximum steam velocity of ~130 ft/sec. Design pressure of 150 psig and design temperature of 400°F were selected to envelop the steam conditions.
- Reboiler feed water pump and piping (Appendix F)
For the pump discharge, a pipe size of 2.5-in., STD schedule carbon steel, 240-ft long was modeled, resulting in a maximum water velocity of approximately 10 ft/sec. In the actual design, stainless steel was used. Later refinement of this design reduced this pipe length to ~50 ft (refer to Ref. [19, Attachment K]). Design pressure of 250 psig and design temperature of 150°F were selected to envelop the water conditions, including an additional 50% in pump head rise to shutoff conditions.

For the pump suction, a 3-in. pipe size (one size larger than the discharge to lower suction velocity was selected), STD schedule carbon steel, 40-ft long was modeled, and it resulted in a maximum water velocity of approximately 6.4 ft/sec. Stainless steel was used in the actual design. Design pressure of 50 psig and design temperature of 150°F were selected to envelop the water conditions.

- Pump size

The pump sizing is based on the nominal flow rate of 147.5 gallons per minute (gpm) and the nominal carbon steel pipe characteristics, resulting in a required pump total developed head of approximately 379 ft, requiring approximately 18 horsepower (hp).

- Drain piping from the reboiler to the main condenser (Appendix G)

The drain pipe size of 3.5-in., STD schedule carbon steel, 220-ft long was modeled, resulting in a maximum water velocity of approximately 5.6 ft/sec. In the actual design, stainless steel was used. Design pressure of 200 psig and design temperature of 400°F were selected to envelop the drain conditions.

- Drain control valve size

The drain control valve sizing results in the following requirements:

- Drain flow: 85,238 lbm/hr (~172 gpm)
- Valve differential pressure: ~155.7 psid
- Valve inlet pressure: ~158 psia

Note that due to a very high valve differential pressure, there is a high potential for valve flashing and cavitation; therefore, a severe duty drain control valve should be considered for this application and for an internal baffle plate to protect condenser internals.

2.2.3 Demineralized Water Storage Requirement

Onsite storage of demineralized water provides reserve capacity for periods when supply flow from the H₂ facility RO system is unavailable. The appropriate onsite capacity of stored demineralized water is at the discretion of plant engineering and management to ensure continued operation during maintenance evolutions, for example. This decision would likely consider the amount of time that the HTEF is expected to be in use, the expected availability of the RO water supply, and upfront costs associated with installation of a large storage tank. The size (and therefore capacity) of the tank may also be limited by the available space near the H₂ steam reboiler, where a tank could be located. For this preconceptual design, a reserve capacity of 110,000 gallons was chosen. Appendix C shows that a demineralized water flowrate of approximately 150 gpm is required to generate the desired steam flow to the HTEF.

Therefore, a storage tank of 110,000 gallons would provide reserve capacity for approximately 8–12 hours of continuous operation. A tank of this size could be approximately 25 ft in diameter and 30-ft tall.

2.2.4 Major Equipment List

The major equipment required to implement the preconceptual modification as described in this report is summarized in Table 7. This listing is not intended to be all-inclusive but to provide a high-level understanding of the major equipment needed in the design. Depending on site-specific design and configuration additional commodities, such as tubing, small-bore piping, cable, and conduit, must also be considered. Materials needed for piping supports, transmission towers, among others are also excluded from this equipment list but are included in the cost estimate in Appendix I.

Table 7. Major equipment needed for 100 MW_{nom} integration design.

| No. | Item | Quantity | Description/Notes |
|------------|---|------------|---|
| 1 | Steam Reboiler | 1 | Refer to Section 4.3.1 for sizing information |
| 2 | Drain Cooler | 1 | |
| 3 | Steam Drum Tank | 1 | Approximately 4 ft diameter |
| 4 | Drain Receiver | 1 | Approximately 2 ft diameter |
| 5 | Demineralized Water Storage Tank | 1 | 10,000-gallon capacity |
| 6 | Reboiler Feed Dump | 1 | 150 gpm at 380 ft TDH (\cong 18 hp) |
| 7 | 8 in. Steam Dispatch Air-Operated FCV | 1 | — |
| 8 | 10 in. Non-Return Valve | 1 | — |
| 9 | 10 in. Steam Manual Isolation Valves | 3 | Double isolation from crossunder pipe and isolation at reboiler |
| 10 | 3.5 in. Air-Operated Level Control Valve | 1 | Refer to Section 2.2.2 for design conditions |
| 11 | 2.5 in. Air-Operated Level Control Valve | 1 | Refer to Section 2.2.2 for design conditions |
| 12 | 10 in. Self-Contained Backpressure Regulating Valve | 1 | — |
| 13 | 12 in. Steam Manual Isolation Valves | 3 | Isolation at reboiler and upstream/downstream |
| 14 | 10 in. Carbon Steel Piping with Fittings | ~240 ft. | Schedule STD |
| 15 | 12 in. Carbon Steel Piping with Fittings | ~1800 ft. | Schedule STD |
| 16 | 2.5 in. Stainless Steel Piping with Fittings | ~50 ft. | Schedule STD |
| 17 | 3 in. Stainless Steel Piping with Fittings | ~40 ft. | Schedule STD |
| 18 | 3.5 in. Stainless Steel Piping with Fittings | ~220 ft. | Schedule STD |
| 19 | 3 in. HDPE Piping with Fittings | ~1800 ft., | Schedule 40 |
| Electrical | | | |
| 1 | 345 kV Manually Operated Disconnect Switch | 2 | 45 kA short circuit |
| 2 | 345 kV high-Voltage Circuit Breaker | 1 | 45 kA short circuit |
| 3 | Transmission Towers for 345-kV Line | 6 | — |
| 4 | Coupling Capacitor Voltage Transformer | 3 | 345 kV/120V |
| 5 | Protective Relay 50BF | 1 | — |
| 6 | Breaker Failure Lockout relay 86BF | 1 | — |
| 7 | Line Differential Protection Relay 411L/87 | 2 | — |
| 8 | Line Differential Protection Relay 311L/87 | 2 | — |
| 9 | Line Differential Lockout Relay 86 | 1 | — |
| 10 | Revenue Meter | 3 | — |
| 11 | 795 kemil Drake ACSR with OPGW Shield Wire | 1600 m | — |

3. 500 MW_{nom} HTEF DESIGN AND EQUIPMENT

Note: Text that is substantially different from the 100 MW_{nom} HTEF Design and Equipment (Section 2) is marked with italics.

3.1 Design

3.1.1 Description of Modification

Similar to the 100-MW_{nom} preconceptual design, process steam from the crossunder (cold reheat) piping of the MS system will be extracted for the 500-MW_{nom} design. *Given the larger volume of steam needed, extraction is taken from two crossunder lines, one on each side of the HP turbine, to avoid turbine imbalances. Manual isolation is provided for both carbon steel lines at the tap location before the lines combine into a common header inside the TB. After routing out of the building, the header branches into two lines to supply the steam to the HTEF in two independent, identical reboiler loops. Each line is equipped with a station instrument air controlled FCV before passing into the respective steam reboiler. During a turbine trip, air supply to the FCVs would stop, causing the valves to close and isolate the lines.*

The P&ID provided in Appendix A shows the arrangement of steam extraction for this 500-MW_{nom} design. *The two independent loops help to improve gradual startup of the system, reduce pipe sizing, and enable partial hydrogen production during system maintenance. Using a single reboiler loop would require larger, more expensive equipment while increasing the potential for operating issues associated with startup and shutdown transients of the NPP and HTEF.*

The layout of the HSS equipment is the same as for the 100 MW_{nom} HTEF design.

The 345-kV transmission line (H₂ feeder) and other electrical equipment for the HTEF is identical to that of the 100 MW_{nom} HTEF design. A conceptual site plan showing the interfaces between the HTEF and the NPP is provided in Ref. [19, Attachment U].

3.1.2 Mechanical Design

3.1.2.1 Selection of NPP Steam Dispatch Location

The heat balance diagrams included in Appendix C illustrate the expected plant operating conditions when considering station operation without thermal extraction and station operation with 105-MW_{th} extraction to the HTEF. As previously noted, it is expected that only approximately 100 MW_{th} is required by the HTEF while the remaining 5 MW_{th} is extracted to account for thermal losses and potential inefficiencies in the HSS system.

The design conditions for the 105 MW_{th} extraction system are the same as for the 25 MW_{th} dispatch design, except as noted below.

3.1.2.2 Selection of NPP Drain Return Location

The preferred location selected to return the condensed drain flow is at the main condenser. The rationale is the same as for the 25 MW_{th} dispatch design.

3.1.2.3 Thermal Analysis

A PEPSE Heat Balance model of a reference 4-loop Westinghouse PWR NPP was used to determine the impact on the plant considering various levels of thermal extraction. The analysis methodology and approach are the same as for the 25 MW_{th} dispatch design. Appendix C provides heat balance drawings showing the impact to the NPP considering 105-MW_{th} power extraction levels. Table C.2 in Appendix C provides the station impact to significant parameters throughout the power cycle, considering 105-MW_{th} power extraction.

3.1.2.4 Impact on Plant Hazards

Same as for the 25 MW_{th} dispatch design.

3.1.2.5 Evaluation of Plant Transients

The methodology and approach for the evaluation of plants transients are the same as for the 105 MW_{th} dispatch design. PEPSE Heat Balance diagrams (shown in Appendix C) are developed to evaluate the impact of extracting steam from the nuclear power cycle to supply thermal energy to a reboiler unit used to preheat the process steam for H₂ production. Table 8 provides a summary of the important parameters for the 105-MW_{th} extraction. Note that only parameters exhibiting some degree of change are shown. Other values, such as most system temperatures, show virtually no change. Additional details are presented in Appendix C.

Table 8. Summary of important system parameters for 105-MW_{th} extraction.

| Parameter | Unit | Extraction Level | | Total Δ for 2 Trains |
|--|------------------|--------------------|----------------------|------------------------|
| | | 0 MW _{th} | 105 MW _{th} | |
| Reactor thermal Power | MW _{th} | 3659 | 3659 | — |
| Generator Output | MW _e | 1239.6 | 1217.2 | -22.47 MW _e |
| Main Stream Flow | Mlb/hr | 16.28 | 16.28 | 0.00% |
| Cold Reheat Flow | Mlb/hr | 12.73 | 12.70 | -0.20% |
| 105 MW _{th} Thermal Extraction Flow | lb/hr | 0 | 355,193 | — |
| Extracted Steam Fraction of Cold Reheat Flow | % | 0 | 2.80 | 2.80% |
| Remaining Steam to MSRs | Mlb/hr | 12.73 | 12.35 | -2.99% |
| Hot Reheat Flow | Mlb/hr | 11.26 | 10.90 | -3.18% |
| Heater Drain Forward Temperature | °F | 339.7 | 337.0 | -2.7°F |
| HP FWH Cascading Drain Flow | Mlb/hr | 1.39 | 1.38 | -0.92% |
| LP FWH Cascading Drain Flow | Mlb/hr | 2.42 | 2.37 | -1.72% |
| Heater Drain Tank Pressure | psia | 185.5 | 179.5 | -6.0psi |

NOTE: Cascading drain conditions are averaged. Individual feedwater heater drain lines may have higher variations in conditions. Changes from 0 MW_{th} to 105 MW_{th} are calculated in Microsoft Excel. There may be slight differences due to truncation of values when entering the values in the table.

As displayed in Table 8, the 105-MW_{th} extraction from cold reheat requires 355,193 lb/hr (~177,597 lb/hr per train) of steam; this corresponds to approximately 2.80% (1.4% per train) of total cold reheat flow. Normal startup of the HTEF involves startup of one reboiler train at a time, which requires opening of the steam extraction line from cold reheat to the reboiler unit. This operation diverts a small portion, approximately 1.4% (for one train), of the total cold reheat flow and reduces the hot reheat flow to the low-pressure (LP) turbines by approximately 1.6% (for one train). These changes result in a 22.4-MW_e (11.2 MW_e per train) reduction in main generator output, which represents approximately 1.8% of the total generator output.

It is also noted that the extraction of steam from the cycles, as described in this report, is operationally similar to a LP turbine bypass. Plants are typically designed with approximately 25% or more turbine bypass capability and plant transients are already analyzed with turbine bypass much greater than the level of steam extraction described. Similarly, for normal shutdown (shutting one reboiler train at a time) of the H₂ plant, the changes are relatively small and should not cause a significant burden on the existing plant operation. Only during an unexpected event, such as loss of total power to the HTEF, a transient involving the shutdown of two reboiler trains at the same time could be expected.

3.1.2.6 Impact on Core Reactivity

The impact on core reactivity associated with extracting steam from the secondary cycle must be assessed for any plant-specific modification as described within this report. Based on 2.8% of secondary mass flow extraction, reactivity impacts are not anticipated to be insignificant. *However, even sudden perturbations resulting from events at the HTEF should not exceed the capabilities of the normal NPP controls system response. From a mechanical design perspective, the largest impact to the NPP would come from an event in the HSS. An event that suddenly halts the HSS would impact the NPP in a similar manner as a load rejection event. That is, a loss of HTEF steam demand would result in a similar plant controls systems response as that which occurs when there is a loss of generator load. In the case of a ~3% load rejection, the NPP rod control system should provide ample control capability to prevent the need for any protective functions to actuate or the need for any immediate operator actions. Operators would follow their indications to take actions appropriately using alarm response or other plant operating procedures. In the case of a steam line break in the HSS piping, there is no discernible difference from a break in other areas of steam piping in the NPP. If a break occurs, the automated and operator responses will be the same as they would be for another steam break somewhere in the NPP steam systems. The HTEF steam piping will be equipped with isolation valves that will enable isolation of the HSS system and continued operation of the NPP. Similar to a loss of HTEF steam demand, operators would follow their indications to take actions appropriately using an alarm response or other plant operating procedures.*

3.1.3 Electrical Design

The HTEF requires 500 MW_e power for the electrolysis process and approximately 50 MW_e for auxiliary loads. Using a power factor of 0.92 for HTEF processes, the total power required for by the HTEF is 600 MVA. Spacing between the electrolyzers and NPP equipment is approximately 0.5 km; therefore, power is supplied from the NPP via a 345-kV transmission line spanning the plant separation.

3.1.3.1 Selection of NPP Electrical Dispatch Location

The methodology and approach for the evaluation of plants transients is the same as for the 100 MW_{nom} HTEF, except as noted below. The electrical physical layout diagram in Appendix B illustrates the preferred electrical system tie-in point, which is the high-voltage side of the NPP's main GSU transformer, for the 500 MW_{nom} HTEF.

3.1.3.2 Electrical Design and Equipment within NPP Boundary

The design and equipment for the 500 MW_{nom} HTEF is identical to the 100 MW_{nom} HTEF, except as noted below.

The 345-kV transmission line will be tapped to the line between the NPP GSU transformer's high-voltage bushing and the switchyard. The H₂ transmission line routes over a transmission tower to a 345-kV circuit breaker and its two MOD switches for line protection/maintenance. PTs will be installed between the MOD switch and the high-voltage breaker for new line's revenue meters. This equipment is in the NPP protected area or yard area, depending on available space in the protected area. For a plant

separation distance of 500 m, the H₂ transmission line will be routed over six more transmission towers to reach the HTEF area.

At the HTEF, there are two two-winding step-down transformers rated for 345 kV-delta/34.5 kV-wye, 190/253/306MVA ONAN/ONAF/ONAF, 9% nominal impedance H-X. The 34.5-kV windings are resistance-grounded. Within the H₂ plant are nine two-winding step-down transformers rated for 34.5 kV-delta/13.8 kV-wye, 42/56/70 MVA ONAN/ONAF/ONAF, 7.5% nominal impedance H-X 34.5kV/13.8 kV to supply power at the 13.8-kV level to the H₂ electrolyzers. The equipment at the HTEF is part of the HTEF design and is outside the scope of this report. See Ref. [19, Attachment V] for the H₂ transmission line electrical physical layout.

3.1.3.3 Transmission Line Control and Protection

Identical to that the 100 MW_{nom} HTEF design.

3.1.3.4 Power Requirements for Hydrogen Steam Supply Equipment

Identical to the 100 MW_{nom} HTEF design.

3.1.3.5 Switchyard Arrangement and Offsite Power

Identical to the 100 MW_{nom} HTEF design.

3.1.3.6 Electrical Short Circuit and Load Flow/Voltage Drop Analysis

The design and analysis for the 500 MW_{nom} HTEF design is identical to the 100 MW_{nom} HTEF design, except as noted below. The step-down transformer supplying the HTEF is specified as a *two-winding unit to supply 500 MW_e* to the HTEF plus 10% additional capacity for auxiliary loads.

A short circuit analysis was performed in ETAP to determine estimated equipment short circuit ratings and aid in sizing the HTEF step-down transformer. The HTEF step-down transformers were modeled as *190/253/306MVA ONAN/ONAF/ONAF two-winding* transformers. The high-voltage winding is connected in delta and the medium-voltage winding is connected in wye. The short circuit analysis model shows that a *9% nominal impedance between the H-X windings (with ±7.5% tolerance) on the 190 MVA* self-cooled base of the secondary windings allows for the use of *40-kA 34.5-kV circuit breaker and 40-kA 13.8-kV* medium-voltage switchgear at the HTEF.

Similar to the 100-MW_{nom} HTEF, ETAP model shows that the addition of the HTEF has a negligible impact on the existing NPP equipment. The analysis and results for the 500 MW_{nom} HTEF design is identical to the 100 MW_{nom} HTEF design, except as noted below.

The load flow analysis shows the *316 MVA* top rating of the HTEF step-down transformers is sufficient to carrying the full load of the HTEF. The voltage drop across the 0.5-km high-voltage transmission line is not significant. *For the 500-MW_{nom} HTEF, a two-conductor bundle, such as a 2-1113 kcmil Bluejay ACSR or higher based on common transmission practices in the area, is recommended based on the line thermal loading.*

The voltage drop analysis performed with the ETAP model shows that the hydrogen plant step-down transformer does not require an on-load tap *changer if the transmission voltage is maintained within approximately a ±2.5% bandwidth*. Per NUC-001, this applies to NPPs that operate per a voltage schedule and to NPPs that require strict voltage regulation for offsite power (assuming the offsite power source is supplied from the same location in the transmission system).

3.1.3.7 Protective Relaying Design

Nearly identical to the 100 MW_{nom} HTEF design. Table 9 shows the required trip logic for different fault locations following electrical tie-in of the hydrogen plant.

Table 9. Electrical fault condition trip logic.

| Fault Location | Initial Trip Device | H ₂ Breaker Failure Trip Device |
|---|---|--|
| Existing high-voltage line and line tap to new high-voltage circuit breaker | Existing high-voltage switchyard circuit breakers Generator circuit breaker (if equipped) New high-voltage circuit breaker | None |
| New high-voltage line to HTEF | New high-voltage circuit breaker New high-voltage step-down transformer circuit breaker | Existing high-voltage switchyard circuit breakers Generator circuit breaker (if equipped) |
| HTEF transformer | New high-voltage step-down transformer circuit breaker inside the H ₂ island <i>34.5 kV circuit breakers in the HTEF</i> <i>13.8 kV breakers in the HTEF</i> | New high-voltage circuit breaker |

NOTE: Same as Table 4 for 100 MW_{nom} HTEF design, except for the addition of the last two lines.

3.1.3.8 Electrical Transient Analysis

Sensitivity analysis shows that the HTEF load can be increased up to the maximum output power rating of the generator without causing the generator to become unstable following a trip of the high-voltage transmission line feeding the HTEF, either with or without a fault. This bonds the design being considered for the 500-MW_{nom} HTEF. Note that this model is based on typical plant and transmission system data, which may not be representative of the available capacity for all plants.

3.1.3.9 Bulk Electric System Regulatory Impacts

Similar to the 100-MW_{nom} design, the high-voltage transmission line supplying the HTEF is classified as a BES element because the line is connected to a radial system with a generator that has a gross individual nameplate rating of greater than 25 MVA and a voltage of 100 kV or above. The BES classification subjects the transmission line and connected facilities (e.g., circuit breakers, disconnect switches, instrument transformers, and protective relays) to compliance with NERC Reliability Standards. Table 4 provides a summary of the applicable NERC Reliability Standards. Note that the NPP is already subjected to the following standards.

3.1.4 Instrumentation and Controls Design

3.1.4.1 Operator Control Capabilities

The operator control capabilities for this 500-MW_{nom} design are identical to those capabilities described in the design for the 100 MW_{nom} HTEF. Given the duplication of HSS equipment (e.g., reboilers, pumps, and tanks), equipment-specific controls will need to be duplicated in this area based on the new equipment. A single HMI can still be used in the Main Control Room for indication and control of steam supply and electrical transmission equipment.

3.1.4.2 Available Process Parameters for Monitoring

Available processing parameters for monitoring are identical to the 100-MW_{nom} design.

3.1.4.3 Response to Faulted Conditions

Overall response to faulted conditions is similar to the 100-MW_{nom} design, with differences as noted below.

Extraction Steam leak to reboiler—Response depends on the severity and location of the leak. With two trains of reboilers, the leak could be isolated to the affected train, allowing the second train to operate. HTEF steam supply would be halved. If the leak is located so that both trains must be isolated, then H₂ plant shutdown would occur. If isolation is not possible, a manual trip of the plant NPP would occur, which is similar to the response to an unisolable MS line leak. The addition of a remote manual (motor- or air-operated valve) at the extraction point would allow for the online construction of parts of the steam extraction line and would facilitate positive isolation in the event of a steam leak in the steam extraction line. Steam isolation transients are described in this report.

- Process steam leak to HTEF—With two separate trains of process steam, it may be possible to isolate the affected train. The leak could be isolated to the affected train, allowing the second train to operate. HTEF steam supply would be halved. This transient is described in the transient section of this report. The generator would pick up load from the affected train and the grid would absorb the additional load.
- Reboiler drain valve fails closed—This should not occur since the valve is set to fail open. However, if this event were to occur, the level would rise in the affected reboiler. Either the extraction steam supply valve for the affected train would close on high-high level or an emergency dump valve would open to the lower level. It is recommended to have a drain bypass valve open on high level and the steam line isolated on high-high level. The affected train could be isolated, allowing the second train to operate. HTEF steam supply would be halved.
- Reboiler drain valve fails open—The level in the affected reboiler would drop and steam could be passed to the condenser. A low-level switch should be implemented to close the steam admission valve on low-level and drain valve open position. The affected train could be isolated, allowing the second train to operate. HTEF steam supply would be halved.
- Extraction steam supply valve fails open—This should not occur since the valve is set to fail closed. However, if this event were to occur, the design pressure of both sides of the reboiler are equal to or greater than the steam conditions. The amount of condensation would be controlled by the demand from the HTEF. The condensate level would be controlled by the condensate drain valves. With normal operation of the reboiler feed supply, the plant would continue to operate normally.
 - Extraction steam supply valve fails closed—With two trains of extraction steam supply and reboilers, a closed valve will only affect one train. The level in the affected reboiler level would fall; the condensate drain line would control level by closing. One train of process steam to the H₂ plant would cease to flow. Steam flow to the LP turbines would increase by ~1.7%. The closure of the steam line may start to increase the level in the steam generator. The feedwater control system would reduce feedwater flow to match the reduced steam demand and stabilize the level. The transient to the grid is described below. In the longer term, the generator output could be reduced to match the grid demand.
 - Rapid trip of HTEF—Steam demand would cease, the process feed level on the hydrogen-side of the reboiler would increase, and the supply water admission valve would close in response. This would remove cooling from the plant-side of the reboiler, and steam condensation would decrease. The condensate drain valve would close to maintain level and the HSS going to the reboiler would be rerouted to the LP turbines. Steam flow to the LP turbines would increase by 3.3%. The closure of the steam line would immediately start to increase the level of the steam generator. The feedwater control system would reduce feedwater flow to match the reduced steam

demand and stabilize level. The transient to the grid is described below. In the longer term, the generator output could be reduced to match grid demand.

- Short in high-voltage line—Overcurrent protection, as discussed in this report, would trip the HTEF, and the balance of the transient would be like the rapid trip of the HTEF.
- Open in high-voltage line—An open in the high-voltage line would trip the HTEF and the NPP would respond in the same manner as a rapid trip of the HTEF.

3.1.4.4 Design Attribute Review

When performing an engineering change in accordance with IP-ENG-001, the responsible engineer completes the DAR, which is a series of questions that aids in identifying impacted disciplines, stakeholders, and programs. As part of the preconceptual design, a sample DAR has been completed and provided as Appendix J. While this effort must be performed on a plant-/design-specific basis when performing a similar modification, the information is provided as an example to guide the process.

The following design attributes are unique to the 500-MW_{nom} design.

3.1.4.5 Electrical

- This conceptual design covers the installation of 0.5 km of 345-kV transmission line between the GSU transformer and H₂ plant. A 345-kV high-voltage circuit breaker and two associated disconnect switches, PTs, and transmission line tower will be installed in the plant's protected area or the yard area, depending on the available space around the GSU transformer. *End of the line, inside the HTEF will have two step-down transformers, step the power down from 345 kV to 34.5 kV. Each transformer will have one 345-kV circuit breaker and two 345-kV disconnect switches. Also, two outdoor 34.5-kV buses with nine 34.5-kV breakers, each connected to step-down transformer, will step the power down from 34.5 kV to 13.8 kV switchgears.*
 - The load flow analysis demonstrates the change in the switchyard voltage due to the addition of the 500-MW_e electrical load plus auxiliaries is negligible. As such, there is no impact to generator VAR loading, which is controlled based on switchyard voltage.
 - The load flow analysis demonstrates the change in the switchyard voltage due to the addition of the 500-MW_e electrical load plus auxiliaries is negligible. Therefore, the status of offsite power voltage regulating devices is not impacted.

3.1.4.6 Mechanical

Identical to the 100 MW_{nom} HTEF design.

3.1.4.7 Instrumentation and Controls (I&C)

Identical to the 100 MW_{nom} HTEF design.

3.1.4.8 Structural

Identical to the 100 MW_{nom} HTEF design.

3.1.4.9 Programs

Identical to the 100 MW_{nom} HTEF design.

3.1.4.10 Stakeholders

Identical to the 100 MW_{nom} HTEF design.

3.1.5 Additional Design Options and Considerations

3.1.5.1 Additional Circuit Breaker

Developing site-specific design criteria may include alternatives to the design proposed within this report. Options for an additional circuit breaker, different piping materials, onsite RO, and net metering are all discussed in reference to the 100 MW_{nom} HTEF design and are equally relevant for the 500 MW_{nom} design. Further alternate design options are described below.

3.1.5.2 Plate and Frame Reboiler Option

The preconceptual design put forth in this section uses a 3.1.5.2-style shell and tube heat exchanger as the extraction steam reboiler. Other heat exchangers may also be used at the discretion of the plant. Discussions with other vendors have revealed that a plate and frame reboiler may provide an alternate design solution. The plate and frame design is more compact compared to the kettle-style reboiler, but it is at the expense of a more complex arrangement required through the addition of an external steam drum. The cost of this option is comparable to the kettle-style shell and tube heat exchanger and should be considered during detailed design for a similar modification.

In Section 2, a plate and frame reboiler was provided for the 100-MW_{nom} preconceptual design to show its feasibility. The contrasting complexity and size of these designs is illustrated through the respective P&IDs and physical reboiler arrangements in Appendix A.

3.1.5.3 Main Steam Extraction

Section 5.4 discusses in detail the limitations of cold reheat extraction. Of notable importance is the potential for imbalances and stresses on the turbines with large volumes of extraction and available space within the TB for the routing of two 14-in. steam lines. Main steam extraction is a viable alternative to the location used for this report. Table 10 highlights the benefits and drawbacks of both locations. The improved efficiency of cold reheat is expected to make this option financially preferable at this scale, but other factors, such as spatial availability and turbine loading, should be considered in detail to determine which extraction location is best for a given plant. Turbine manufacturers should be consulted to validate conclusions of the site. Appendix C provides detailed thermal analysis of both extraction locations.

Table 10. Pros and cons of different extraction locations for 500-MW_{nom} design.

| | Pros | Cons |
|------------------------|--|---|
| Cold Reheat Extraction | Greatest plant efficiency (+15.5 MW _e vs. main steam extraction) Lower-temperature extraction than Main Steam can lower material and maintenance costs | Larger piping is more expensive and harder to route through the Turbine Building Reduced mass flow to LP turbines can cause wear on the turbines and may reduce the life span of equipment |
| Main Steam Extraction | Smaller piping is less expensive and easier to route through the Turbine Building No turbine imbalances | Lower plant efficiency than cold reheat extraction HELB analysis will be required due to steam conditions Higher temperature extraction requires more resilient materials for piping and greater HSS equipment costs High-pressure turbine operating pressure may drop below minimum-pressure limit due to lower mass flow |

Main steam and cold reheat are the best locations for steam extraction based on the steam properties. Extracting steam too far upstream will result in plant efficiency losses by removing high-quality steam from the NPP power cycle. Extractions too far downstream provides low quality, low energy steam for the HTEF, decreasing electrolyzer efficiency. It is anticipated that cold reheat will be the preferable location at low extraction levels (3% of mass flow).

3.1.5.4 Decreased Separation Between NPP and HTEF

Identical to the 100 MW_{nom} HTEF design.

3.2 Major Equipment Required for Preconceptual Design

The approach and methodology are identical to the 100 MW_{nom} HTEF design.

3.2.1 Reboiler Sizing

Performance parameters for the steam reboiler are determined using the PEPSE analysis provided in Appendix C. Sizing information for input to reboiler vendors is provided considering 105-MW_{th} thermal power extraction in Table 11. Note that the parameters in Table 11 are at the connections to/from the reboiler.

Table 11. Reboiler sizing parameters for 105-MW_{th} power extraction.

| Connection Location | Mass Flow Rate | | Temperature | | Pressure | |
|-------------------------------|----------------|--------|-------------|----|-----------|------|
| | | | | | | |
| Steam Supply from Cold Reheat | 355,193 | lbm/hr | ~360 | °F | ~154 | psia |
| Drain to Main Condenser | 355,193 | lbm/hr | 120 | °F | by Vendor | |
| Demineralized Water Supply | 306,980 | lbm/hr | 60 | °F | 140 | psia |
| Steam Supply to HTEF | 306,980 | lbm/hr | 350 | °F | 120 | psia |

3.2.2 Piping and Reboiler Feed Pump Sizing Summary

Adding the hydrogen production facility to the existing NPP requires sizing the various pipelines, which is performed based on the 105-MW_{th} thermal extraction. Steam pipe sizes are determined in Ref. [19, Attachment B] and Ref. [19, Attachment C]. Water pipe sizes are determined in Ref. [19, Attachment D] and Ref. [19, Attachment E]. In addition, the reboiler feed pump is sized and reboiler drain control valve conditions are determined.

The results of pipe sizing are summarized as follows:

- Extraction steam piping to the H₂ plant steam reboiler Ref. [19, Attachment N].

Two 14-in. pipes were connected to the cold reheat pipes on either side of the HP turbine for extraction. Each of these lines was STD (standard pipe size) schedule carbon steel and 40-ft long. These lines joined to a 20-in., STD schedule carbon steel header that was 200-ft long. After routing out of the TB, the header once again split into two 14-in., STD schedule carbon steel lines that spanned 20 ft each until reaching their respective steam reboilers. Maximum steam velocity was ~153 ft/sec. Design pressure of 250 psig and design temperature of 400°F were selected to envelop the steam conditions.

- Process steam piping to the HTEF Ref. [19, Attachment O].

Pipe size of 18-in., STD schedule carbon steel and 1750-ft long was modeled from the steam boiler to the HTEF, resulting in a maximum steam velocity of ~130 ft/sec. Design pressure of 150 psig and design temperature of 400°F were selected to envelop the steam conditions.

- Reboiler feed water pump and piping Ref. [19, Attachment D].

For the pump discharge, a pipe size of 3.5-in., STD schedule carbon steel and 240-ft long was modeled, resulting in a maximum water velocity of approximately 10 ft/sec. *Stainless steel piping was used for the actual design, resulting in a conservative pump sizing.* Design pressure of 250 psig and design temperature of 150°F were selected to envelop the water conditions, including an additional 50% in pump head rise to shutoff conditions.

For the pump suction, a 4-in. pipe size (one size larger than the discharge to lower suction velocity was selected) of STD schedule carbon steel and 40-ft long was modeled, and it resulted in a maximum water velocity of approximately 7.7 ft/sec. Stainless steel was used in the actual design, *resulting in a conservative pump sizing.* Design pressure of 50 psig and design temperature of 150°F were selected to envelop the water conditions.

- Pump size

The pump sizing is based on the *nominal flow rate of 306.8 gallons per minute (gpm)* and the nominal carbon steel pipe characteristics, resulting in a required pump total developed head of approximately 367 ft, *requiring approximately 36 horsepower (hp).*

- Drain piping from the reboiler to the main condenser Ref. [19, Attachment E].

The *drain pipe size of 5-in.*, STD schedule carbon steel and 220-ft long was modeled, resulting in a maximum water velocity of *approximately 6 ft/sec.* In the actual design, stainless steel was used. Design pressure of 200 psig and design temperature of 400°F were selected to envelop the drain conditions.

- Drain control valve size

The drain control valve sizing results in the following requirements:

- Drain flow: 177,597 lbm/hr (~358.8 gpm)
- Valve differential pressure: ~1552.0 psid
- Valve inlet pressure: ~154.1 psia

Note that due to a very high valve differential pressure, there is a high potential for valve flashing/cavitation. Therefore, a severe duty drain control valve should be considered for this application and an internal baffle plate to protect condenser internals.

3.2.3 Demineralized Water Storage Requirement

Design considerations are similar to those for the 100 MW_{nom} HTEF design. For the purposes of this preconceptual design, a reserve capacity of 110,000 gallons was chosen. Ref. [19, Attachment A] shows that a demineralized water flowrate of approximately 310 gpm per loop is required to generate the desired steam flow to the HTEF. Therefore, a storage tank of 110,000 gallons would provide reserve capacity for *approximately 4–6 hours* of continuous operation. A tank of this size is expected to be approximately 25 ft in diameter and 30 ft tall.

3.2.4 Major Equipment List

The approach and considerations are similar to those for the 100 MW_{nom} HTEF design. The major equipment required to implement the preconceptual modification as described in this report is summarized in Table 12.

Table 12. Major equipment needed for 500 MW_{nom} integration design.

| No. | Item | Quantity | Description/Notes |
|-------------------|---|-----------|--|
| 1 | Steam Reboiler | 2 | Refer to Section 3.2.1 for sizing information |
| 2 | Drain Cooler | 2 | |
| 3 | Drain Receiver | 2 | Approximately 3 ft diameter |
| 4 | Demineralized Water Storage Tank | 2 | 10,000-gallon capacity |
| 5 | Reboiler Feed Dump | 2 | 310 gpm at 367 ft TDH (approximately 36 hp) |
| 6 | 12 in. Steam Dispatch Air-Operated FCV | 2 | — |
| 7 | 14 in. Non-Return Valve | 2 | — |
| 8 | 14 in. Steam Manual Isolation Valves | 10 | Double isolation at both crossunder tie-ins, double isolation after header branches, and isolation to reboiler |
| 9 | 5 in. Air-Operated Level Control Valve | 2 | Refer to Section 3.2.2 for design conditions |
| 10 | 3.5 in. Air-Operated Level Control Valve | 2 | Refer to Section 3.2.2 for design conditions |
| 11 | 14 in. Self-Contained Backpressure Regulating Valve | 2 | — |
| 12 | 18 in. Steam Manual Isolation Valves | 6 | Isolation at reboiler and upstream/downstream isolation PCV |
| 13 | 14 in. Carbon Steel Piping with Fittings | ~120 ft. | Schedule 30 |
| 14 | 18 in. Carbon Steel Piping with Fittings | ~3500 ft. | Schedule STD |
| 15 | 20 in. Carbon Steel Piping with Fittings | ~200 ft. | Schedule 20 |
| 16 | 3.5 in. Stainless Steel Piping with Fittings | ~480 ft. | Schedule STD |
| 17 | 4 in. Stainless Steel Piping with Fittings | ~80 ft. | Schedule STD |
| 18 | 5 in. Stainless Steel Piping with Fittings | ~440 ft. | Schedule STD |
| 19 | 3.5 in. HDPE Piping with Fittings | ~3600 ft. | Schedule 40 |
| Electrical | | | |
| 1 | 345 kV, 300A Manually Operated Disconnect Switch | 2 | 50 kA short circuit |
| 2 | 345 kV, 300A High-Voltage Circuit Breaker | 1 | 50 kA short circuit |
| 3 | Steel Poles for 345 kV line | 6 | Transmission line tower |

| No. | Item | Quantity | Description/Notes |
|-----|---|----------|---------------------------------|
| 4 | Coupling Capacitor Voltage Transformer (CCVT) | 3 | 345 kV/120V |
| 5 | Protective Relay 50BF | 1 | — |
| 6 | Communication System: Cabinet NEMA 4X with meters and Aux. telecommunication for revenue meters | 1 | — |
| 7 | A standalone HMI for control and indications of the H ₂ power line and steam supply, in the Main Control Room | 1 | — |
| 8 | Breaker Failure relay (50BF) | 1 | — |
| 9 | Breaker Failure Lockout relay (86BF) | 1 | — |
| 10 | Line Differential Protection Relay 411L/87 | 3 | — |
| 11 | Line Differential Protection Relay 311L/87 | 3 | — |
| 12 | Line Differential Lockout Relay 86 | 1 | — |
| 13 | Revenue Meter | 3 | — |
| 14 | 1113 kmil Bluejay ACSR with OPGW Shield Wire | 3200 m | Transmission line cable outdoor |

4. PLANT INTEGRATION COST ESTIMATING

The development of an accurate cost estimate for a nuclear-integrated hydrogen production facility requires a detailed understanding of plant specifications, vendor price estimates, and indirect costs associated with the project construction and development. For each of these general preconceptual designs, a cost estimate is developed for the integration activities within the scope of the NPP only; costs associated with design and construction of the equipment inside the HTEF boundary are excluded from these estimates. The Association for the Advancement of Cost Engineering (AACE) has developed a classification system for assessing the expected accuracy of cost estimates (see Reference 21). Based on the maturity level of project definition deliverables and the use of this report as a preconceptual guide, these cost estimates fall into Class 5. Following the methodology described by this class, the accuracy of these estimates is expected to vary between -50% and +100%. The actual value depends on the risk and suitability of assumptions associated with each cost item. Plant-specific studies are required to improve these assumptions and increase estimated accuracy. Vendor estimates should be included on a plant-specific basis. The purpose of these estimates is to allow plant owners to understand the magnitude of capital costs required for the NPP-associated modifications with pursuing a 100-MW_{nom} and 500-MW_{nom} HTEF addition. This study provides a quantifiable reference for engineering, installation, and turnover/procurement costs for a project of a similar magnitude. This study can be used to inform plant-specific feasibility studies and assess the capital necessary to pursue nuclear-integrated hydrogen at the scale investigated.

4.1 Scope of Included Costs

These estimates aim to consider all costs associated with NPP modifications included in Table 7 and Table 12. A cost analysis breakdown was performed for each of the following activities:

- HSS
- Civil work (e.g., excavation, disposal, backfill, and caisson)
- Concrete work (e.g., foundation, embedment, formwork, and reinforcing)
- Mechanical equipment (e.g., reboiler and demineralized water storage tank)
- Piping (e.g., above ground, buried, supports, valves, and insulation)
- Electrical equipment (e.g., heat tracing, control panel, and transformer)
- I&C
- Steel supports
- Electrical and Transmission Line
- Civil work (e.g., excavation, disposal, backfill, and caisson)
- Concrete work (e.g., foundation, embedment, formwork, and reinforcing)
- Switchyard (e.g., transmission tower pole and hardware, breakers and disconnects, transformers, and wiring)
- Electrical equipment (e.g., revenue meter, grounding, and control panels)
- Cables and conduits
- HMI
- Steel supports.

4.1.1 Methodology

Estimates are based on an engineer, procure, construction management (EPCM) multiple contract approach. This approach has one main contractor, typically an architect/engineer (A/E) firm to produce the design, assist in the procurement of goods and services, and provide construction management services during construction. The EPCM contractor generally acts as an agent for the owner when purchasing such goods and services, meaning contracts and purchase orders are written on the owner's letterhead.

These cost estimates are developed using a mix of semi-detailed unit costs with assembly-level line items and detailed unit costs with forced detailed take-off (i.e., detailed takeoff quantities generated from preliminary drawings and incomplete design information). As such, these estimates are generated using a deterministic estimating method with many unit cost line items. These estimates were developed with a factored approach using previous HTEF costs estimates and other relevant cost estimates as a basis.

Quantity development is dependent on the method used to create the line-item estimate. Item quantities are identified based on the major equipment identified in Table 7 and Table 12, which was determined through thermal and electrical analyses (see Sections 2.1.2, 2.1.3, 3.1.2, and 3.1.3). Capacity-factored or equipment-factored cost estimates do not use quantities of materials for cost estimation.

4.1.2 Cost Items

To further break down project costs, items were categorized into direct, indirect, and contingency costs; escalation costs were not included. Direct costs are those expenses directly tied to the construction of HSS and electrical and transmission line equipment identified in Section 3.1.3. To support project construction and labor efforts, indirect costs were also considered. A buffer for unanticipated issues is covered through contingency costs. Each of these categories is described in greater detail below.

4.1.3 Direct Costs

The cost associated with the addition of new permanent equipment is broken down into five subcategories: labor, materials, subcontract, construction equipment, and process equipment costs. The cost of each item is made up of one or more of each of these costs.

4.1.3.1 Labor

Construction labor cost considers wage rates, installation hours, labor productivity, labor availability, and construction indirect costs. Installation hours represent the labor/hours to install an item and collectively all craft hours to install the entire scope of facilities. Labor productivity is evaluated based on factors such as jobsite location, job position, and site congestion. A regional nuclear power labor productivity multiplier of 1.6 is included to account for the additional effort, oversight, and requirements associated with work performed within an NPP in a congested area without radiation protection and a portion of the work performed during an outage. This productivity factor has been developed based on historical data and is dependent upon several factors, such as congestion, outage or non-outage activities, and the level of radiation protection. Installation hours are increased proportional to this productivity factor. The labor wage rate was selected using the prevailing wage in Bloomington, IL. This data was obtained from "RS Means Labor Rates for the Construction Industry," 2022 edition. Costs have been added to cover social security, worker's compensation, and unemployment insurance.

4.1.3.2 Material

The pricing for permanently installed materials are based on S&L in-house data, vendor catalogs, industry publications, and other related projects. Major material quantities are described in Table 7 and Table 12.

4.1.3.3 Subcontract

Subcontract costs as defined within this estimate are all-inclusive costs. This means there are no additional markups, such as general conditions, overheads, or other construction indirect costs associated with the line item.

4.1.3.4 Construction Equipment

Construction equipment cost is included on each line item as needed based on the type of activity and construction equipment requirements to perform the work. This includes costs for rental of all construction equipment, fuel, oil, and maintenance. Equipment operators are included in direct labor costs.

4.1.3.5 Process Equipment

Pricing for permanently installed equipment is based on S&L in-house data, vendor catalogs, industry publications, and other related projects. Equipment pricing was reviewed to ensure that the following criteria were addressed and taken into consideration where necessary.

4.1.3.6 Indirect Costs

All accompanying costs that do not result from the direct installation of NPP equipment to support hydrogen production are considered indirect costs. These costs are categorized into additional labor costs, site overheads, other construction indirects, and project indirects.

4.1.3.7 Additional Labor Costs

To support the labor associated with the construction and implementation of equipment, there are several ancillary labor costs to consider. These include the additional pay of labor supervisors beyond the prevailing wage rate, show-up time, and overtime. The cost of overtime pay and extended hours caused by worker inefficiency are included based on a 50-hour work week (5–10-hour days). Further overtime and per diem costs are not considered in this estimate.

4.1.3.8 Site Overheads

To ensure the smooth execution of the project, the following overheads are considered: construction management, field office expenses, material and quality control, material handling, safety program administration and personnel, temporary facilities, indirect craft labor, mobilization/demobilization, and legal expenses.

4.1.3.9 Other Construction Indirects

Additional construction costs required include small tools and consumables, scaffolding, general liability insurance, construction equipment mobilization/demobilization, material freight, contractor general and administrative (G&A) expenses, and contractor profit. The freight on process equipment and sales tax are not considered in this section.

4.1.3.10 Project Indirects

Project indirect costs are required to ensure the project is carried out in a timely and high-quality manner. Professional engineering and construction management (CM) services are required to monitor project schedules, costs, quality, safety, and scope. Startup and commissioning services provided the procedures and testing necessary to ensure proper function of the systems prior to plant operation. Startup spare parts are also included in this section. Excess liability insurance, indirect sales tax, owner's cost, and engineering/procurement/contractor firm (EPC) fees are not included in this estimate.

4.1.4 Contingency Costs

Based on project definitions, contingency costs are treated as separate line items and are described as a percentage of costs as described below. A 50% contingency was used to account for a first-of-a-kind project type (all calculated at 50% of costs):

- Labor Contingency Costs
- Material Contingency Costs
- Subcontract Contingency Costs
- Construction Equipment Contingency Costs
- Process Equipment Contingency Costs
- Project Indirect Contingency Costs.

4.2 Excluded Items

These estimates represent only the costs contained above; the estimate does not include allowances for any other costs not listed and incurred by the owner. Additionally, the cost of the hydrogen facility (and all equipment within the HTEF boundary) is not included.

There may be additional costs that the owner should consider. The following are some considerations:

- Lost electricity generation revenue due to extraction steam beyond those covered in Table 14.
- Financing
- Licensing
- Insurance
- Owner staff and facility support
- Safety incentives
- Power consumption due to temporary grid connection
- Per diem/travel expenses
- Spare parts
- Applicable taxes
- Permitting
- Plant staff training
- Legal/accounting fees
- Schedule acceleration or delay costs.

4.3 Nuclear-Hydrogen Integration Cost Estimate Summary

A complete overview of the methodology and breakdown of cost estimating for the 100-MW_{nom} and 500-MW_{nom} integration designs is provided in Appendix I, which also includes a detailed breakdown of the costs of the 500-MW_{nom} integration for a distance of 500 m between the HTEF and the NPP. Detailed cost breakdowns for the other cases can be found in [19]. This section briefly summarizes key results. An overview of the direct, indirect, and contingency costs for the 100-MW_{nom} and 500-MW_{nom} facilities are provided below in Table 13. The estimate for the integration of the NPP HSS equipment and associated electrical infrastructure for the 100-MW_{nom} design totals approximately \$246/kW_{nom}, while the 500-MW_{nom} integration modifications are estimated to cost \$78/kW_{nom}. Based on these estimates, the

standardized cost of the 500-MW_{nom} design is approximately one-third of the 100-MW_{nom} design. This reduction can be explained by the consolidation of equipment under the larger design and reducing material and labor costs with respect to production capacity. Changing the number of piping trains, power lines, or integration equipment (mechanical and electrical) for these designs will alter the capital cost of these modifications accordingly. One potential cost-reduction strategy is to decrease the separation distance between the NPP and HTEF. This adjustment would decrease the length of piping and power lines, which would have subsequent benefits, including reduced excavation and foundation costs, better efficiency (reduced thermal and electrical losses), and the potential utilization of smaller, less expensive equipment. Reducing thermal and electrical separation by 50%, from 500 m to 250 m, is assumed to be physically feasible for some plants (additional hazard analysis and licensing evaluation is necessary to assess overall regulatory compliance but is not considered within this study). Table 13 shows an approximately 20% reduction in integration cost across both designs by reducing plant separation. Another important point regarding Table 13 is that the funds set aside for contingencies are relatively large, roughly equal to the direct costs. Large contingency budgets are appropriate for first-of-a-kind installations. The contingency funds can likely be decreased by 50% or more for subsequent installations that follow similar engineering designs.

Table 13. Installation cost summary for integration of nuclear and hydrogen plants (2022 USD).

| Parameter | 100 MW _{nom} | | 500 MW _{nom} | |
|--|-----------------------|------------------|-----------------------|------------------|
| | 500 m separation | 250 m separation | 500 m separation | 250 m separation |
| Direct Costs | | | | |
| Steam direct cost (\$MM) | 6.12 | 4.28 | 11.7 | 8.95 |
| Electric direct cost (\$MM) | 1.31 | 1.14 | 1.40 | 1.21 |
| Total direct cost (\$MM) | 7.42 | 5.42 | 13.1 | 10.2 |
| Indirect Costs | | | | |
| Steam indirect cost (\$MM) | 7.49 | 5.78 | 11.6 | 8.84 |
| Electric indirect cost (\$MM) | 1.49 | 1.37 | 1.49 | 1.37 |
| Total indirect cost (\$MM) | 8.98 | 7.15 | 13.07 | 10.22 |
| Contingency | | | | |
| Steam contingency (\$MM) | 6.78 | 4.92 | 11.73 | 8.92 |
| Electric contingency (\$MM) | 1.42 | 1.28 | 1.42 | 1.28 |
| Total contingency (\$MM) | 8.20 | 6.20 | 13.2 | 10.2 |
| Total Costs | | | | |
| Total steam cost (\$MM) | 20.4 | 15.0 | 35.0 | 26.7 |
| Total electric cost (\$MM) | 4.21 | 3.79 | 4.31 | 3.86 |
| Total cost (\$MM) | 24.6 | 19.0 | 39.0 | 30.6 |
| Standardized (std.) Costs | | | | |
| Std. steam cost (\$/kW _{nom}) | 204 | 150 | 70.0 | 53.4 |
| Std. electric cost (\$/kW _{nom}) | 42.1 | 37.9 | 8.62 | 7.73 |
| Std. total cost (\$/kW _{nom}) | 246 | 190 | 78.1 | 61.2 |

Notes: Direct costs include labor, materials, subcontracts, construction equipment, and process equipment. Indirect costs include additional labor, site overheads, other construction costs and project indirects. Contingencies are included for all categories.

It is helpful to compare the cost estimates in Table 13 with assumptions that have been made in previous analyses that have estimated the costs of hydrogen production, assuming a similar production

configuration in which a HTEF is coupled to a PWR. In a study by Wendt, Knighton, and Boardman [2], it was assumed that a 1,000 MW_{nom} HTEF was coupled to a NPP at a distance of 1 km. The direct capital cost of the steam delivery system from the NPP was estimated to be \$41.1 million, which is in good agreement with the estimated cost presented in Table 13, after accounting for differences in scale and assumed steam delivery distance. Importantly, however, as shown in the simplified cost summary in Table 14, operating costs dominate the total costs for HTEFs that are 500 MW_{nom} and larger.

The simplified analysis includes direct capital costs and annual inflation of 2% but neglects financing and tax costs. The dominating operating cost is the loss of PWR electric power output due to thermal power dispatch to the HTEF. As indicated in Table 3 and Table 8, the PWR electric power output decreases by 5.3 MW_e and 22.4 MW_e, respectively, for the 100-MW_{nom} and 500-MW_{nom} HTEF cases. These values are lower than estimated in the previous hydrogen production cost study [2] because extracting steam from cold reheat in the PWR has less impact on electric power production than removing steam from the main steam line, as assumed in the previous work. The previous work assumed that the reduction in electric power production was equal to the thermal power delivery to the HTEF divided by the thermal-to-electric conversion efficiency of the PWR, which would have corresponded to 8.5 MW_e for the 100 MW_{nom} HTEF case and 35.7 MW_e for 500 MW_{nom} HTEF case, respectively. **Extracting steam from the cold reheat reduces the operating costs of the thermal power dispatch system by approximately 37% in each case, compared to extracting steam from the main steam line. The lowest standardized (Std.) cost of steam supply is associated with the 500 MW_{nom} HTEF case and is 7.56 \$/MWh_{th}, which exhibits a marked improvement compared to the estimate of 11.6 \$/MWh_{th} from [2].** As noted, costs estimated in this study are for a first-of-a-kind installation with high contingency budgets. **Subsequent installations with similar designs may have substantially lower costs if contingency costs can be avoided.**

Table 14. Simplified total cost summary for integration of nuclear and hydrogen plants (2022 U.S. dollars).

| Parameter | 100-MW _{nom} | | 500-MW _{nom} | |
|--|-----------------------|------------------|-----------------------|------------------|
| | 500 m separation | 250 m separation | 500 m separation | 250 m separation |
| Nuclear Thermal Power Input Cases | | | | |
| NPP power reduction (MW _e) | 5.3 | 5.3 | 22.47 | 22.47 |
| Annual cost of NPP power reduction (\$MM) ^a | 1.45 | 1.45 | 6.16 | 6.16 |
| 20 Year lifetime operating cost (\$MM) | 24.1 | 24.1 | 102.3 | 102.3 |
| 20 Year lifetime total cost (\$MM) | 48.7 | 43.7 | 141.3 | 132.9 |
| Ratio lifetime capital to operating costs | 102% | 79% | 38% | 30% |
| Std. steam cost per unit of delivered heat (\$/MWh _{th}) | 13.9 | 12.3 | 8.04 | 7.56 |
| Std. steam cost from [2] (\$/MWh _{th}) | 11.6 | | | |
| Electric Boiler Case | | | | |
| Annual operating costs w/ 100% electricity (\$MM) | 5.26 | 5.26 | 26.30 | 26.30 |
| Direct capital cost of electric boiler (\$MM) | 1.00 | 1.00 | 3.00 | 3.00 |
| 20 Year lifetime total cost (\$MM) | 88.4 | 88.4 | 440 | 440 |
| Std. cost per unit of delivered heat (\$/MWh _{th}) | 25.2 | 25.2 | 25.1 | 25.1 |

a Assumes an electricity sales price of \$30/MWh_e.

4.3.1 HTE via Electrical Only with Electric Steam Boiler

For the purposes reducing costs and modifications to the NPP, an additional case was considered where only electrical power is delivered from the NPP to the HTEF. The steam extraction and delivery system is replaced by an electrical boiler that converts deionized or demineralized water to high-temperature steam for use in the HTE process and provides the electrical power required for electrolysis. The initial costs associated with implementing this option are expected to be significantly lower due to the amount of mechanical equipment that will not be required. Additionally, the equipment listed in Table 14 would either move from the NPP to the HTEF or be removed from the design as described below.

For the 100-MW_{nom} scale, this option was found to incur a much lower initial capital cost because the HSS equipment used to supply thermal energy from the NPP was not needed for this electric-only option. However, lower efficiency for the electric-only option would result in considerably higher operating costs, which more than offsets the reduced capital costs. This same behavior is observed for a 500-MW_{nom} design.

Table 15 also shows simplified costs associated with replacing the thermal power extraction and delivery system with an electric boiler located at the HTEF. The simplified analysis includes direct capital costs and annual inflation of 2% but neglects financing and tax costs. The operating costs of the electric boiler are much higher than the capital cost, which means the standardized cost is approximately \$25 per MWh_{th} for all cases, regardless of separation distance or HTEF nominal size. The standardized cost of operating the electric boiler could be reduced by approximately 10% by regenerative cooling of the product stream to preheated to feedwater entering the electric boiler to 250°F. For an exact comparison, sites will need to conduct a formal evaluation of the relative performance between an electric reboiler and a steam reboiler.

Table 15. Equipment changes for electrical integration only.

| Equipment | Required | Description |
|---------------------------------------|----------|--|
| Reboiler | Yes | The lack of steam input from the plant through the use of an electric reboiler allows reboiler siting within the HTEF boundary. This allows for regenerative drain cooling. The electric reboiler is expected to be more expensive than its steam reboiler counterpart and will require more maintenance for long-term operation. |
| Demineralized Water Tank | No | The demineralized water tank is intended to enable continued hydrogen production in the event the RO system is down for maintenance. For this reason, it is recommended that a tank be included and located within the HTEF boundary. Depending on the expected frequency of RO maintenance, it may be desirable to remove the tank. |
| Interface piping between NPP and HTEF | No | In the absence of plant steam extraction, piping can be routed within the HTEF, from the RO system to the electric reboiler and subsequently the electrolyzers. This additionally reduces heat and pressure losses caused by pipe routing between the NPP and HTEF. |
| Flow and Level Control Valves | No | No thermal energy transfer will occur between the NPP and HTEF, removing any process control interface between the NPP and HTEF. |

4.4 Total Project Cost

According to the study by Wendt, Knighton, and Boardman [2], expected costs for the construction cost of large-scale HTE facilities are discussed. Adjusted for inflation (2022 U.S. dollars), the baseline hydrogen facility balance of plant equipment was expected to cost approximately \$650/kWe DC (\$1/kWe DC is approximately equal to $\$1/\text{kW}_{\text{nom}}$ for both designs considered in this report), with cost-reduction strategies enabling facility costs as low as \$350/kWe DC. Slight increases in standardized cost were projected for facilities smaller than 250 MW_e DC; hence, it is expected that the 100-MW_{nom} design HTEF balance of plant equipment would be more expensive than the 500-MW_{nom} balance of plant equipment.

Total facility capital costs were projected to be between \$750–1,250/kWe DC for a 1,000 MW_e DC hydrogen plant. Scaling these costs to the 100-MW_{nom} and 500-MW_{nom} designs, the total project costs are expected to be at the medium-to-high ends of that range. As with the balance of plant costs, the standardized total project cost of the 100-MW_{nom} design is expected to be greater than the total project cost of the 500-MW_{nom} design. This is further supported by the larger standardized integration costs for the 100-MW_{nom} design (see Table 13).

Based on the estimates of Section 4.3, integration costs are expected to comprise approximately 5–20% of the total project cost for a 100-MW_{nom} facility and 500-MW_{nom} facility, although these values can change considerably with different integration designs and site-specific conditions. Based on these estimates and the conclusions of Bloom Energy [6] it is expected that the addition of a 500-MW_{nom} HTEF to an NPP similar to the reference plant used in this study will have a lower dollar-per-kilowatt-nominal cost than the addition of a 100-MW_{nom} hydrogen plant to a similar NPP.

5. HYDROGEN PLANT CONSIDERATIONS

5.1 Maximum Achievable Electrical Diversion from Power Plant

An additional sensitivity analysis was performed to determine the maximum power that can be transmitted radially from the NPP to a nearby HTEF without impacting the stability of the NPP generator during a loss of load. The additional runs show that the HTEF load can be increased up to the maximum output power rating of the generator without causing the generator to become unstable following a trip of the high-voltage transmission line feeding the H₂ plant, either with or without a fault. Note that this model is based on typical plant and transmission system data, which may not be representative of the available capacity for all plants.

5.2 Minimum Power Requirements for Hydrogen Facility

To protect solid oxide cells in the HTEF and prolong their lifespans, a hot standby state should be used when electricity is diverted from the HTEF to the grid. During hot standby, the electrolyzers maintain steady-state temperature but electrolysis temporarily halts. Sustaining hot standby requires a small but non-negligible portion of the thermal and electrical power used for electrolysis. This requirement depends on the specifications of the HTEF vendor. Alternatively, the solid oxide cells may be allowed to cool; however, a small amount of electrical power and steam are consumed during the cool-down process. Additionally, if freezing conditions exist, the HTEF components must be thoroughly dried or maintained at a temperature above freezing.

The NPP is expected to supply these minimum demands during normal plant operation while also handling the transients associated with flexible operation of the HTEF. However, in the event of a faulted condition, a loss of offsite power or reactor shutdown (e.g., planned outage), a safe HTEF shutdown may be required. During unplanned events, one or more sources of emergency power (thermal and electrical) will be needed to ensure the electrolyzers are cooled without damage. The hydrogen vendor should work with the NPP to ensure the necessary emergency power is provided to the HTEF in the event of a loss of thermal or electrical power.

5.3 Hydrogen Facility Siting

From a project cost perspective, minimizing the spacing between the NPP and HTEF is ideal, as shown in Section 4.3. Nevertheless, there are several limitations to the adjacent siting of the TB and the HTEF. The primary limitation is the explosion risk an HTEF presents to the safety-related systems, structures, and components of the NPP. Depending on the size of the HTEF and the extent of its protective measures, minimum separation requirements between the HTEF and NPP can be determined by performing a hazard assessment. The size of the HTEF itself also poses limitations on siting. An HTEF is anticipated to require an area on the order of half an acre per megawatt-nominal. As a result, it is unlikely there will be sufficient space within the NPP's protected area for siting of the facility. Existing pathways, plant structures, and topographic features inside of the OCA (but outside of the protected area) may further restrict the siting of the HTEF and increase the separation between plants.

5.4 Thermal Power Extraction

While cold reheat is preferable for this preconceptual design since it maximizes plant efficiency, there are several limitations. The first is pipe routing. Plants will need to find the space available to route new extraction piping through the TB and structural modifications may be needed to support these additions. Of similar or greater importance are the effects of extraction on the main turbines. For the 500-MW_{nom} design, a 6-psi pressure reduction is observed at the discharge of the HP turbine relative to no thermal extraction. This reduction in mass flow downstream of the HP turbine is expected to be within the design margins of the equipment. However, with large degrees of cold reheat extraction, there is a potential for turbines to operate outside of their intended design capabilities; plants should work with original equipment manufacturers (OEMs) to ensure the turbines can perform in accordance with their design specifications. Turbines should be evaluated for shaft imbalance, blade loading, and thrust verification. Additional modifications can be implemented to ensure turbines operate within their intended design capabilities. One such modification would be the installation of a control valve downstream of extraction to maintain upstream pressures (at the HP turbine discharge). Alternatively, some plants already perform cold reheat extraction for equipment such as feedwater heaters. If the turbines are unable to handle extraction for HTE, other extraction flows can be reduced or taken out of service to reduce turbine imbalances. These changes would reduce plant efficiency but may still be the optimal solution for safe operation from cost and efficiency standpoints. To eliminate turbine stability concerns, extraction steam could be drawn from main steam; Section 3.1.5.3 discusses the benefits and drawbacks of extraction from main steam as opposed to cold reheat.

6. CONCLUSIONS

This study develops a preconceptual design for the integration between a large-scale high-temperature electrolysis facility and a NPP. Two hydrogen facility sizes are considered: 100 MW_{nom} and 500 MW_{nom}. Both steam supply designs use cold reheat steam extraction as a heat source. A reboiler inside the protected area of the power plant transfers steam heat to the demineralized water supply for the hydrogen plant. After the heat transfer, the extracted steam condenses and returns to the condenser while the process steam routes out of the protected area to the electrolyzers. Electrical power is tapped off from the high-voltage side of the GSU transformer, where it is then transported via a 345-kV transmission line to the hydrogen facility. Circuit breakers and disconnects are located at both ends of the transmission line. Step-down transformers and miscellaneous switchgear/buses are located at the end of the transmission line inside the HTEF boundary. Control capabilities for the steam interfacing equipment and electrical dispatch are accessible from the Main Control Room, and protective relays for the transmission line are located inside the Relay Room.

Computer modeling was performed for the thermal and electrical designs. PEPSE analysis provided the steady-state parameters for thermal extraction from the turbine cycle. These parameters were used to inform transients and size equipment in combination with Applied Flow Technology (AFT) Arrow and AFT Fathom modeling for steam and water piping, respectively. Electrical transients were analyzed using PSCAD. An ETAP model was used to evaluate power flow and short circuit, which enabled the sizing of transformers and protective equipment.

A cost estimate was developed for both integration designs when considering plant separation distances of 250 m and 500 m. From these estimates, the modifications for thermal and electrical interfacing of a first-of-a-kind nuclear-integrated hydrogen facility are anticipated to cost between \$60–250/kW_{nom}. With a total project cost in the range of \$750–1,250/kW_{nom} [7], integration costs account for up to 20% of the total project cost. The standardized cost of heat supplied from the nuclear power plant was found to range from approximately \$7.5/MWh_{th} to \$14/MWh_{th}. Standardized integration costs were shown to decrease with larger hydrogen facilities and reduced separation distances.

Nuclear steam extraction can provide a profit avenue for many plants and is not restricted to hydrogen production. Ammonia production, oil refining, and paper production, among other industrial processes all require thermal energy, which can be provided by NPPs. Future work should look further at the details of thermal extraction for a variety of use cases. This can include increased levels of extraction and multiple simultaneous users. Additionally, site-specific studies should be performed to develop industry experience and improve cost accuracy.

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Appendix A: Process and Instrumentation Diagrams

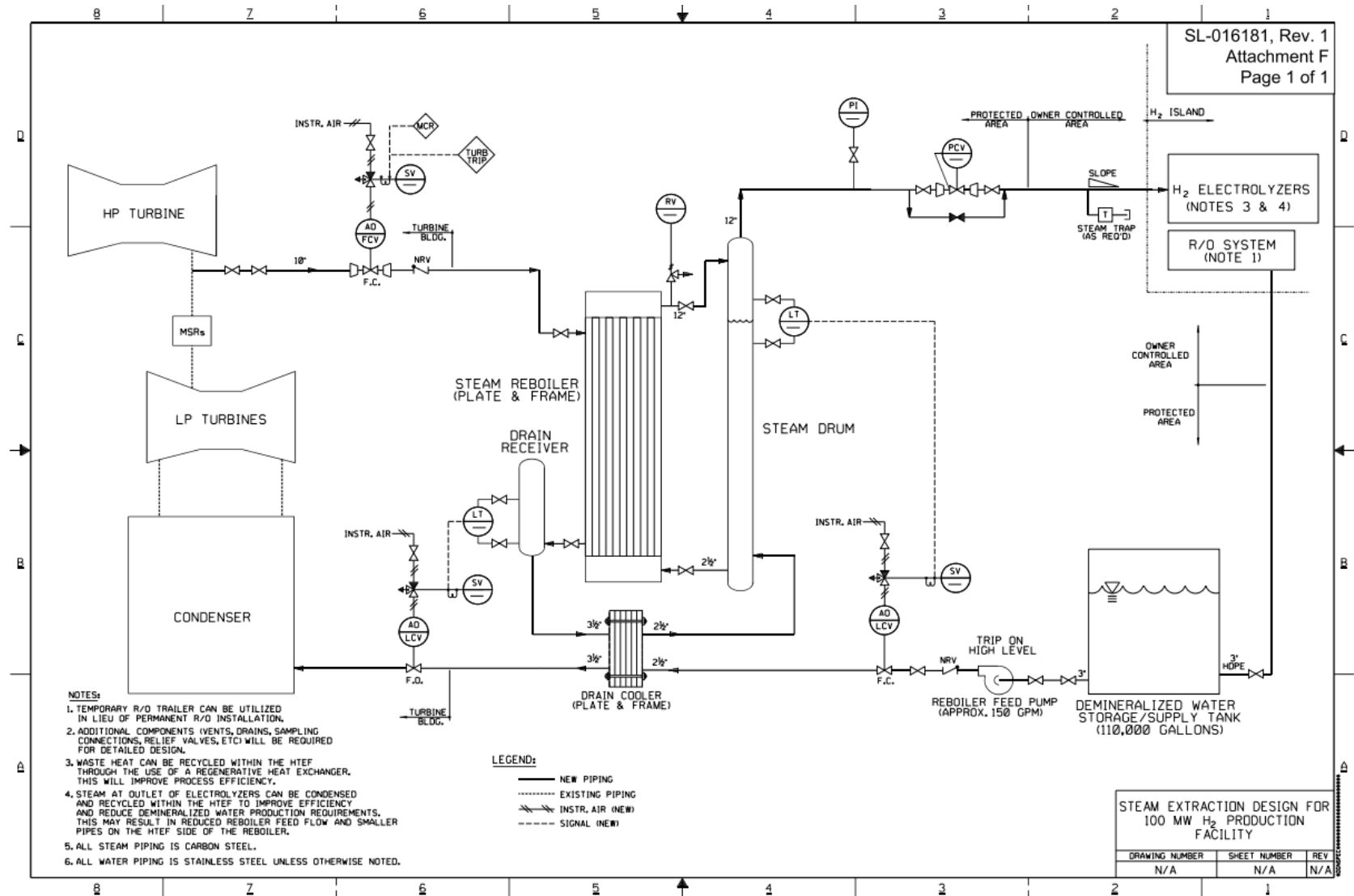


Figure A-1. 100 MW_{nom} P&ID.

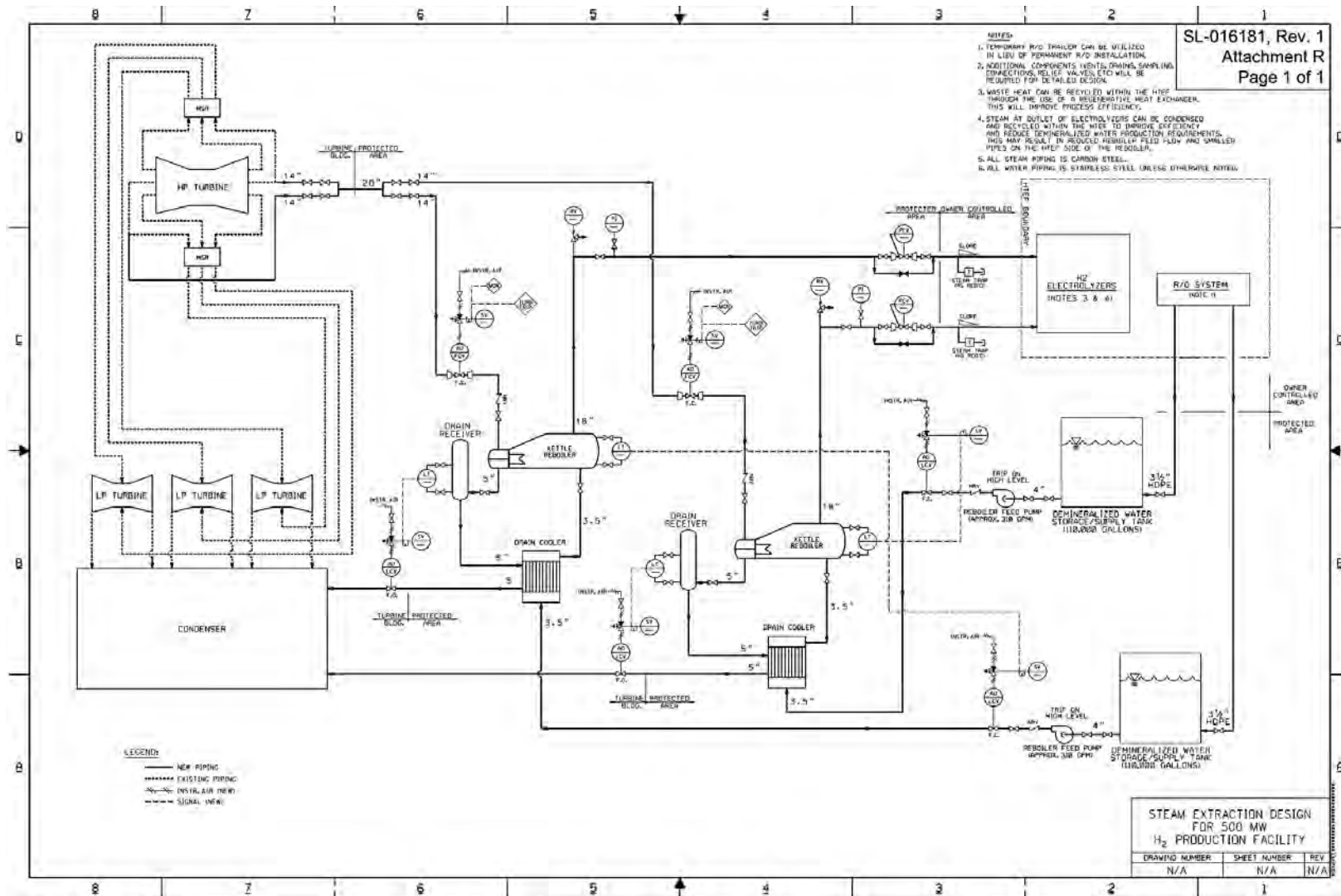


Figure A-2. 500 MW_{nom} P&ID.

Appendix B: Preconceptual Design Layouts

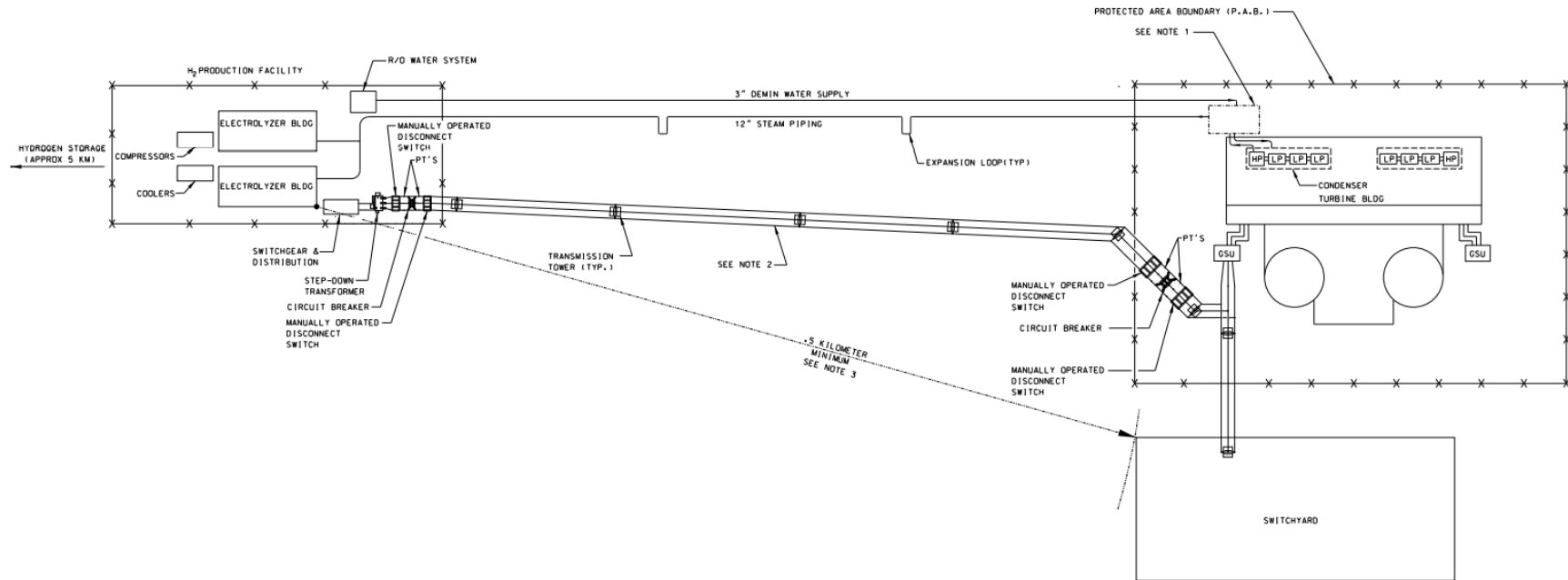


Figure B-1. Layout of preconceptual design with 100 MW_{nom} HTEF located 500 m from the PWR.

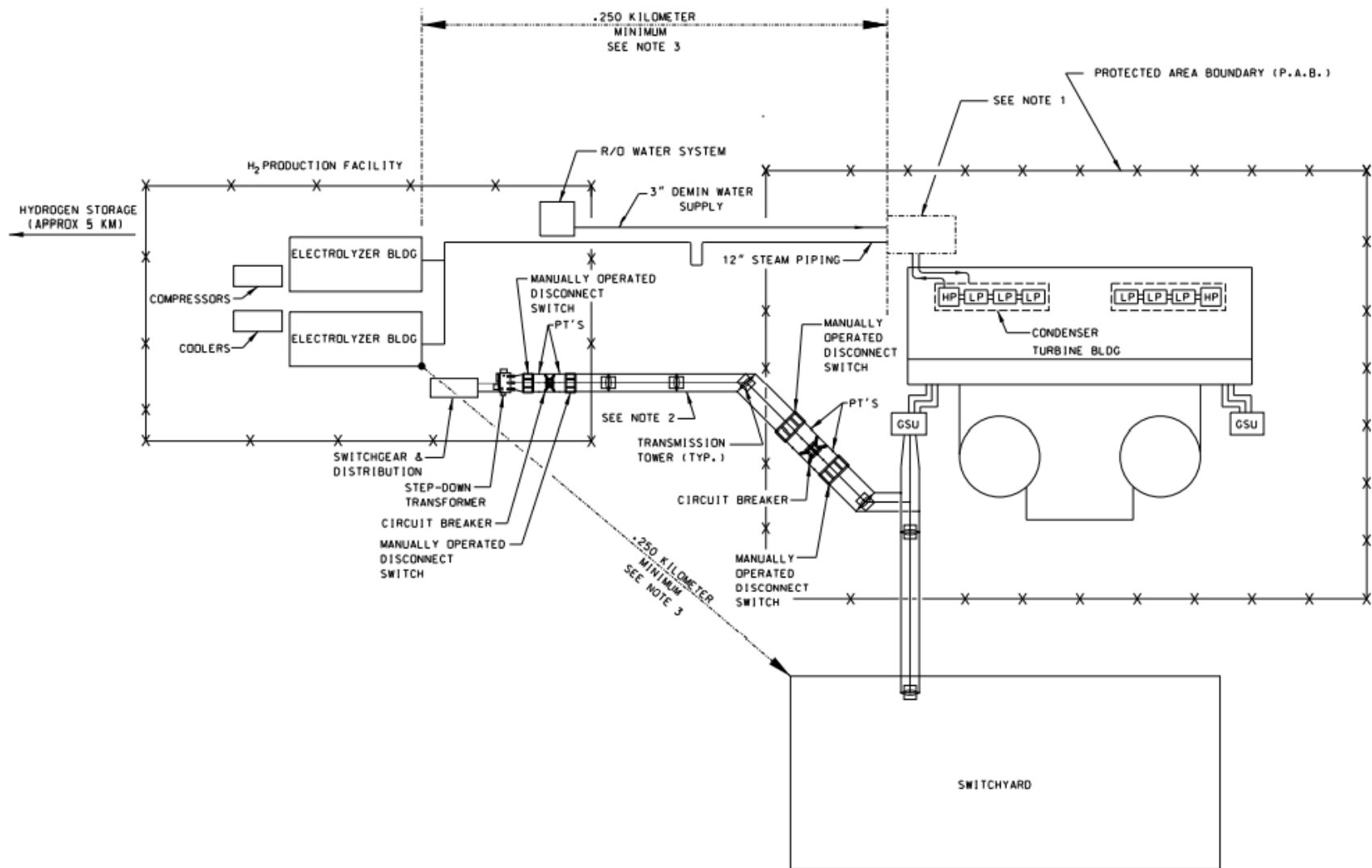


Figure B-2. Layout of preconceptual design with 100 MW_{nom} HTEF located 250 m from the PWR.

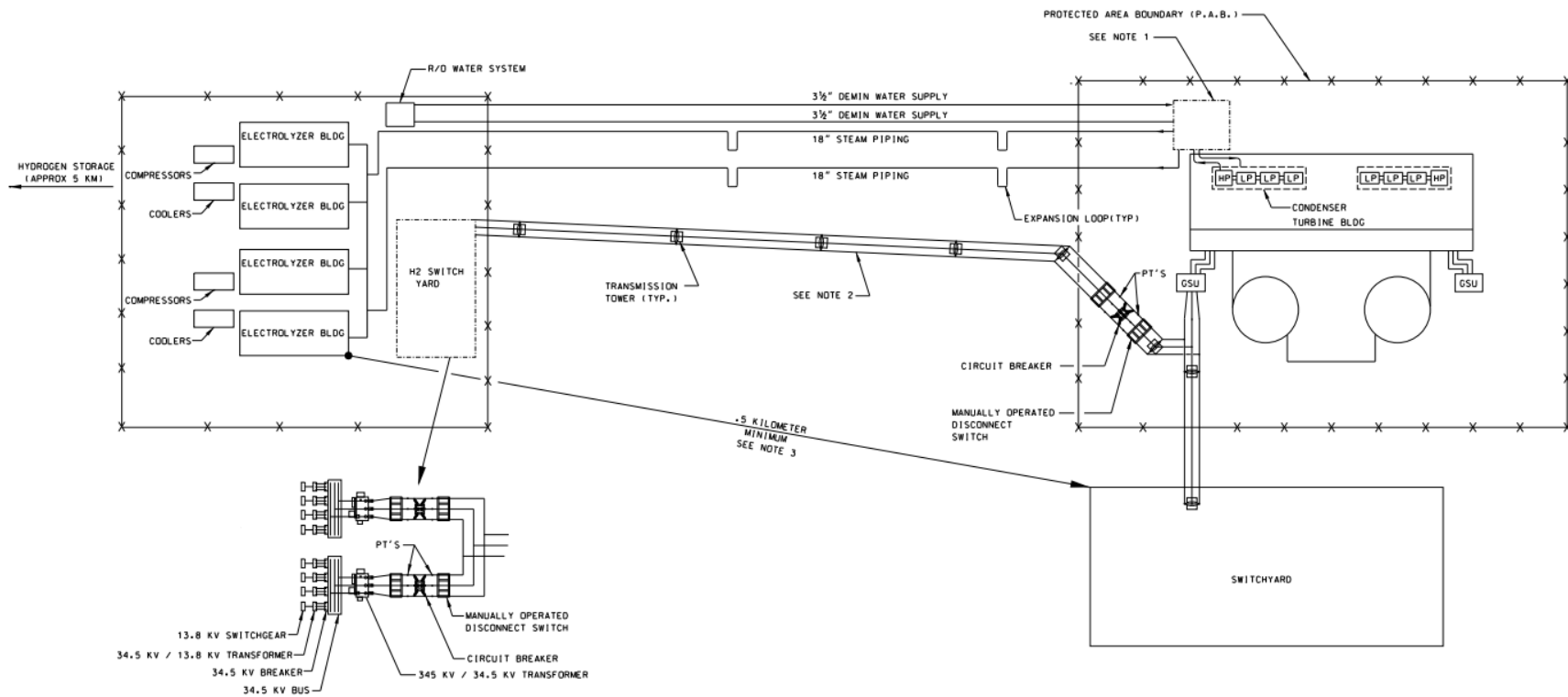


Figure B-3. Layout of preconceptual design with 500 MW_{nom} HTEF located 500 m from the PWR.

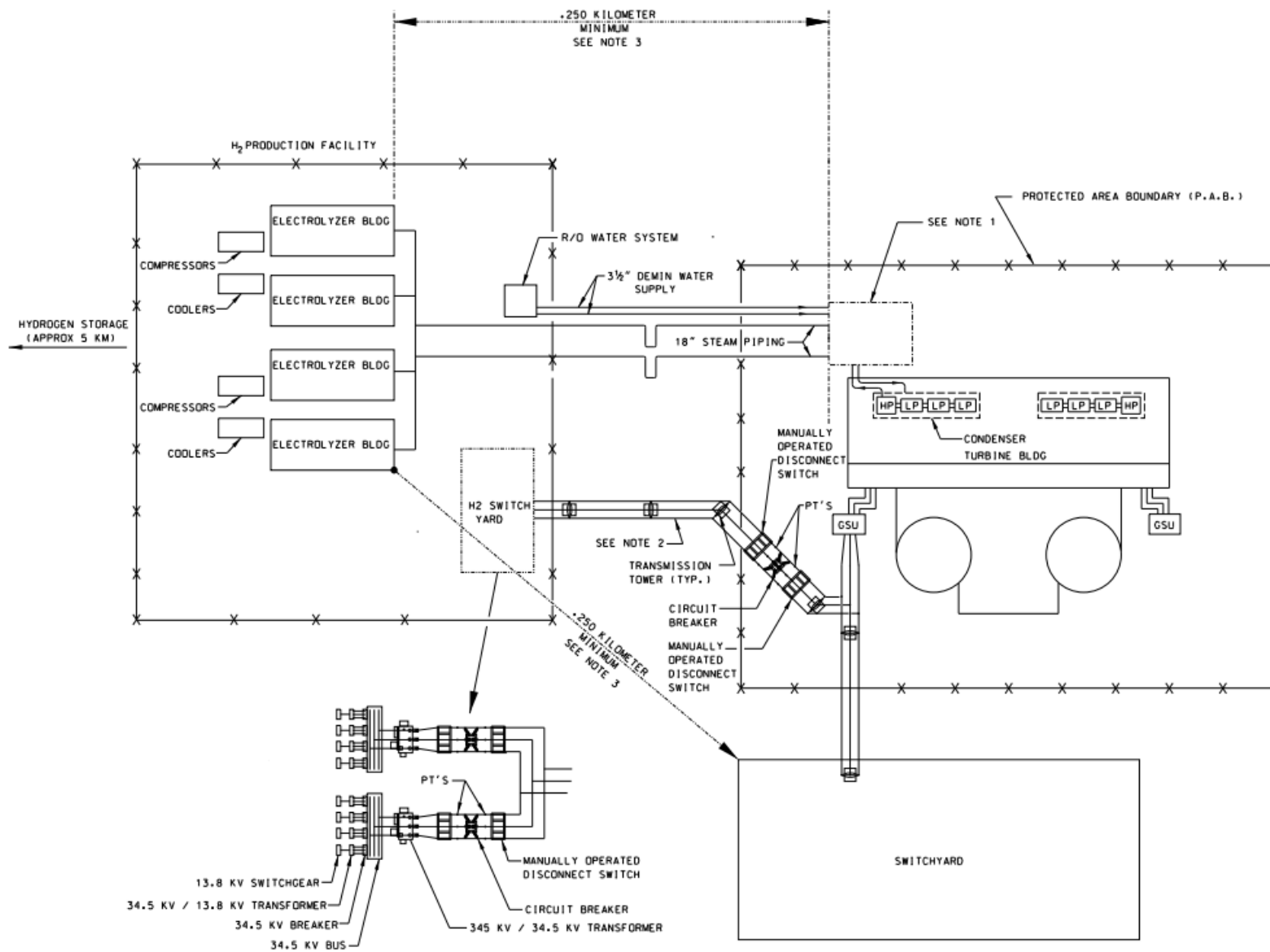


Figure B-4. Layout of preconceptual design with 500 MW_{nom} HTEF located 250 m from the PWR.

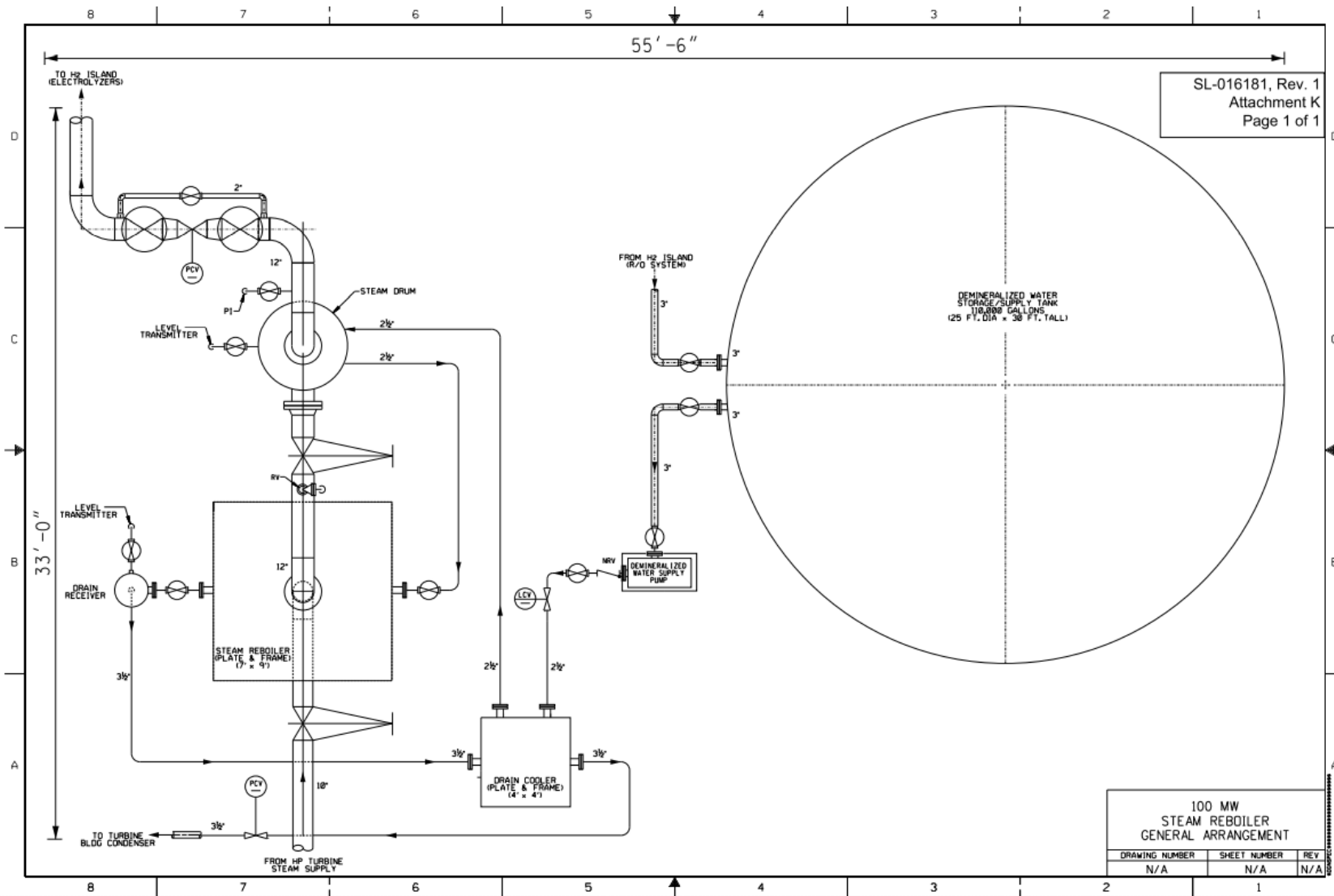


Figure B-5. 100 MW_{nom} Steam Reboiler Arrangement Drawing.

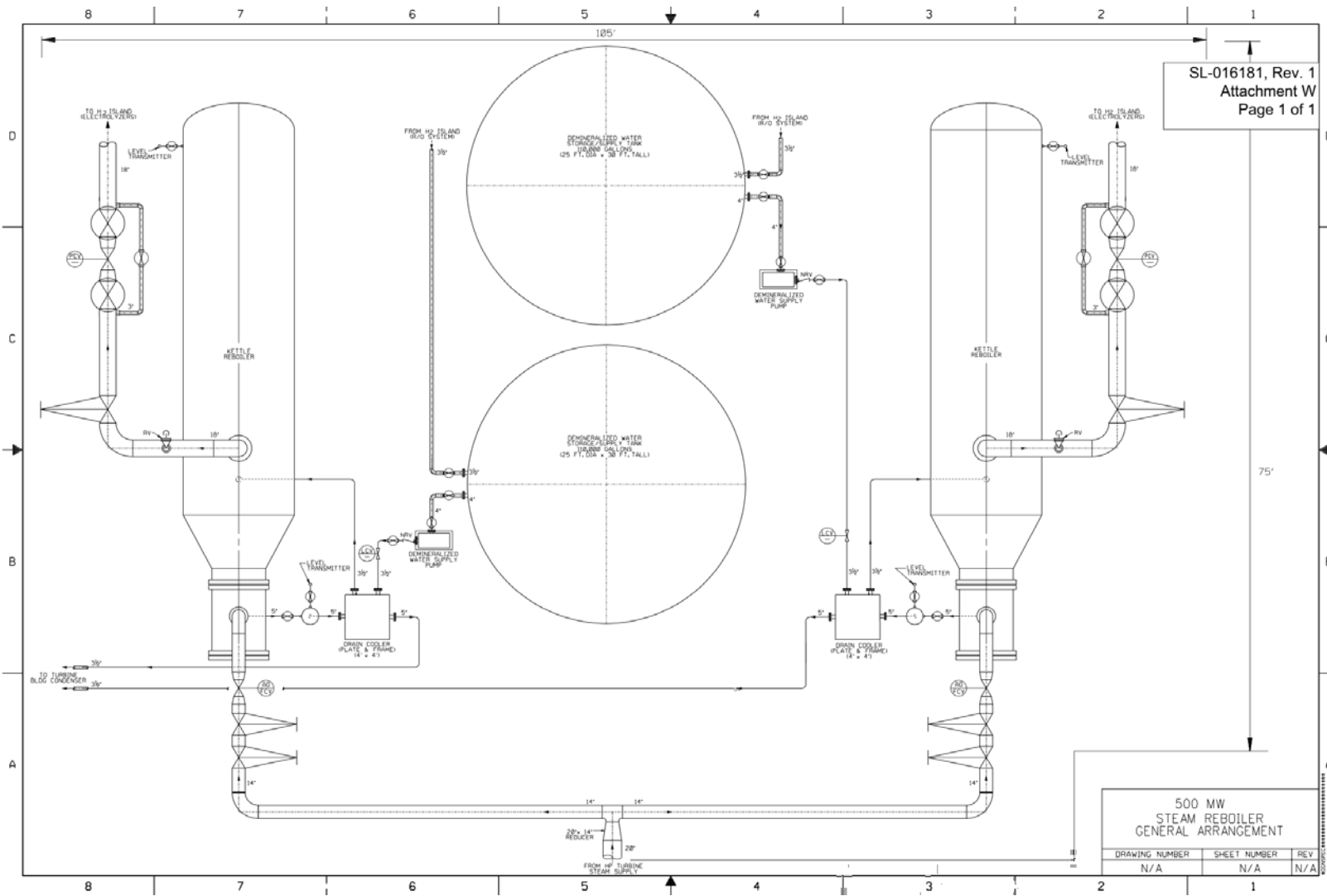
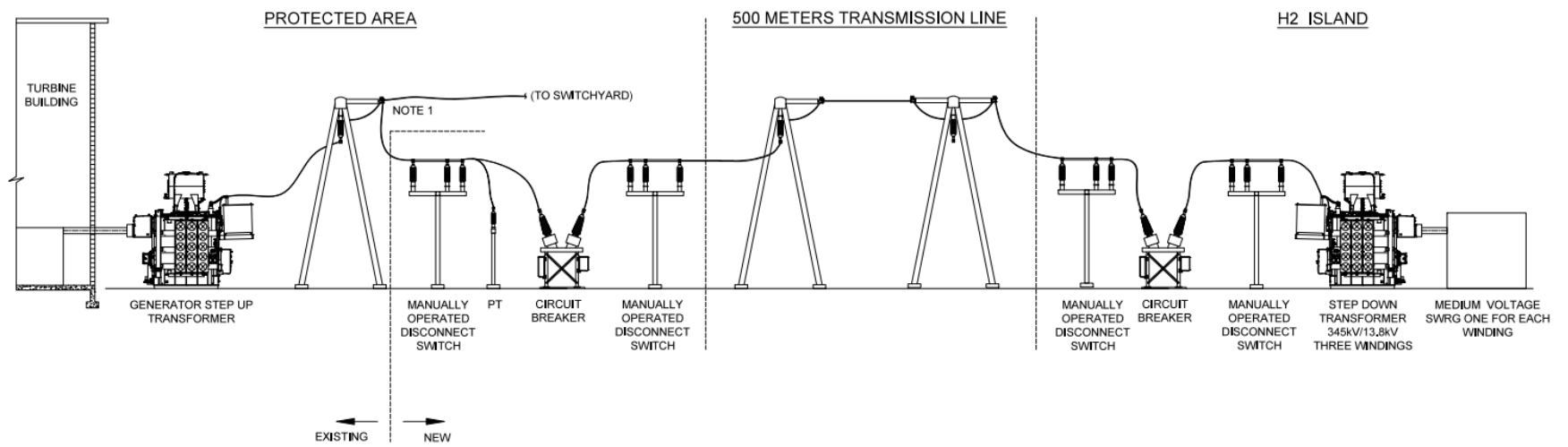


Figure B-6. 500 MW_{nom} Steam Reboiler Arrangement Drawing



NOTE:

1. CONNECTION LOCATED BEHIND THE METER.

Figure B-7. 100 MW_{nom} HTEF Feeder Electrical Physical Layout.

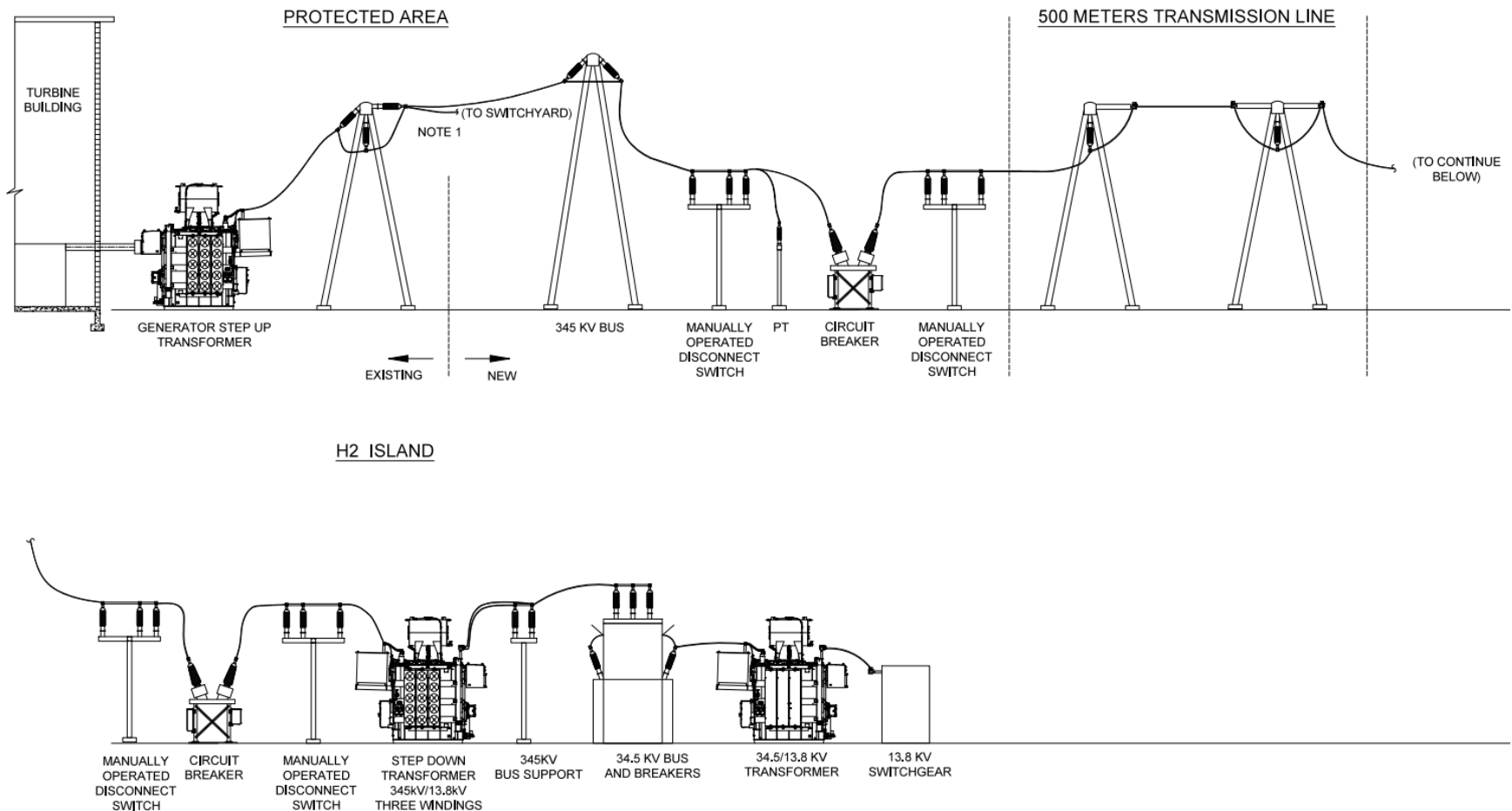


Figure B-8. 500 MW_{nom} HTEF Feeder Electrical Physical Layout

Appendix C: PEPSE Modeling

C-1. PURPOSE

The purpose of this section is to evaluate the impact of extracting steam from the nuclear power cycle to supply thermal energy to a reboiler unit for hydrogen production. The steam is condensed in the reboiler unit and returned to the nuclear power cycle. The thermal energy used by the reboiler unit is used to boil water to steam, which is then directly supplied to the hydrogen production facility. This appendix evaluates $\sim 25 \text{ MW}_{\text{th}}$ and $\sim 105 \text{ MW}_{\text{th}}$ extraction of thermal energy from the main power cycle.

C-2. METHODOLOGY

A generic station PEPSE model is used as the beginning point of this evaluation. The generic station is a representative 4-loop Westinghouse PWR with a targeted generator output of $\sim 1250 \text{ MWe}$. Various extraction locations are considered, including the following locations: (1) main steam, (2) cold reheat, and (3) feedwater. PEPSE case results and diagrams for the preferred extraction (cold reheat) and preferred return (main condenser) location are developed and documented here.

The generic PEPSE model is modified by adding splitters, mixers, and stream components to allow diversion of steam from the preferred extraction location and to return to the main condenser. Pressure and temperature losses to the environment (determined from Arrow models in the Appendices for the case of $\sim 25 \text{ MW}_{\text{th}}$ thermal extraction to the HTEF). Similar Arrow models are available in Ref [18] for the case of $\sim 105 \text{ MW}_{\text{th}}$ thermal extraction to the HTEF. Note that the pressure and temperature losses are developed in Arrow to size the associated piping and components.

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 main power cycle.

A pump component is used to model system pressure increase from a demineralized water supply tank supplying water to the reboiler, which boils this water to steam and is then supplied to the hydrogen production facility. 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 splitter supplying the reboiler.

C-3. INPUTS (ARROW MODELING)

C3.1 Steam piping pressure and temperature losses are taken from the Arrow modeling of these piping systems (see Appendices D and E and Ref. [18]). The Arrow models consider the best estimate of pipe lengths, fittings, and components (including modulating valves) when determining expected pressure conditions through the piping network. The Arrow model also considers insulated piping with extreme cold outdoor temperatures for worst case thermal losses through the piping network from the nuclear power station to the HTEF.

100 MW_{nom} HTEF receiving $\sim 25 \text{ MW}_{\text{th}}$ thermal extraction

The following lists the parameters taken from the Arrow modeling:

- The pressure in the plant steam supply piping at the steam boiler inlet is 161.3 psia at 367.3°F with a pressure drop of 27.3 psid and estimated heat loss of 18,350 Btu/hr.
- The pressure in the steam supply piping to the hydrogen production facility at the reboiler outlet is 120 psia at 350.1°F.

500 MW_{nom} HTEF receiving $\sim 105 \text{ MW}_{\text{th}}$ thermal extraction

The following lists the parameters taken from the Arrow modeling:

- The pressure in the plant steam supply piping at the steam boiler inlet is 153.5 psia at 364.2°F with a pressure drop of 30.6 psid and estimated heat loss of 33,000 Btu/hr. The same pressure drop and heat losses are assumed for the extraction from the main steam.

- The pressure in the steam supply piping to the HTEF at the reboiler outlet is 120 psia at 350.0°F.
- The pressure in the steam supply piping at the hydrogen production facility is 92.5 psia at 335.7°F with a pressure drop of 27.5 psid and estimated heat loss of 623,000 Btu/hr.

C-4. ASSUMPTIONS

- C4.1 The required steam conditions at the hydrogen production facility are assumed at 300°F and 50 psig based on agreement with INL.
- C4.2 Temperature of the condensed and subcooled extraction steam is assumed to be 120°F before it is returned to condenser.
- C4.3 Only for the case of 500 MW_{nom} HTEF receiving ~105 MW_{th} thermal extraction:
The PEPSE case with extraction from main steam maintains the same pressure and temperature losses as the case with extraction from cold reheat. This is reasonable since the steam pipes are sized to limit the steam velocity from exceeding 150 feet/sec. This velocity criteria would be maintained for both cold reheat and main steam extraction. Additionally, the pipe lengths, fittings, and insulation thickness are assumed the same between the cold reheat and main steam extraction cases. Therefore, using the same pressure and temperature losses is a reasonable approximation inlet.

C-5. REFERENCES

- C5.1 PEPSE V84 Computer software, (S&L program # 03.7.551-84.0).

C-6. RESULTS

To determine the preferred location for thermal extraction and return, various factors were considered. As discussed in the purpose, extraction from the main steam lines was considered. This location was not considered a preferred location due to the following reasons:

1. Main steam temperature approaches 500–550°F for typical nuclear power stations. However, the steam conditions required by the hydrogen production facility are only around 300°F. Therefore, the temperature differential between the heating steam (i.e., main steam) and the steam supply to the hydrogen production facility is ~200°F. This high differential temperature is not necessary and may cause additional design requirements for the reboiler to sustain these high temperatures.
2. Extraction from the main steam piping will impact turbine throttle valve operation.
3. Potential transient operation (i.e., loss of supply steam to the hydrogen production facility) would be more severe at this location since it would directly impact the operation of the turbine throttle valve.
4. Last, there is a significant reduction in electrical power production (15.5 MWe) from the nuclear station considering extraction from main steam compared to cold reheat.

Thermal extraction within the feedwater system was also considered. However, the low enthalpy and associated thermal energy available from feedwater required significantly higher flow rates to accomplish the targeted thermal power extraction levels. Therefore, the impact on the nuclear power station is more severe and was disregarded as a potential extraction location.

The preferred extraction location was determined to be at cold reheat (i.e., between the HP turbine outlet and the MSRs). This location provides sufficient supply temperature (~375°F) and associated differential temperature to the required steam condition at the targeted thermal extraction levels. With sufficient reboiler sizing, the returning fluid temperature can be reduced to near the condenser operating temperature to minimize thermal inefficiencies in the nuclear power station, making the main condenser the preferred return location.

With the preferred extraction and return locations determined, the base PEPSE model is modified as discussed in Section C.2 to allow the targeted thermal extraction level to be achieved. The following PEPSE diagrams show the results considering (1) no thermal power extraction (i.e., no hydrogen

production) and (2) thermal extraction of 25 MW_{th} and (3) thermal extraction of 105 MW_{th}. Additionally, Table C-1, Table C-2, and Table C-3 compare important operating parameters within the nuclear power cycle to determine possible significant impact to station equipment.

Table C-1. Summary of important system parameters for 25 MW_{th} extraction.

| Parameter | Unit | Extraction Level | | Δ |
|------------------------------------|-----------------|--------------------|---------------------|----------------------|
| | | 0 MW _{th} | 25 MW _{th} | |
| Reactor Thermal Power | MW _t | 3659 | 3659 | — |
| Generator Output | MW _e | 1239.6 | 1234.3 | -5.3 MW _e |
| Main Steam Flow | Mlb/hr | 16.28 | 16.28 | 0.00% |
| Cold Reheat Flow | Mlb/hr | 12.73 | 12.72 | -0.05% |
| Extracted Steam Portion | % | 0 | 0.67 | 0.67% |
| Remaining Steam to MSRs | Mlb/hr | 12.73 | 12.64 | -0.67% |
| Hot Reheat Flow | Mlb/hr | 11.26 | 11.17 | -0.76% |
| Hot Reheat Temperature | °F | 502.4 | 502.4 | 0.0°F |
| Condensate Hotwell Flow | Mlb/hr | 11.28 | 11.28 | -0.01% |
| Condensate Hotwell Temperature | °F | 121.6 | 121.6 | 0.0°F |
| Heater Drain Forward Flow | Mlb/hr | 5.00 | 5.00 | 0.01% |
| Heater Drain Forward Temperature | °F | 339.7 | 339.0 | -0.7°F |
| HP FWH Cascading Drain Flow | Mlb/hr | 5.00 | 5.00 | -0.23% |
| HP FWH Cascading Drain Temperature | °F | 339.7 | 339.0 | -0.1°F |
| LP FWH Cascading Drain Flow | Mlb/hr | 2.42 | 2.41 | -0.41% |
| LP FWH Cascading Drain Temperature | °F | 131.6 | 131.6 | -0.41% |
| Heater Drain Tank Pressure | psia | 185.5 | 184.0 | -1.5 psi |
| Final Feedwater Temperature | °F | 447.6 | 447.6 | 0.0°F |

NOTE 1: Cascading drain conditions are averaged. Individual feedwater heater (FWH) drain lines may have higher variations in conditions.

NOTE 2: Changes from 0 MW_{th} to 25 MW_{th} are calculated in Microsoft Excel. There may be slight differences due to truncation of values when entering the values in Table C-1.

Table C-2. Summary of important system parameters for 105 MW_{th} extraction.

| Parameter | Unit | Extraction Level | | Δ | 105 MW _{th} | Δ |
|--------------------------------|-----------------|--------------------|----------------------|-----------------------|----------------------|----------------------|
| | | 0 MW _{th} | 105 MW _{th} | | | |
| Extraction Location | - | - | Cold Reheat | Cold Reheat | Main Steam | Main Steam |
| Reactor Thermal Power | MW _t | 3659 | 3659 | - | 3659 | - |
| Generator Output | MW _e | 1239.6 | 1217.2 | -22.47MW _e | 1201.7 | -37.9MW _e |
| Main Steam Flow | Mlb/hr | 16.28 | 16.28 | 0.00% | 16.23 | -0.35% |
| Flow to HP turbine | Mlb/hr | 15.61 | 15.63 | 0.15% | 15.22 | -2.46% |
| HP Exhaust Pressure | psia | 192.1 | 185.9 | -6.2psi | 187.3 | -4.8psi |
| Cold Reheat Flow | Mlb/hr | 12.73 | 12.70 | -0.20% | 12.39 | -2.65% |
| Extracted Steam Portion | lb/hr | 0 | 355,193 | 355,193 | 324,396 | 324,396 |
| Extracted Steam Portion | % | 0 | 2.80 | 2.80% | 2.00 | 2.00% |
| Remaining Steam to MSRs | Mlb/hr | 12.73 | 12.35 | -2.997% | 12.39 | -2.65% |
| Hot Reheat Flow | Mlb/hr | 11.26 | 10.90 | -3.18% | 10.98 | -2.50% |
| Hot Reheat Temperature | °F | 502.4 | 502.4 | 0.0°F | 502.4 | 0.0°F |
| Condensate Hotwell Flow | Mlb/hr | 11.28 | 11.28 | -0.03% | 11.33 | 0.38% |
| Condensate Hotwell Temperature | °F | 121.6 | 121.6 | 0.0°F | 121.6 | 0.0°F |

| Parameter | Unit | Extraction Level | | Δ | 105 MW _{th} | Δ |
|------------------------------------|--------|-----------------------|-------------------------|----------|-------------------------|----------|
| | | 0 MW _{th} | 105 MW _{th} | | | |
| Heater Drain Forward Flow | Mlb/hr | 5.00 | 5.00 | 0.04% | 4.90 | 1.99% |
| Heater Drain Forward Temperature | °F | 339.7 | 337.0 | -2.7°F | 337.5 | -2.2°F |
| HP FWH Cascading Drain Flow | Mlb/hr | 1.39 | 1.38 | -0.92% | 1.38 | -0.79% |
| HP FWH Cascading Drain Temperature | °F | 423.0 | 422.5 | -0.5°F | 420.7 | -2.3°F |
| LP FWH Cascading Drain Flow | Mlb/hr | 2.42 | 2.37 | -1.72% | 2.39 | -1.02% |
| LP FWH Cascading Drain Temperature | °F | 131.6 | 131.6 | 0.0°F | 131.6 | 0.0°F |
| Heater Drain Tank Pressure | psia | 185.5 | 179.5 | -6.0 psi | 180.8 | -4.7psi |
| Final Feedwater Temperature | °F | 447.6 | 447.6 | 0.0°F | 445.2 | -2.4°F |

NOTE 1: Cascading drain conditions are averaged. Individual feedwater heater (FWH) drain lines may have higher variations in conditions.

NOTE 2: Changes from 0 MW_{th} to 105 MW_{th} are calculated in Microsoft Excel. There may be slight differences due to truncation of values when entering the values in Table C-2.

NOTE 3: Main Steam Flow is the flow rate taken from the steam generator. Flow to the HP turbine is the steam into the HP turbine and does not include hot reheat steam flow to the MSRs.

From the above comparison, it is expected that there will be no significant impact to station components when considering 25 MW_{th} or 105 MW_{th} thermal extraction. Important considerations are noted below for each case.

100 MW_{nom} HTEF receiving ~25 MW_{th} thermal extraction

Aside from the cold reheat flow and MSRs, which are directly impacted, the only parameter that is moderately impacted is the heater drain tank pressure, which is slightly reduced. This will slightly reduce the NPSH margin on the heater drain pumps. Therefore, if existing NPSH margin is low on station heater drain pumps, margins will be further reduced and will require further investigation.

500 MW_{nom} HTEF receiving ~105 MW_{th} thermal extraction

The turbine vendor should be consulted to ensure the reduced HP turbine exhaust pressure for extraction from either cold reheat or main steam is acceptable. The cold reheat case is selected as the primary option since it has virtually no impact on the steam flow to the HP turbine and final feedwater temperature plus it saves 15.5 MWe of generator output. Therefore, the follow-on discussions are presented for the cold reheat case only.

The cold reheat flow and MSRs are directly impacted (~3% lower flow), the other parameter that is moderately impacted is the heater drain tank pressure, which is slightly reduced (6 psi lower). This will slightly reduce the NPSH margin on the heater drain pumps. Therefore, if existing NPSH margin is low on station heater drain pumps, margins will be further reduced and will require further investigation.

Additionally, the HP turbine exhaust pressure is lower by ~6 psi. The turbine vendor should be consulted to ensure turbine operation is acceptable with the reduced HP turbine exhaust pressure at essentially the same steam flow rate through the turbine.

Table C-3 summarizes the important system parameters for sizing the reboiler for a duty of 25 MW_{th} thermal power extraction for use at the hydrogen production facility. Note that the parameters defined in Table C-1 are at the connections to/from the reboiler.

Table C-3. Summary of parameters for reboiler sizing for 25 MW_{th} thermal power extraction.

| | Mass Flow Rate | | Temperature | | Pressure | |
|---|----------------|--------|-------------|----|-----------|------|
| Steam Supply from Cold Reheat | 85,238 | lbm/hr | 364 | °F | 161 | psia |
| Drain to Main Condenser | 85,238 | lbm/hr | 120 | °F | by Vendor | |
| Demineralized Water Supply | 73,777 | lbm/hr | 60 | °F | 140 | psia |
| Steam Supply to H ₂ Production | 73,777 | lbm/hr | 350 | °F | 120 | psia |

Table C-4 summarizes the important system parameters for sizing the reboiler for a duty of 105 MW_{th} thermal power extraction (from cold reheat) for use at the hydrogen production facility. Note that the parameters defined in Table C-4 are at the connections to/from the reboiler.

Table C-4. Summary of parameters for reboiler sizing for 105 MW_{th} thermal power extraction.

| | Mass Flow Rate | | Temperature | | Pressure | |
|---|----------------|--------|-------------|----|-----------|------|
| Steam Supply from Cold Reheat | 355,193 | lbm/hr | 360 | °F | 154 | psia |
| Drain to Main Condenser | 355,193 | lbm/hr | 120 | °F | by Vendor | |
| Demineralized Water Supply | 306,980 | lbm/hr | 60 | °F | 140 | psia |
| Steam Supply to H ₂ Production | 306,980 | lbm/hr | 350 | °F | 120 | psia |

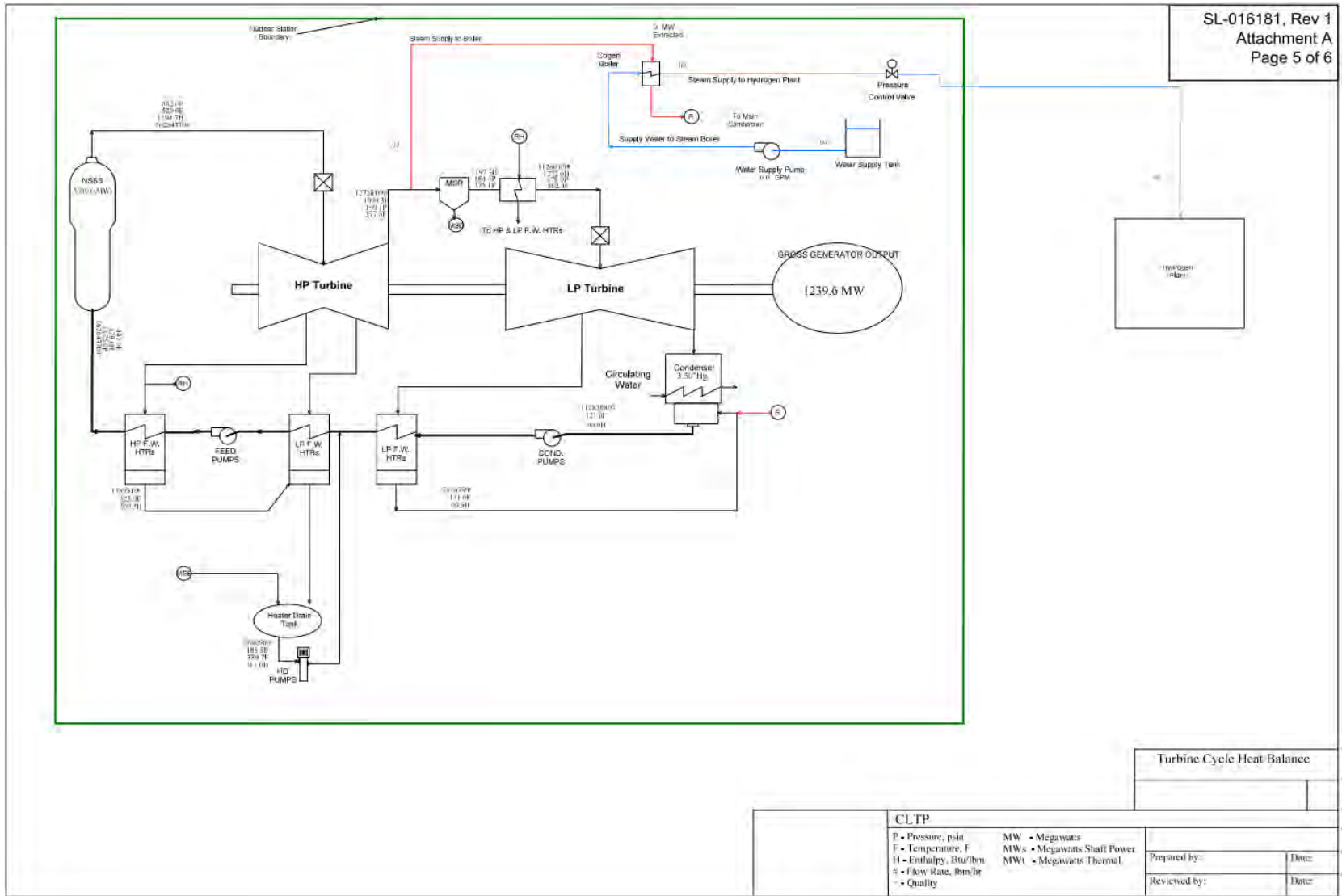


Figure C-1. Process diagram of the PWR Secondary System with connection to a HTEF. The steam extraction valve is closed.

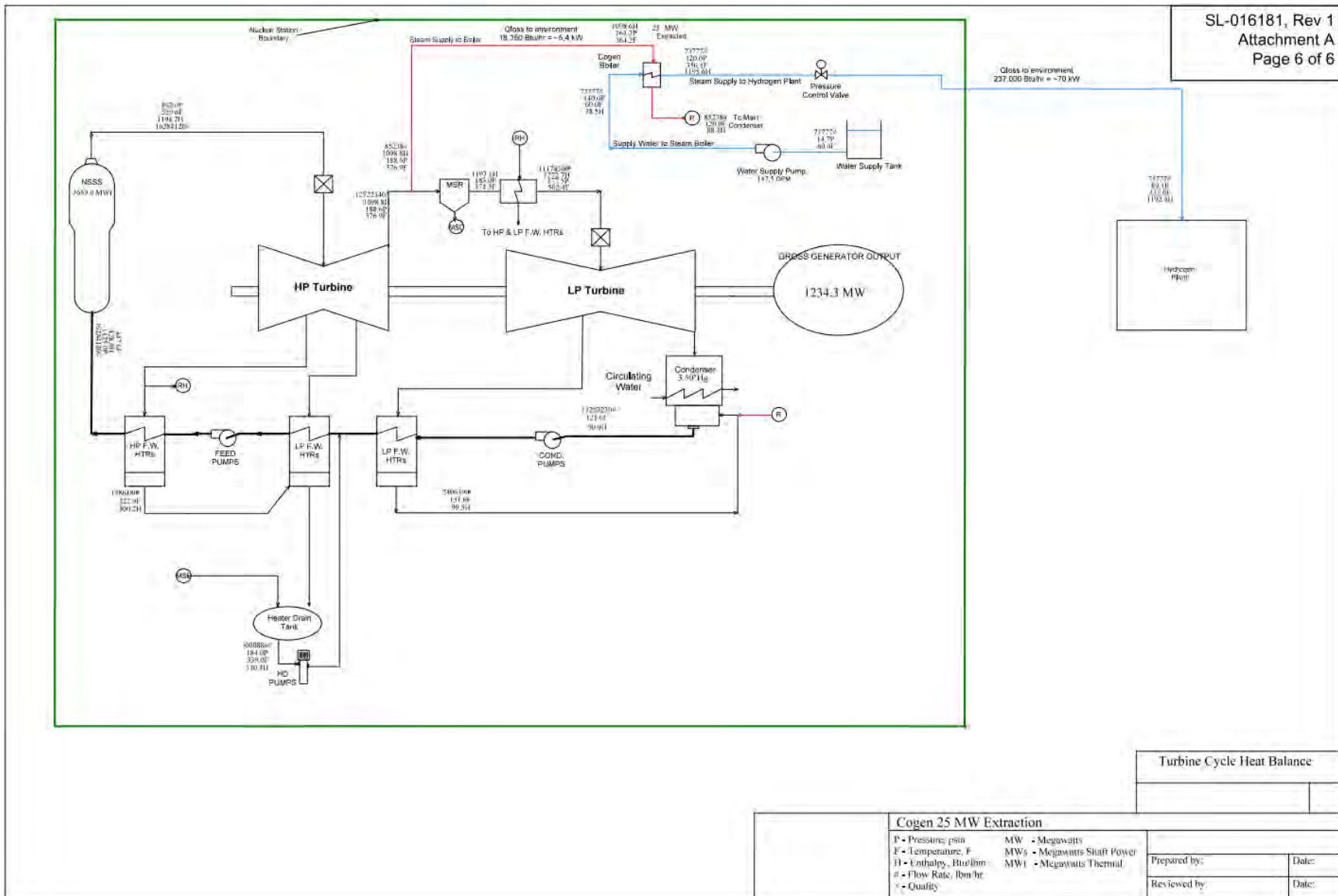


Figure C-2. Process diagram of the PWR Secondary System with connection to a 100 MW_{nom} HTEF operating at full capacity.

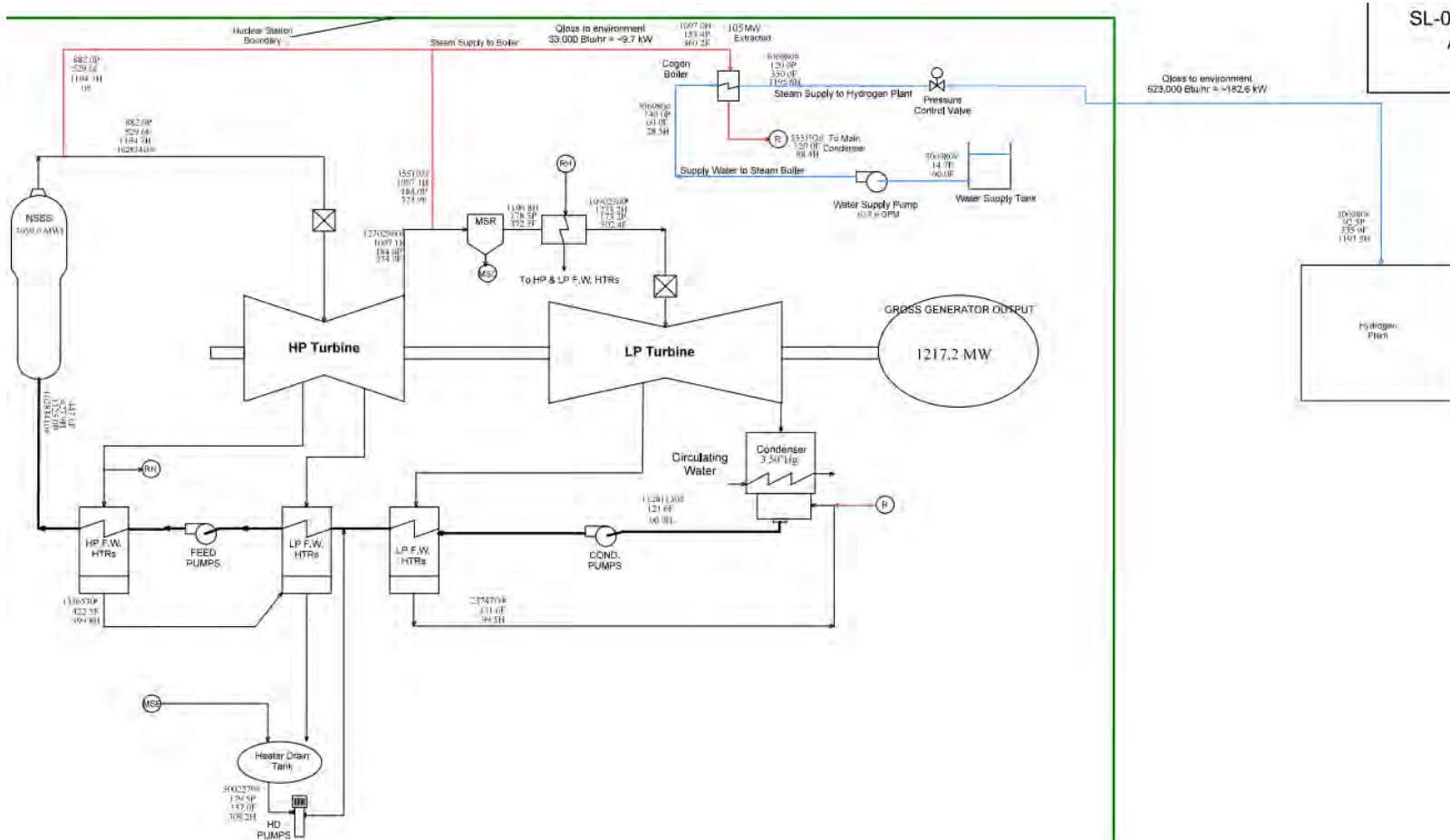


Figure C-3. Process diagram of the PWR Secondary System with connection to a 500 MW_{nom} HTEF operating at full capacity.

Appendix D: 100 MW_{nom} Extraction Steam Pipe Sizing

D-1. PURPOSE

The purpose of this section is to size the extraction steam piping to the HTEF steam generator based on the 25 MW thermal extraction. This extraction steam is to be taken from the HP turbine exhaust and routed to the new heat exchanger (HTEF steam generator/boiler). The pipe is sized to deliver the required steam flow based on the PEPSE Heat balance [Ref. D5.1] with the steam velocity below 150 ft/sec [Ref. D5.3].

D-2. METHODOLOGY

The simplified model is developed in the Arrow computer software [Ref. D5.2] to size the extraction steam piping with the steam velocities below 150 ft/sec [Ref. D5.3]. Steam inlet conditions are based on the PEPSE Heat Balance [Ref. D5.1]. The process steam pipe length, valves, and fittings are based on Assumption D4.1. The piping is assumed to be insulated by 4.5 inches of calcium silicate based on Assumption D4.2. The Turbine Building temperature and air velocity are based on Assumption D4.3.

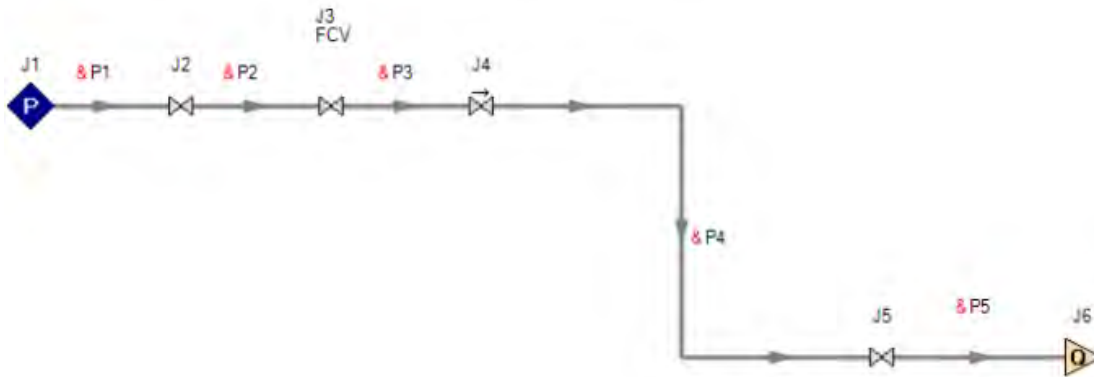
D-3. INPUTS

Steam inlet conditions are based on the PEPSE Heat Balance [Ref. D5.1]. Steam conditions are conservatively chosen to ensure margin to the required steam conditions at the HTEF of 300°F and 50 psig per Assumption D4.5:

- Flow: 85,238 lbm/hr
- Pressure: 188.6 psia
- Temperature: 376.9°F.

D-4. ASSUMPTIONS

D4.1 Extraction piping length, valves, and fittings are assumed based on the diagram shown below:



- Pipes: P1, P2, P3 and P5 are each 10 ft long with 2 - 90 deg (1.5 r/D) elbows (K: 0.2 [Ref. D5.4])
 - Pipe: P4 is 200 ft long with 10 - 90 deg (1.5 r/D) elbows (K: 0.2 [Ref. D5.4])
 - Valves: J2 and J5 are gate valves (K: 0.11 [Ref. D5.4])
 - Flow Control Valve: J3 is assumed to have a constant pressure drop of 20 psid
 - Check Valve: J4 is a stop check 90 deg. globe valve (K: 5.6 [Ref. D5.4]).
- D4.2 Pipe insulation is assumed to be calcium silicate, 4.5 inches in thickness. Insulation properties are based on the Arrow built-in properties [Ref. D5.2]. Insulation is reduced in cost estimate.
- D4.3 Outside air temperature is assumed to be - 10 deg. F and air velocity assumed to be 5 ft/sec. These conditions are reasonable for the typical winter in cold climate.

- D4.4 All piping elevations are assumed to be at same elevation of 0 ft, this is reasonable since for the steam systems the piping elevations have negligible impact on the system design.
- D4.5 The required steam conditions at the HTEF are assumed at 300°F and 50 psig based on agreement with INL.

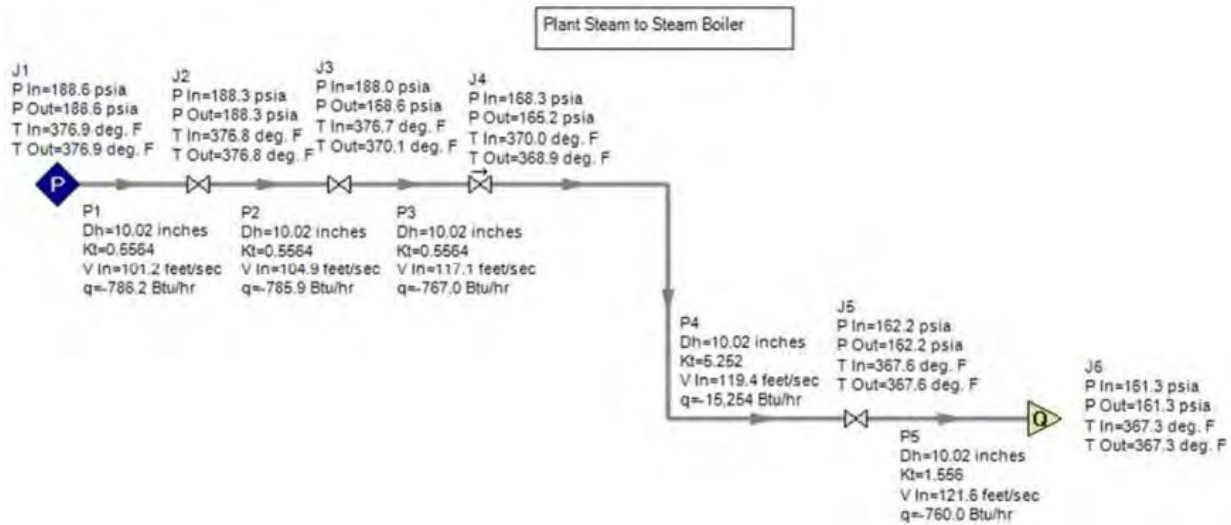
D-5. REFERENCES

- D5.1 PEPSE Heat Balances as shown in Appendix C
- D5.2 Arrow Computer software version 7, (S&L program # 03.7.722-7.0-08/06/2018)
- D5.3 S&L Standard MES 2.11, “Recommended Allowable Velocities in Piping Systems”
- D5.4 Crane Technical Paper 410, 2012 Edition.

D-6. RESULTS

The Arrow model for the extraction steam to the HTEF steam generator was developed and iteratively changed until the final pipe sizes were determined.

A final pipe size of 10 inch, STD schedule, 240 ft in length was modeled and it resulted in a maximum steam velocity of ~120 ft/sec. Design pressure of 250 psig and design temperature of 400°F would envelop the conditions shown. Detailed results are shown on the diagram below:



Appendix E: 100 MW_{nom} Process Steam Pipe Sizing

E-1. PURPOSE

The purpose of this section is to size the process steam piping to the HTEF based on the 25 MW thermal extraction. This process steam is to be taken from the Process Steam Generator/Boiler and routed to the HTEF (~500 meters away). The pipe is sized to deliver the required steam flow based on PEPSE Heat balance [Ref. E5.1] with the steam velocity below 150 ft/sec [Ref. E5.3].

E-2. METHODOLOGY

The simplified model is developed in the Arrow computer software [Ref. E5.2] to size the extraction steam piping with the steam velocities below 150 ft/sec [Ref. E5.3]. Steam inlet conditions are based on the PEPSE Heat Balance [Ref. E5.1]. The process steam pipe length, valves, and fittings are based on Assumption E4.1. The piping is assumed to be insulated by 4.5 inches of calcium silicate based on Assumption E4.2. The Turbine Building temperature and air velocity are based on Assumption E4.3.

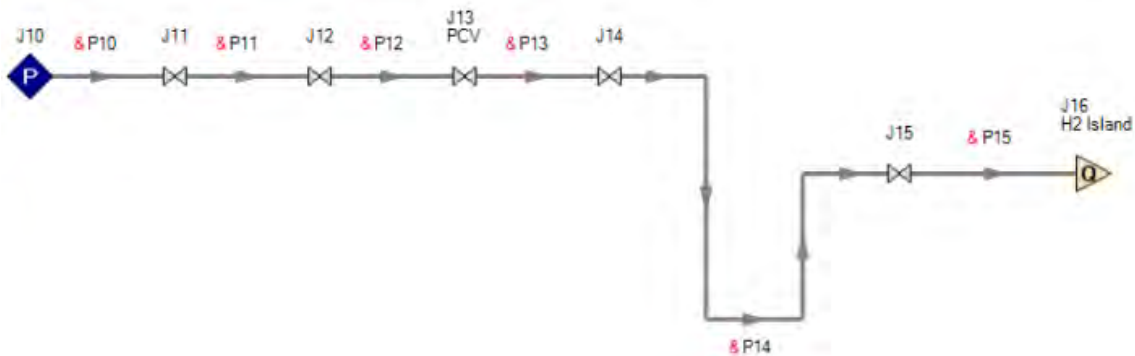
E-3. INPUTS

Steam inlet conditions are based on the PEPSE Heat Balance [Ref. E5.1]. Steam conditions are conservatively chosen to ensure margin to the required steam conditions at the HTEF of 300°F and 50 psig per Assumption D4.5:

- Flow: 73,777 lbm/hr
- Pressure: 120.0 psia
- Temperature: 350.1°F.

E-4. ASSUMPTIONS

E4.1 Extraction piping length, valves, and fittings are assumed based on the diagram shown below:



- Pipes: P10, P11, P12, P13, and P15 are each 10 ft long with 2 - 90 deg (1.5 r/D) elbows (K: 0.2 [Ref. E5.4])
 - Pipe: P14 is 1700 ft long with 20 - 90 deg (1.5 r/D) elbows (K: 0.2 [Ref. E5.4])
 - Valves: J11, J12, J14, and J15 are gate valves (K: 0.10 [Ref. E5.4])
 - Pressure Control Valve: J13 is assumed with constant pressure drop of 20 psid.
- E4.2 Pipe insulation is assumed to be calcium silicate, 4.5 inches in thickness. Insulation properties are based on the Arrow built-in properties [Ref. E5.2]. Insulation is reduced in cost estimate.
- E4.3 Outside air temperature is assumed to be - 10 deg. F and air velocity assumed to be 5 ft/sec. These conditions are reasonable for the typical winter in cold climate.
- E4.4 All piping elevations are assumed to be at same elevation of 0 ft, this is reasonable since for the steam systems the piping elevations have negligible impact on the system design.

E4.5 The required steam conditions at the HTEF are assumed at 300°F and 50 psig based on agreement with INL.

E-5. REFERENCES

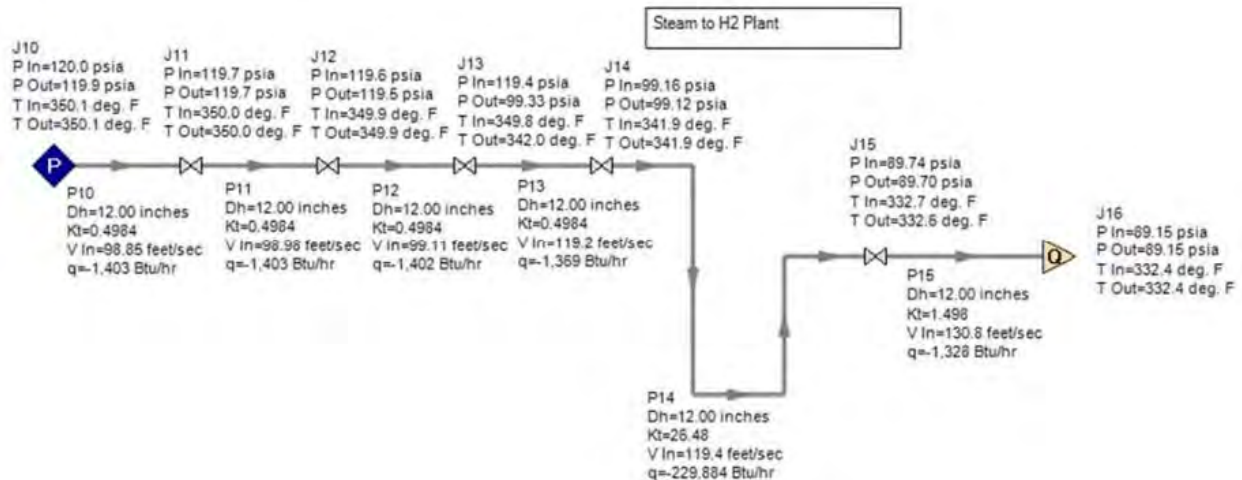
- E5.1 PEPSE Heat Balances as shown in Appendix C
- E5.2 Arrow Computer software version 7, (S&L program # 03.7.722-7.0-08/06/2018)
- E5.3 S&L Standard MES 2.11, “Recommended Allowable Velocities in Piping Systems”
- E5.4 Crane Technical Paper 410, 2012 Edition.

E-6. RESULTS

The Arrow model for the extraction steam to the HTEF was developed and iteratively changed until the final pipe sizes were determined.

Boiler to HTEF

A final pipe size of 12 inch, STD schedule, 1,750 ft in length was modeled from the steam boiler to the HTEF and it resulted in a maximum steam velocity of ~130 ft/sec. Design pressure of 150 psig and design temperature of 400°F would envelop the conditions shown. Detailed results are shown on the diagram below:



Appendix F: 100 MW_{nom} Reboiler Feed Pipe Sizing

F-1. PURPOSE

The purpose of this section is to size the reboiler feed water pump and piping to the HTEF steam generator (reboiler) based on the 25 MW thermal extraction. This water is to be taken from the new demineralized water storage tank and routed to the new pump which will deliver the water to the new heat exchanger (HTEF steam generator/boiler). The pipe is sized to deliver the required water flow based on PEPSE Heat balance [Ref. F5.1] with the water velocity below 10 ft/sec based on general service piping recommendation [Ref. F5.3].

F-2. METHODOLOGY

The simplified model is developed in the Fathom computer software [Ref. F5.2] to size the reboiler feed water piping with the water velocities below 10 ft/sec [Ref. F5.3]. The required water flow rate is taken from the PEPSE Heat Balance [Ref. F5.1]. Water storage tank inlet conditions are based on Assumption F4.2. The pipe length, valves, and fittings are based on Assumption F4.1. For this analysis no heat transfer is modeled from the water piping.

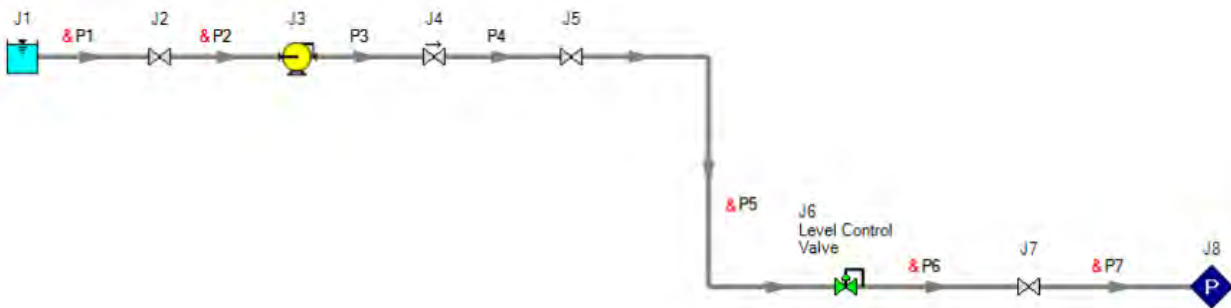
F-3. INPUTS

F3.1 The required water flow rate is based on the PEPSE Heat Balance [Ref. F5.1].

- Flow: 73,777 lbm/hr (~147.5 gpm)

F-4. ASSUMPTIONS

F4.1 The reboiler feed water piping length, valves, and fittings are assumed based on the diagram below:



- Pipes: P1 and P2 are each 20 ft long with 2 - 90 deg (1.5 r/D) elbows (K: 0.25 [Ref. F5.4]), note that the pump suction piping was selected one size larger than the discharge to lower suction velocity
- Pipes: P3 and P4 are each 10 ft long with no fittings
- Pipe: P5 is 200 ft long with 10 - 90 deg (1.5 r/D) elbows (K: 0.25 [Ref. F5.4])
- Pipes: P6 and P7 are each 10 ft long with 2 - 90 deg (1.5 r/D) elbows (K: 0.25 [Ref. F5.4])
- Valves: J2, J5, and J7 are gate valves (K: 0.14 [Ref. F5.4])
- Level Control Valve: J6 is assumed with constant pressure drop of 20 psid, this value should enable reasonable controllability of the control valve.
- Check Valve: J4 is a swing check with 90 deg. seat (K: 0.9 [Ref. F5.4])

F4.2 Demineralized Storage Tank conditions are assumed as follows:

- Tank Water Level: 5 ft

- Water Temperature: 60°F
- Tank Surface Pressure: 0 psig.

Note that for the detailed design purposes an additional case needs to be developed with the expected maximum water temperature to determine the pump Net Positive Suction Head available (NPSHa).

- F4.3 The reboiler pressure is set at 140 psia to allow for the assumed pressure change 20 psid. This is consistent with the PEPSE Heat Balance diagram (Appendix C) and the sizing of the steam supply piping to the HTEF (Appendix E).
- F4.4 All piping elevations are assumed to be at same elevation of 0 ft, this is reasonable since for the it is expected that new equipment will be at similar elevation. During the detailed design phase, actual piping routing and elevations need to be utilized.
- F4.5 The pump efficiency is assumed at 80%.

F-5. REFERENCES

- F5.1 PEPSE Heat Balances as shown in Appendix C
- F5.2 AFT Fathom Computer software version 11, (S&L program # 03.7.721-11-06/18/2020)
- F5.3 S&L Standard MES 2.11, “Recommended Allowable Velocities in Piping Systems”
- F5.4 Crane Technical Paper 410, 2012 Edition.

F-6. RESULTS

The Fathom model for the demineralized water to the HTEF steam generator (reboiler) was developed and iteratively changed until the final pipe sizes are determined.

F6.1 Pipe Size:

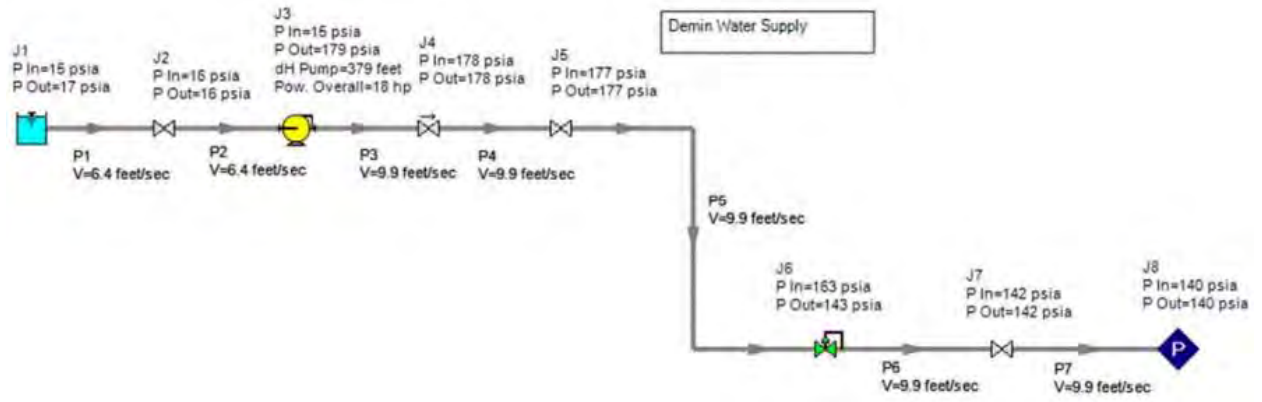
For the pump discharge a pipe size of 2.5 inch, STD schedule, Carbon Steel (for conservatism), 240 ft in length was modeled and it resulted in a maximum water velocity of ~10 ft/sec. Design pressure of 250 psig and design temperature of 150°F would envelop the conditions shown including up additional 50% in pump head rise to shutoff conditions.

For the pump suction a pipe size (was selected one size larger than the discharge to lower suction velocity) 3 inch, STD schedule, Carbon Steel (for conservatism), 40 ft in length was modeled and it resulted in a maximum water velocity of ~6.4 ft/sec. Design pressure of 50 psig and design temperature of 150°F would envelop the conditions shown.

F6.2 Pump Size:

The initial pump sizing is based on the nominal flowrate of 147.5 gpm along with the nominal carbon steel pipe characteristics resulted in a required pump total developed head of ~379 ft, with horsepower requirement of ~18 hp. Note that the final pump sizing needs to consider appropriate design margin and NPSH requirements.

Detailed results are shown on the diagram below:



Appendix G: 100 MW_{nom} Reboiler Drain Pipe Sizing

G-1. PURPOSE

The purpose of this section is to size the reboiler drain piping from the HTEF steam generator (reboiler) to the main condenser based on the 25 MW thermal extraction. Additionally, the required differential pressure across the level control valve is determined. The pipe is sized to deliver the required water flow based on PEPSE Heat balance [Ref. G5.1] with the water velocity below 7 ft/sec based on heater drain piping recommendation [Ref. G5.3].

G-2. METHODOLOGY

The simplified model is developed in the Fathom computer software [Ref. G5.2] to size the reboiler drain water piping with the water velocities below 7 ft/sec [Ref. G5.3]. The required water flow rate is taken from the PEPSE Heat Balance [Ref. G5.1]. Drain inlet and condenser conditions are taken from the PEPSE Heat Balance [Ref. G5.1]. The pipe length, valves, and fittings are based on Assumption G4.1. For the purpose of this analysis no heat transfer is modeled from the water piping.

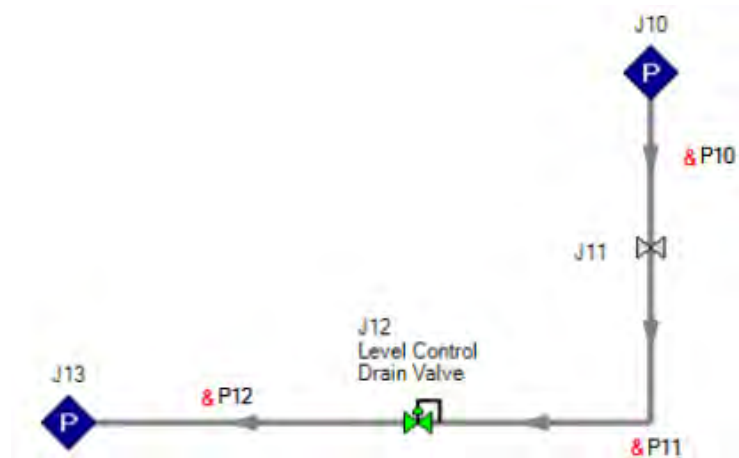
G-3. INPUTS

G3.1 The required water flow rate and boundary conditions are based on the PEPSE Heat Balance [Ref. G5.1].

- Drain Flow: 85,238 lbm/hr (~172 gpm)
- Drain Inlet Pressure: 161.3 psia (to maximize the DP, boiler shell inlet pressure is used)
- Drain Inlet Temperature: 120°F
- Condenser Pressure: 1.7 psia (3.5 in HgA)

G-4. ASSUMPTIONS

G4.1 The reboiler feed water piping length, valves, and fittings are assumed based on the diagram shown below:



- Pipes: P10 and P12 are each 10 ft long with 2 - 90 deg (1.5 r/D) elbows (K: 0.24 [Ref. G5.4])
- Pipe: P11 is 200 ft long with 10 - 90 deg (1.5 r/D) elbows (K: 0.24 [Ref. G5.4])
- Valve: J11 is a gate valve (K: 0.14 [Ref. G5.4])
- Drain Control Valve: J12 modeled to control the required drain flow.

G4.2 All piping elevations are assumed to be at same elevation of 0 ft, this is reasonable since for the it is expected that new equipment will be at similar elevation. During the detailed design phase, actual piping routing and elevations need to be utilized.

G-5. REFERENCES

- G5.1 PEPSE Heat Balances as shown in Appendix C
- G5.2 AFT Fathom Computer software version 11, (S&L program # 03.7.721-11-06/18/2020)
- G5.3 S&L Standard MES 2.11, "Recommended Allowable Velocities in Piping Systems"
- G5.4 Crane Technical Paper 410, 2012 Edition.

G-6. RESULTS

The Fathom model for the condensate return from the reboiler to the main condenser was developed and iteratively changed until the final pipe sizes are determined.

G6.1 Pipe Size:

The final drain pipe size of 3.5 inch, STD schedule, Carbon Steel (for conservatism), 220 ft in length was modeled and it resulted in a maximum water velocity of ~5.6 ft/sec. Design pressure of 200 psig and design temperature of 400°F would envelop the conditions shown.

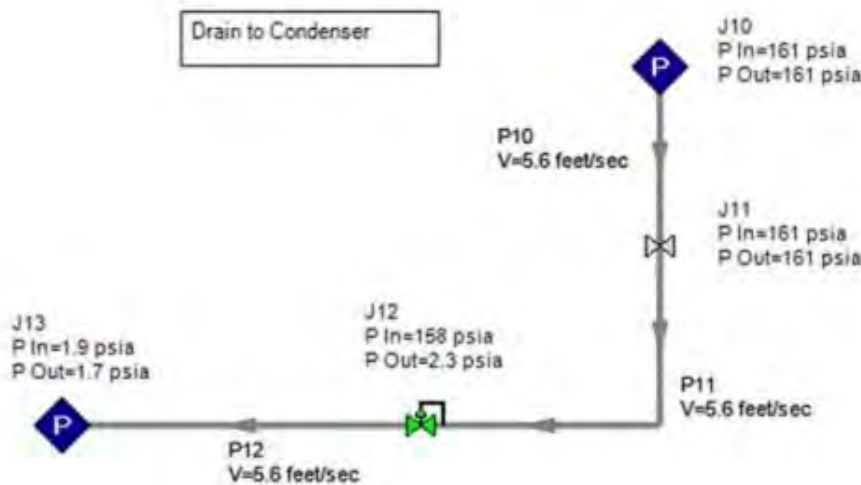
G6.2 Drain Control Valve Size:

The drain control valve sizing results in the following requirements:

- Drain Flow: 85,238 lbm/hr (~172 gpm)
- Valve DP: ~155.7 psid
- Valve inlet Pressure: ~158 psia

Note that due to a very high valve dp, there is a high potential for valve cavitation, this needs to be considered when specifying the drain control valve.

Detailed results are shown on the diagram below:



Appendix H: 100 MW_{nom} HTEF Feeder Electrical Single Line Diagram and ETAP Model

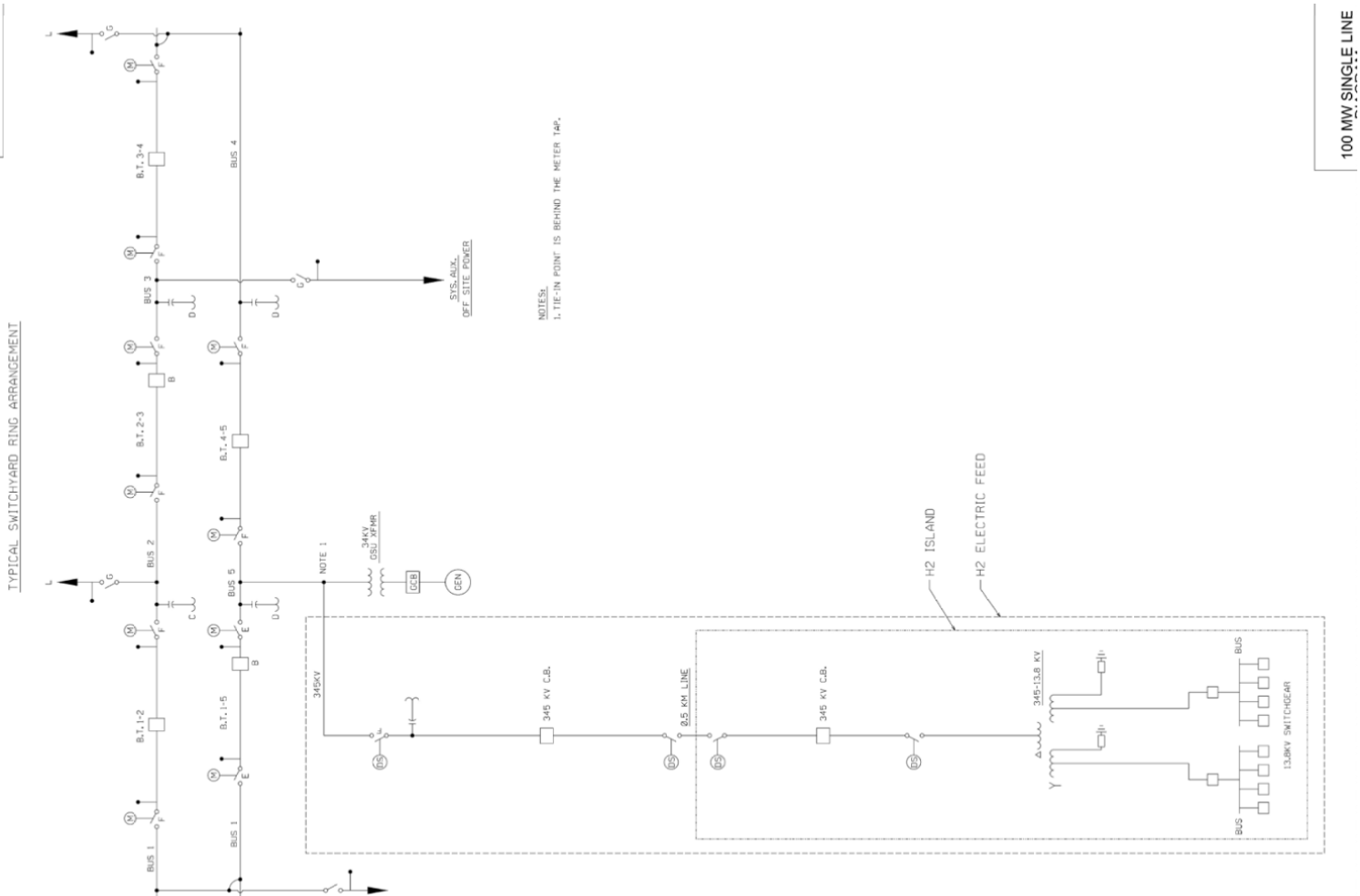


Figure D-1. 100 MW_{nom} HTEF Single Line Electrical Diagram showing typical switchyard ring arrangement.

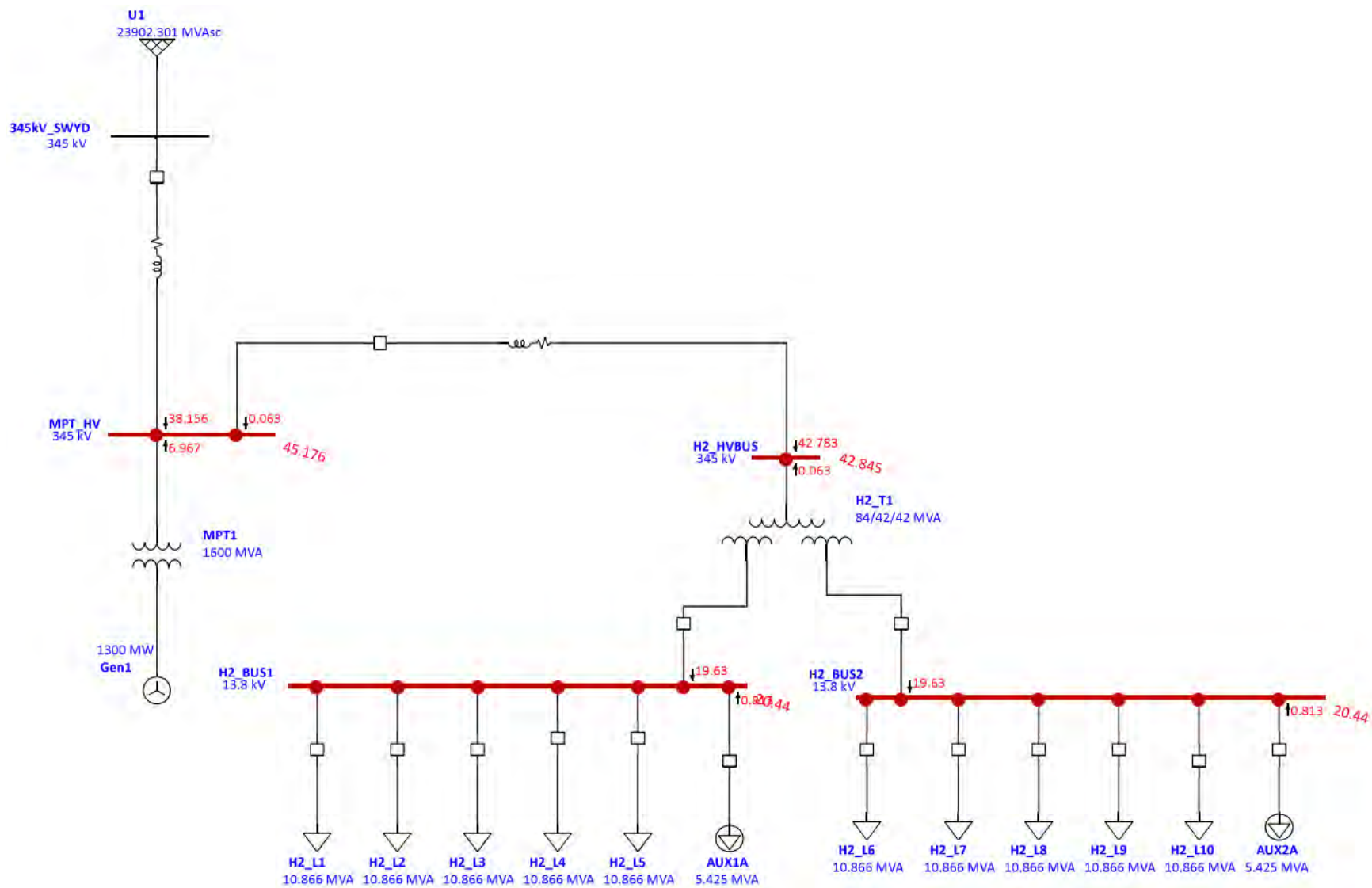


Figure D-2. 100 MW_{nom} HTEF One-line diagram OLV1 short circuit analysis.

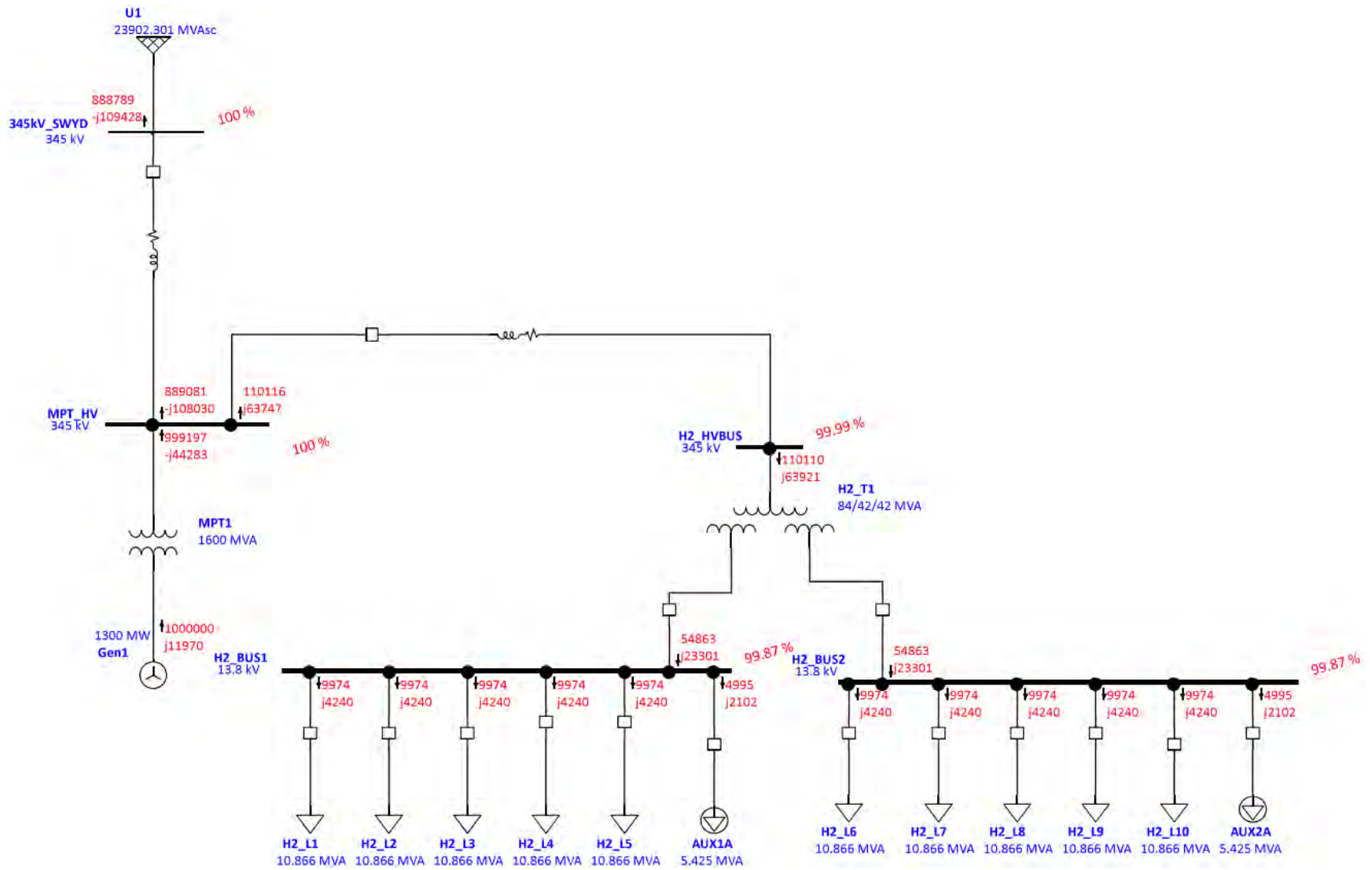


Figure D-3. 100 MW_{nom} HTEF One-line diagram OLV1 load flow analysis

Appendix I: Basis of Estimate

I-1. INTRODUCTION

This document describes and identifies the basis upon which the cost estimate(s) mentioned herein has been developed by documenting the purpose, scope, methods, parameters, cost estimating methodology, strategy, assumptions, source information and exclusions.

The purpose of the estimate(s) is to provide capital cost information for either project planning, screening/feasibility, budgeting, **or** project alternative evaluations. It is expected that the estimate be used in a manner where the end usage takes into consideration the Estimate's Classification and accuracy of the represented costs.

This cost estimate was developed utilizing engineering scope information. It is based largely on experience on similar projects, conceptual design layout and configuration, equipment and system component sizing, and material take-offs. Detailed engineering has not been performed to firm up the project details, and specific site characteristics have not been fully analyzed. We have attempted to assign allowances where necessary to cover issues that are likely to arise but are not clearly quantified at this time.

I-2. GENERAL INFORMATION

- Estimate Number(s): 35995A, 36103A, 36104A, 36105A
- Facility Location: - Not identified
- Facility Type: - Nuclear
- Capacity Rating: - Not required
- New or Existing Facility: - Existing site
- Unit of Measurement: - U.S. Imperial.
- Currency: - U.S. Dollar.

I-3. ESTIMATE SCOPE DESCRIPTION

Listed below is a summary level scope (not all inclusive) of facilities included in the estimate. See cost estimate(s) for a detailed listing of the work breakdown structure and scope.

- Civil work
- Structural work
- Concrete work
- Mechanical work
- Electrical work
- Instrumentation and controls.

I-4. METHODOLOGY

This cost estimate is developed using a mix of semi-detailed unit costs with assembly-level line items and detailed unit cost with forced detailed take off (i.e. detailed takeoff quantities generated from preliminary drawings and incomplete design information). As such, it can be said that this estimate is generated using a deterministic estimating method with many unit cost line items.

In general, the estimate plan and execution process involve:

1. Preliminary engineering and project definition

2. Prepare estimate
3. Review.

I-5. ESTIMATE CLASSIFICATION

Based on the maturity level of the project definition deliverables and the estimating methods used, this estimate can be categorized as a Class 5 Estimate and assigned a probable accuracy range -50% to +100%. Accuracy range is calculated on the total cost estimate after the application of appropriate contingency.

The AACE International has established a classification system for cost estimates listed in the following table.

Source: (AACE International Recommended Practice No. 18R-97)

| Estimate Class | Maturity Level of Project Definition Deliverables % of complete definition | End Usage Typical purpose of estimate | Methodology Typical Estimating Method | Expected Accuracy Range |
|----------------|---|--|--|-------------------------------------|
| Class 5 | 0% to 2% | Concept screening | Capacity factored, parametric model, judgement, or analogy | L: -20% to -50% H: +30% to +100% |
| Class 4 | 1% to 15% | Study or feasibility | Equipment factored or parametric models | L: -15% to -30% H: +20% to +50% |
| Class 3 | 10% to 40% | Budget authorization or control | Semi-detailed unit costs with assembly level line items | L: -10% to -20% H: +10% to +30% |
| Class 2 | 30% to 70% | Control or bid/tender | Detailed unit cost with forced detailed take-off | L: -5% to -15% H: +5% to +20% |
| Class 1 | 50% to 100% | Check estimate or bid/tender | Detailed unit cost with detailed take-off | L: -3% to -10% H: +3% to +15% |

This table illustrates typical ranges of accuracy ranges that are associated with the process industries. The +/- value represents typical percentage variation at an 80% confidence interval of actual costs from the cost estimate after application of contingency (typically to achieve a 50% probability of project overrun versus underrun) for given scope. Depending on the technical and project deliverables (and other variables) and risks associated with each estimate, the accuracy range for any estimate is expected to fall into the ranges identified (although extreme risks can lead to wider ranges).

The purpose of the estimate(s) is to provide capital cost information for either project planning, screening/feasibility, budgeting, project alternative evaluations. It is expected that the estimate be used in a manner where the end usage takes into consideration the Estimate's Classification and accuracy of the represented costs.

I-6. QUANTITY DEVELOPMENT

Quantity development is dependent on the estimating method used to create the estimate. Capacity factored or equipment-factored cost estimates do not use quantities of materials for cost estimation.

Conceptual/preliminary designs and layouts were developed as needed to establish a basis to quantify the equipment and bulk materials to cost estimate the defined scope of facilities.

The quantities and scope of facilities to be cost estimated were based on input from engineering consistent with the level of project definition required by the estimate plan. Input was received by the following disciplines:

- Mechanical engineering

- Electrical engineering
- Project management

Detailed engineering for any of the disciplines has not been performed to firm up the project details, and specific site characteristics have not been fully analyzed. Allowances have been assigned where necessary to cover issues that are likely to arise but are not clearly quantified at this time.

I-7. STRUCTURE AND CODING OF THE ESTIMATE

Based Standard coding and structure within the estimating system have been used in preparing the estimate. The structure of the estimate follows a predefined format whereas the cost information is organized and presented by grouping costs with similar attributes. The basic presentation of the overall estimate hierarchy follows:

- Direct Costs
- General Conditions Costs
- Project Indirect Costs
- Contingency
- Escalation.

Within the direct cost group, the costs are segregated into 5 categories of costs in columnar format in the estimate. The direct cost line items may further be grouped by areas or sub-areas and is evident on the summary page if this formatting structure is used.

1. Subcontract Cost
2. Material Cost
3. Equipment Cost
4. Labor Cost
5. Construction Equipment Cost.

A standard coding structure has been used to categorize each direct cost line item within the estimate. A sample of the commonly used codes in the standard coding structure of the estimating system at its highest level of the hierarchy follows. (Any estimate may contain one or more of these codes)

11.00.00 DEMOLITION
 21.00.00 CIVIL WORK
 22.00.00 CONCRETE
 23.00.00 STEEL
 24.00.00 ARCHITECTURAL
 27.00.00 PAINTING AND COATING
 31.00.00 MECHANICAL EQUIPMENT
 35.00.00 PIPING
 36.00.00 INSULATION
 41.00.00 ELECTRICAL EQUIPMENT
 42.00.00 RACEWAY, CABLE TRAY & CONDUIT
 43.00.00 CABLE
 44.00.00 CONTROL & INSTRUMENTATION.

I-8. DIRECT COSTS

Direct field costs represent the permanently installed facilities and include subcontract costs, material costs, process equipment costs, labor costs and construction equipment costs. Each line item in the estimate may have any combination of these cost categories.

I-8.1 Process Equipment Cost Category

Pricing for permanently installed equipment are based on S&L in-house data, vendor catalogs, industry publications and other related projects, with exception of the following items for which a budgetary vendor quote was received. Vendor quotes are furnish-only unless otherwise noted.

Equipment pricing was reviewed to ensure that the following criteria were addressed and taken into consideration where deemed necessary:

- Allowance for attendance by vendor representatives for technical field assistance
- Freight
- Spare parts
- Start-up spares

I-8.2 Material Cost Category

Pricing for permanently installed materials are based on S&L in-house data, vendor catalogs, industry publications and other related projects, with exception of the following items for which a budgetary vendor quote was received.

- No quotes solicited for this estimate.

I-8.3 Labor Cost Category

Development of construction labor cost takes into account the quantity, wage rates, installation hours, labor productivity, labor availability and construction indirect costs. A more detailed description and methodology follows.

Installation Hours

Installation hours represent the labor/man-hours to install an item and collectively all craft hours to install the entire scope of facilities. These include the time of all craft personnel, supervisors and include time spent in inductions, training, toolbox meetings, clean-ups and bus drivers. Sargent and Lundy maintains a database of standard unit installation hours. The database represents standard installation rates for U.S. Gulf Coast Region. Standard unit installation rates were applied to the quantities and equipment in the estimate. The resultant hours were further adjusted for local productivity (described below). Man-hours associated with subcontract labor cost are not represented in the estimate.

Equipment setting labor/man-hours were developed using a combination of several techniques. Installation was developed using equipment weights, equipment size and fabrication completeness upon delivery.

Both bulk material and equipment installation labor/man-hours may also be based on anyone of the many public domain resources readily available and at our disposal.

Labor Productivity

In evaluating productivity, factors such as jobsite location, type of work and site congestion were considered. A labor productivity multiplier of 1.6 is included for work performed at a nuclear facility. Productivity multiplier does not include weather-related delays. Effectively, this factor increases the installation hours (or decreases productivity) in proportion to the factor.

Labor Wage Rates

Labor profile: Prevailing wages for Bloomington, Illinois.

Craft labor rates were developed in part from the publication “RS Means Labor Rates for the Construction Industry”, 2022 edition. These prevailing rates are representative of union or non-union rates, whichever is prevailing in the area. Costs have been added to cover social security, workmen’s compensation, federal and state unemployment insurance. A composite of one or more burdened craft rates are combined based on their participation to form a crew suitable for the task being performed. Composite crew rates are used in the estimate, not the individual craft rates. Construction indirect and general conditions costs allowances are not included in the crew rates. These cost allowances are itemized separately.

I-8.4 Construction Equipment Cost Category

Construction equipment cost is included on each line item as needed based on the type of activity and construction equipment requirements to perform the work. Includes costs for rental of all construction equipment, fuel, oil and maintenance. Equipment operators are included with direct labor costs.

Depending on the nature of the work, additional cost for construction equipment and operators such as heavy lifting cranes may be required to perform the work activity which would then be included as a separate line item and included in the subcontract cost category. For this project, a supplemental construction equipment cost is not necessary.

I-8.5 Subcontract Cost Category

Subcontract costs as defined within this estimate are all inclusive costs. It has nothing to do with the contracting strategy or subcontractors. A subcontract cost simply does not include any additional markups such as “General Conditions”, “Overheads” or “Other Construction Indirect Costs”. Subcontract costs; however, are subject to and included in the contingency and escalation calculations if applicable. Subcontract costs may or may not have a labor component and as such do not identify associated installation labor/man-hours.

I-9. Construction Direct/Indirect Costs and General Conditions

The estimate is constructed in such a manner where most of the direct construction costs are determined directly and several direct construction cost accounts are allowances and determined indirectly by taking a percentage of the directly determined costs. These percentages are based on our experience with similar type and size projects. Listed below are the additional costs included unless noted as not included.

I-9.1 Additional Labor Costs

- Labor Supervision (additional pay over that of a journeyman)
- Show-up time
- Cost of overtime pay and inefficiency due to extended hours is included, on the basis of working a 50-hour work week (5 – 10 hour days.)
- Per diem is not included or deemed required.

No additional incentives such as bonuses have been included to attract labor. The estimate is based on an adequate supply of qualified craft personnel being available to staff this project.

I-9.2 Site Overheads

- CM (Includes project manager, superintendents, project controls, site clerical)
- Field Office Expenses (trailer rental, furniture, office equipment, computers, site communication, office supplies)
- Material and Quality Control (inspectors, quality assurance personnel)

- Material Handling (Labor cost to receive, unload and properly store material and equipment delivered to the site. Includes materials management. Labor to retrieve materials and equipment from storage and deliver to the worksite)
- Safety program administration and personnel. (Includes safety manager, personal protective equipment, drug testing kits including lab fees, jobsite orientation materials and materials required to maintain a safe jobsite)
- Temporary Facilities (Includes any temporary structures or utilities required at the job site such as temporary warehouse, change trailers, site security, temporary electric grid, water consumed during construction, trash hauling fees, sanitary facilities)
- Indirect Craft Labor (Includes tool control, training, welder certification, fire watch, site cleanup, dust control)
- Mobilization/Demobilization to the jobsite
- Legal Expenses/Claims.

I-9.3 Other Construction Indirects

- Small Tools and Consumables
- Scaffolding (includes rental, erection and removal)
- General Liability Insurance (covers premiums likely to be incurred) Construction Equipment
- Mobilization/Demobilization
- Freight on Material
- Freight on Process Equipment
- Sales Tax – not included
- Contractors General & Administration (G&A) Expense
- Contractors Profit

Contractors G&A and Profit is the markup that contractors will apply to materials and labor services provided under their respective contracts regardless of the contracting approach for the overall project.

I-10. Project Indirect Costs

Listed below are additional project indirect costs included unless noted as not included. Regardless of the contracting approach or which organization provides them (owner or non-owner), professional services are required and itemized to show transparency and the incremental cost value associated with each.

- Professional Engineering Services
- Professional CM Services (Includes management of the project schedule, cost, quality, safety, scope and function)
- Professional Start-up and Commissioning support services (Includes the development and implementation of the procedures and testing to energize plant systems and turnover a fully operational facility to the owner)
- Start-Up Spare Parts
- Owner's cost – not included
- EPC Fee – not included

- Allowance for Funds Used During Construction (AFUDC) - not included.

I-11. Contingency

Based on project definition, contingency costs are included in the estimate as separate line items as

- Material Contingency Cost.....Calculated @ 50% of cost
- Process Equipment Contingency Cost.....Calculated @ 50% of cost
- Labor Contingency Cost.....Calculated @ 50% of cost
- Construction Equipment Contingency Cost.....Calculated @ 50% of cost
- Subcontract Contingency Costs.....Calculated @ 50% of cost
- Indirect Contingency Costs.....Calculated @ 50% of cost.

The rates relate to pricing and quantity variation in the specific scope estimated. The contingency does not cover new scope or exclusions outside of what has been estimated, only the variation in the defined scope. The rates do not represent the high range of all costs, nor is it expected that the project will experience all actual costs at the maximum value of their range of variation. The addition of contingency improves the probability of not having a cost overrun. Even with the inclusion of contingency, the estimate is still subject to cost a cost overrun in accordance with the accuracy range previously defined.

I-12. Escalation

Escalation is not included.

I-13. Contracting Approach

The estimate(s) are based on an Engineer – Procure – Construction Manage (EPCM) multiple contract approach. This approach basically has one main contractor, typically an A/E firm to produce the design, assist in the procurement of goods and services and provide CM services during construction. The EPCM contractor generally acts as an agent for the owner when purchasing said goods and services, meaning contracts and purchase orders are written on the owner’s letterhead.

There may be several purchase orders to purchase the necessary engineered equipment and engineered bulks for the project. These items would be handed to the installation contractors to install. There are no markups by the EPCM contractor on any of the purchase orders or construction contracts.

Installation is achieved through using multiple subcontractors. Contractors are responsible for purchasing non-engineered bulk materials. Contractors will apply a markup on the value of non-engineered bulk materials for overhead and profit.

The estimate(s) are based on warranties being provided by the equipment manufacturers. Additionally, the EPCM contract does not include plant performance, pricing or schedule guarantees.

I-14. Items Excluded

All known or conceptual scope of required physical facilities as provided by the project team to encompass a complete project has been included in the estimate. Any known intentional omissions are documented in the “Notes/Assumptions/Clarifications” section.

The cost estimate represents only the costs listed in the estimate. The estimate does not include allowances for any other costs not listed and incurred by the owner. Excluded costs are any that are not listed in the estimate.

There may be additional costs that the Owner should consider such as (the list below is not all-inclusive):

- Owner's Staff - Project management, engineering support, procurement services, IT support, clerical staff
- Site Facilities for Owner's Personnel, CM, and Start-Up and Commissioning (offices/trailers, guard houses, furniture, signage, staff parking, vehicles, access control, computer network/servers, safety equipment, etc.)
- Site Services for Owner's Personnel, CM, and Start-Up and Commissioning (Telephone, electricity, natural gas, potable water, sewage, sanitary, garbage collection, recycled materials/metals collection (may also be collected from contractors, depending on Owner's policy), snow removal, dust control, janitorial services, internet, cable services, reprographics, etc.)
- Land acquisition/Rights of Way Costs
- Project Development Costs
- Safety Incentives (any Owner's safety incentive, over and above contractor's programs)
- Lock-out/Tag-Out Program (personnel, procedures, and hardware)
- Power consumption costs from temporary power grid connection, if any.
- First Fills
- Spare Parts
- Furnishings for new Office, Warehouse and Laboratory
- Plant Staff Training (time for personnel being trained) is Owner's cost. Also includes Owner's time for preparation and/or modification of plant operating procedures.)
- Legal and accounting fees
- Per diem/Travel expenses for Owner's Personnel assigned to site
- Applicable taxes
- Independent inspection company to perform code required testing and inspection
- Permitting
- Insurance
- Owner's bond fees
- Owner's contingency
- Project financing, Allowance for Funds Used During Construction (AFUDC)
- Community Relations (if applicable, costs associated with any special provisions or facilities required by the local community, such as support for schools, fire department, police due to increased temporary population, etc.)
- Schedule acceleration costs
- Schedule delays and associated costs caused by
 - Unexpected site conditions
 - Unidentified ground conditions
 - Labor disputes
 - Lack of labor resources
 - Weather related conditions

- Force majeure
- Permit applications.

I-15. Notes/Assumptions/Clarifications

15.1. None

Table I-1. Detailed cost breakdown for integrating a PWR with a 500 MW_{nom} HTEF with 500 m standoff distance. Detailed costs for other designs are in [19].

| Estimate Totals | | | |
|-------------------------------------|-------------------|-------------------|--------|
| Description | Amount | Totals | Hours |
| Labor | 3,596,659 | | 47,146 |
| Material | 3,896,426 | | |
| Subcontract | 1,795,951 | | |
| Construction Equipment | 814,510 | | |
| Process Equipment | 2,956,650 | | |
| | <u>13,060,296</u> | 13,060,296 | |
| General Conditions | | | |
| Additional Labor Costs | | | |
| 90-1 Labor Supervision | 215,800 | | |
| 90-2 Show-up Time | 71,933 | | |
| 90-3 Cost Due To OT 5-10's | 703,694 | | |
| 90-4 Cost Due To OT 6-10's | | | |
| 90-5 Per Diem | | | |
| Site Overheads | | | |
| 91-1 Construction Management | 1,553,757 | | |
| 91-2 Field Office Expenses | 478,596 | | |
| 91-3 Material&Quality Control | 121,310 | | |
| 91-4 Site Services | 99,635 | | |
| 91-5 Safety | 76,736 | | |
| 91-6 Temporary Facilities | 58,382 | | |
| 91-7 Temporary Utilities | 63,976 | | |
| 91-8 Mobilization/Demob. | 61,529 | | |
| 91-9 Legal Expenses/Claims | 9,089 | | |
| Other Construction Indirects | | | |
| 92-1 Small Tools & Consumables | 116,532 | | |
| 92-2 Scaffolding | 271,907 | | |
| 92-3 General Liability Insur. | 38,844 | | |
| 92-4 Constr. Equip. Mob/Demob | 81,451 | | |
| 92-5 Freight on Material | 194,821 | | |
| 92-6 Freight on Process Equip. | 147,433 | | |
| 92-7 Sales Tax | | | |
| 92-8 Contractors G&A | 1,736,741 | | |
| 92-9 Contractors Profit | <u>2,481,056</u> | | |
| | 5,593,624 | 21,643,830 | |
| Project Indirect Costs | | | |
| 93-1 Engineering Services | 3,500,000 | | |
| 93-2 CM Support | 649,315 | | |
| 93-3 Start-Up/Commissioning | 216,438 | | |
| 93-4 Start-Up/Spare Parts | 9,313 | | |
| 93-5 Excess Liability Insur. | | | |
| 93-6 Sales Tax On Indirects | | | |
| 93-7 Owners Cost | | | |
| 93-8 EPC Fee | <u>4,375,066</u> | | |
| | | 26,018,896 | |
| Contingency | | | |
| 94-1 Contingency on Const Eq | 586,447 | | |
| 94-3 Contingency on Material | 2,741,136 | | |
| 94-4 Contingency on Labor | 5,044,110 | | |
| 94-5 Contingency on Subcontr. | 897,976 | | |
| 94-6 Contingency on Process Eq | 1,552,247 | | |
| 94-7 Contingency on Indirect | <u>2,187,533</u> | | |
| | 13,009,449 | 39,028,345 | |
| Escalation | | | |
| 95-1 Escalation on Const Equip | | | |
| 95-3 Escalation on Material | | | |
| 95-4 Escalation on Labor | | | |
| 95-5 Escalation on Subcontract | | | |
| 95-6 Escalation on Process Eq | | | |
| 95-7 Escalation on Indirects | | | |
| | | 39,028,345 | |
| 98 Interest During Constr | | | |
| | | 39,028,345 | |
| Total | | 39,028,345 | |

| Area | Group | Phase | Description | Notes | Quantity | Subcontract Cost | Process Equipment Cost | Material Cost | Man Hours | Labor Cost | Equip Amount | Total Cost |
|------|----------|----------|---|---|-------------|------------------|------------------------|---------------|-----------|------------|--------------|------------|
| 1 | | | STEAM SUPPLY | | | | | | | | | |
| | 21.00.00 | | CIVIL WORK | | | | | | | | | |
| | | 21.17.00 | EXCAVATION | | | | | | | | | |
| | | | FOUNDATION EXCAVATION, CLAY USING 1 CY BACKHOE | HYDROGEN INTERFACE EQUIPMENT | 194.22 CY | - | - | | 53 | 4,224 | 935 | 5,158 |
| | | | FOUNDATION EXCAVATION, CLAY USING 1 CY BACKHOE | (2) DRAIN COOLER FOUNDATIONS | 39.56 CY | - | - | | 11 | 860 | 190 | 1,051 |
| | | | FOUNDATION EXCAVATION, CLAY USING 1 CY BACKHOE | (2) DEMINERALIZED WATER TANK AND PUMP | 203.33 CY | - | - | | 55 | 4,422 | 978 | 5,400 |
| | | | FOUNDATION EXCAVATION, CLAY USING 1 CY BACKHOE | (2) STEAM REBOILER | 217.33 CY | - | - | | 58 | 4,726 | 1,046 | 5,772 |
| | | | TRENCH EXCAVATION 6FT TO 15FT DEEP, DENSE HARD CLAY USING 0.75 CY EXCAVATOR | BURIED RIO SUPPLY PIPE | 1,174.46 CY | - | - | | 106 | 8,451 | 1,870 | 10,321 |
| | | | EXCAVATION | | | | | | 284 | 22,683 | 5,019 | 27,701 |
| | | 21.19.00 | DISPOSAL | | | | | | | | | |
| | | | DISPOSAL OF EXCESS MATERIAL USING DUMP TRUCK, 4 MI ROUND TRIP | HYDROGEN INTERFACE EQUIPMENT | 194.22 CY | - | - | | 19 | 1,491 | 330 | 1,821 |
| | | | DISPOSAL OF EXCESS MATERIAL USING DUMP TRUCK, 4 MI ROUND TRIP | (2) DRAIN COOLER FOUNDATIONS | 39.56 CY | - | - | | 4 | 304 | 67 | 371 |
| | | | DISPOSAL OF EXCESS MATERIAL USING DUMP TRUCK, 4 MI ROUND TRIP | BURIED RIO SUPPLY PIPE | 422.93 CY | - | - | | 30 | 2,435 | 539 | 2,973 |
| | | | DISPOSAL OF EXCESS MATERIAL USING DUMP TRUCK, 4 MI ROUND TRIP | (2) DEMINERALIZED WATER TANK AND PUMP | 203.33 CY | - | - | | 20 | 1,961 | 345 | 1,906 |
| | | | DISPOSAL OF EXCESS MATERIAL USING DUMP TRUCK, 4 MI ROUND TRIP | (2) STEAM REBOILER | 217.33 CY | - | - | | 21 | 1,868 | 369 | 2,037 |
| | | | DISPOSAL | | | | | | 93 | 7,458 | 1,650 | 9,108 |
| | | 21.20.00 | BACKFILL | | | | | | | | | |
| | | | FOUNDATION BACKFILL, SELECT STRUCTURAL FILL | HYDROGEN INTERFACE EQUIPMENT | 70.02 CY | - | - | 2,241 | 17 | 1,344 | 297 | 3,882 |
| | | | FOUNDATION BACKFILL, SELECT STRUCTURAL FILL | (2) DRAIN COOLER FOUNDATIONS | 36.29 CY | - | - | 1,161 | 9 | 696 | 154 | 2,012 |
| | | | FOUNDATION BACKFILL, SELECT STRUCTURAL FILL | (2) DEMINERALIZED WATER TANK AND PUMP | 87.51 CY | - | - | 2,800 | 21 | 1,679 | 372 | 4,851 |
| | | | FOUNDATION BACKFILL, SELECT STRUCTURAL FILL | (2) STEAM REBOILER | 122.16 CY | - | - | 3,909 | 29 | 2,344 | 519 | 6,772 |
| | | | TRENCH BACKFILL, PREVIOUSLY EXCAVATED MATERIAL | BURIED RIO SUPPLY PIPE | 1,045.14 CY | - | - | | 125 | 10,027 | 2,219 | 12,246 |
| | | | TRENCH BACKFILL, SAND BEDDING | BURIED RIO SUPPLY PIPE | 460.66 CY | - | - | 8,611 | 63 | 4,997 | 1,105 | 12,914 |
| | | | BACKFILL | | | | | 16,923 | 264 | 21,067 | 4,666 | 42,676 |
| | | 21.43.00 | FENCEWORK | | | | | | | | | |
| | | | SECURITY AND FENCING MODIFICATIONS | | 1.00 LB | 200,000 | - | - | | | | 200,000 |
| | | | FENCEWORK | | | 200,000 | | | | | | 200,000 |
| | | 21.54.00 | CAISSON | | | | | | | | | |
| | | | 3 FT DIA X 6 FT DEEP CAISSON | PIPE RACK PIERS - EACH CAISSON = 1.57CY X \$1,300 = \$2,041 EA. | 180.00 EA | 367,380 | - | - | | | | 367,380 |
| | | | CAISSON | | | 367,380 | | | | | | 367,380 |
| | | | CIVIL WORK | | | 567,380 | | 16,923 | 641 | 51,227 | 11,335 | 646,965 |
| | 22.00.00 | | CONCRETE | | | | | | | | | |
| | | 22.13.00 | CONCRETE | | | | | | | | | |
| | | | MAT FOUNDATION LESS THAN 5 FT THICK, 4500 PSI | HYDROGEN INTERFACE EQUIPMENT | 133.33 CY | - | - | 19,333 | 287 | 16,216 | 3,472 | 41,021 |
| | | | MAT FOUNDATION LESS THAN 5 FT THICK, 4500 PSI | (2) DRAIN COOLER FOUNDATIONS | 8.00 CY | - | - | 1,160 | 16 | 1,093 | 208 | 2,461 |
| | | | MAT FOUNDATION LESS THAN 5 FT THICK, 4500 PSI | (2) DEMINERALIZED WATER TANK AND PUMP | 127.24 CY | - | - | 18,449 | 254 | 17,383 | 3,313 | 39,145 |
| | | | MAT FOUNDATION LESS THAN 5 FT THICK, 4500 PSI | (2) STEAM REBOILER | 111.11 CY | - | - | 16,111 | 222 | 15,180 | 2,893 | 34,184 |
| | | | CONCRETE | | | | | 55,053 | 789 | 51,872 | 9,887 | 116,612 |
| | | 22.15.00 | EMBEDMENT | | | | | | | | | |
| | | | EMBEDMENTS, STAINLESS STEEL | HYDROGEN INTERFACE EQUIPMENT | 1,353.33 LB | - | - | 14,000 | 107 | 7,484 | 201 | 21,684 |
| | | | EMBEDMENTS, STAINLESS STEEL | (2) DRAIN COOLER FOUNDATIONS | 80.00 LB | - | - | 840 | 6 | 449 | 12 | 1,301 |
| | | | EMBEDMENTS, STAINLESS STEEL | (2) DEMINERALIZED WATER TANK AND PUMP | 1,272.35 LB | - | - | 13,380 | 102 | 7,141 | 191 | 20,692 |
| | | | EMBEDMENTS, STAINLESS STEEL | (2) STEAM REBOILER | 1,111.11 LB | - | - | 11,667 | 89 | 6,236 | 167 | 18,070 |
| | | | EMBEDMENT | | | | | 39,866 | 304 | 21,311 | 571 | 61,748 |
| | | 22.17.00 | FORMWORK | | | | | | | | | |
| | | | BUILT UP INSTALL & STRIP | HYDROGEN INTERFACE EQUIPMENT | 420.00 SF | - | - | 1,050 | 134 | 9,815 | 1,107 | 11,973 |
| | | | BUILT UP INSTALL & STRIP | (2) DRAIN COOLER FOUNDATIONS | 144.00 SF | - | - | 360 | 46 | 3,365 | 360 | 4,105 |
| | | | BUILT UP INSTALL & STRIP | (2) DEMINERALIZED WATER TANK AND PUMP | 508.94 SF | - | - | 1,272 | 163 | 11,894 | 1,342 | 14,508 |
| | | | BUILT UP INSTALL & STRIP | (2) STEAM REBOILER | 720.00 SF | - | - | 1,800 | 230 | 16,826 | 1,899 | 20,525 |
| | | | FORMWORK | | | | | 4,482 | 574 | 41,900 | 4,728 | 51,110 |
| | | 22.25.00 | REINFORCING | | | | | | | | | |

| Area | Group | Phase | Description | Notes | Quantity | Subcontract Cost | Process Equipment Cost | Material Cost | Man Hours | Labor Cost | Equip Amount | Total Cost |
|------|----------|----------|---|---|-------------|------------------|------------------------|---------------|-----------|------------|--------------|------------|
| | | 22.25.00 | REINFORCING | | | | | | | | | |
| | | | UNCOATED A615 GR60 | HYDROGEN INTERFACE EQUIPMENT | 10.00 TN | - | - | 11,200 | 288 | 20,485 | 3,263 | 34,946 |
| | | | UNCOATED A615 GR60 | (2) DRAIN COOLER FOUNDATIONS | 0.80 TN | - | - | 672 | 17 | 1,229 | 196 | 2,097 |
| | | | UNCOATED A615 GR60 | (2) DEMINERALIZED WATER TANK AND PUMP | 9.54 TN | - | - | 10,888 | 275 | 19,549 | 3,114 | 33,351 |
| | | | UNCOATED A615 GR60 | (2) STEAM REBOILER | 8.33 TN | - | - | 9,333 | 240 | 17,071 | 2,719 | 29,123 |
| | | | REINFORCING | | | | | 31,893 | 820 | 58,334 | 9,292 | 99,519 |
| | | | CONCRETE | | | | | 131,295 | 2,457 | 173,417 | 24,477 | 329,190 |
| | 23.00.00 | | STEEL | | | | | | | | | |
| | | 23.25.00 | ROLLED SHAPE | | | | | | | | | |
| | | | MEDIUM WEIGHT MEMBERS, 21 LBLF TO 40 LBLF, TWO COAT PAINTED | PIPE RACK | 400.00 TN | - | - | 1,392,400 | 8,160 | 720,936 | 231,336 | 2,344,672 |
| | | | ROLLED SHAPE | | | | | 1,392,400 | 8,160 | 720,936 | 231,336 | 2,344,672 |
| | | | STEEL | | | | | 1,392,400 | 8,160 | 720,936 | 231,336 | 2,344,672 |
| | 27.00.00 | | PAINTING & COATING | | | | | | | | | |
| | | 27.17.00 | PAINTING | | | | | | | | | |
| | | | STEEL PAINTING ALLOWANCE | | 1.00 LS | 10,000 | - | - | - | - | - | 10,000 |
| | | | PAINTING | | | 10,000 | | | | | | 10,000 |
| | | | PAINTING & COATING | | | 10,000 | | | | | | 10,000 |
| | 31.00.00 | | MECHANICAL EQUIPMENT | | | | | | | | | |
| | | 31.65.00 | HEAT EXCHANGER | | | | | | | | | |
| | | | STEAM REBOILER | | 2.00 EA | - | 2,000,000 | - | 448 | 32,516 | 5,389 | 2,037,905 |
| | | | HEAT EXCHANGER | | | | 2,000,000 | | 448 | 32,516 | 5,389 | 2,037,905 |
| | | 31.75.00 | PUMP | | | | | | | | | |
| | | | CENTRIFUGAL PUMP, 310 GPM, 367 FT, 38 HP | DEMINERALIZED FEEDWATER | 2.00 EA | - | 80,000 | - | 288 | 20,903 | 3,465 | 84,368 |
| | | | PUMP | | | | 80,000 | | 288 | 20,903 | 3,465 | 84,368 |
| | | 31.83.00 | TANK | | | | | | | | | |
| | | | 110,000 GAL FIELD FABRICATED TANK, STAINLESS STEEL | DEMINERALIZED WATER TANK | 2.00 EA | 900,000 | - | - | - | - | - | 900,000 |
| | | | TANK | | | 900,000 | | | | | | 900,000 |
| | | 31.99.00 | MECHANICAL EQUIPMENT, MISCELLANEOUS | | | | | | | | | |
| | | | DRAIN COOLER | | 2.00 EA | - | 400,000 | - | 288 | 20,903 | 3,465 | 424,368 |
| | | | DRAIN RECEIVER, 3 FT DIA | | 2.00 EA | - | 22,000 | - | 128 | 9,290 | 1,540 | 32,830 |
| | | | MECHANICAL EQUIPMENT, MISCELLANEOUS | | | | 422,000 | | 416 | 30,193 | 5,004 | 457,198 |
| | | | MECHANICAL EQUIPMENT | | | 900,000 | 2,482,000 | | 1,162 | 83,612 | 13,859 | 3,479,471 |
| | 35.00.00 | | PIPING | | | | | | | | | |
| | | 35.13.01 | SS 304, ABOVE GROUND, PROCESS AREA | | | | | | | | | |
| | | | 3 IN DIA, SCH 40S | PCV-206A BYPASS LINE | 8.00 LF | - | - | 310 | 42 | 3,074 | 782 | 4,186 |
| | | | 3 IN DIA, SCH 40S | PCV-206B BYPASS LINE | 8.00 LF | - | - | 310 | 42 | 3,074 | 782 | 4,186 |
| | | | 3.5 IN DIA, SCH 40S | "A" FEEDWATER PUMP DISCHARGE TO STEAM REBOILER | 240.00 LF | - | - | 11,268 | 1,252 | 92,211 | 23,472 | 126,951 |
| | | | 3.5 IN DIA, SCH 40S | "B" FEEDWATER PUMP DISCHARGE TO STEAM REBOILER | 240.00 LF | - | - | 11,268 | 1,252 | 92,211 | 23,472 | 126,951 |
| | | | 4 IN DIA, SCH 40S | TANK-201A DISCHARGE LINE TO FEEDWATER PUMP PMP-001A | 40.00 LF | - | - | 2,204 | 233 | 17,160 | 4,368 | 23,732 |
| | | | 4 IN DIA, SCH 40S | TANK-201B DISCHARGE LINE TO FEEDWATER PUMP PMP-001B | 40.00 LF | - | - | 2,204 | 233 | 17,160 | 4,368 | 23,732 |
| | | | 5 IN DIA, SCH 10S | "A" REBOILER DRAIN TO CONDENSER | 220.00 LF | - | - | 15,884 | 841 | 47,190 | 12,012 | 74,886 |
| | | | 5 IN DIA, SCH 10S | "B" REBOILER DRAIN TO CONDENSER | 220.00 LF | - | - | 15,884 | 841 | 47,190 | 12,012 | 74,886 |
| | | | SS 304, ABOVE GROUND, PROCESS AREA | | | | | 58,893 | 4,334 | 319,267 | 81,268 | 469,429 |
| | | 35.13.10 | CARBON STEEL, ABOVE GROUND, PROCESS AREA | | | | | | | | | |
| | | | 14 IN DIA, 3/8" STD | HP TURBINE REHEAT STEAM TO REBOILER | 120.00 LF | - | - | 30,492 | 551 | 40,590 | 10,332 | 81,414 |
| | | | 20 IN DIA, 3/8" STD | JOINED HP TURBINE REHEAT LINES TO SPLIT FOR STEAM REBOILERS | 200.00 LF | - | - | 100,080 | 1,901 | 110,549 | 28,140 | 238,769 |
| | | | CARBON STEEL, ABOVE GROUND, PROCESS AREA | | | | | 130,572 | 2,052 | 151,139 | 38,472 | 320,183 |
| | | 35.14.10 | CARBON STEEL, STRAIGHT RUN | | | | | | | | | |
| | | | 18 IN DIA, 3/8 IN STD | "A" REBOILER TO H2 PLANT | 1,750.00 LF | - | - | 430,325 | 4,914 | 381,965 | 92,138 | 884,428 |
| | | | 18 IN DIA, 3/8 IN STD | "B" REBOILER TO H2 PLANT | 1,750.00 LF | - | - | 430,325 | 4,914 | 381,965 | 92,138 | 884,428 |

| Area | Group | Phase | Description | Notes | Quantity | Subcontract Cost | Process Equipment Cost | Material Cost | Man Hours | Labor Cost | Equip Amount | Total Cost |
|------|----------|---|--|--|-------------|------------------|------------------------|---------------|-----------|------------|--------------|------------|
| | | | CARBON STEEL, STRAIGHT RUN | | | | | 860,650 | 9,828 | 723,930 | 184,275 | 1,768,655 |
| | 35.15.30 | HOPE, BURIED | 3.5 IN DIA, DR 11 | BURIED R/O SUPPLY LINE FROM HYDROGEN PLANT | 3,600.00 LF | -- | -- | 17,802 | 1,987 | 146,377 | 37,260 | 201,439 |
| | | HOPE, BURIED | | | | | | 17,802 | 1,987 | 146,377 | 37,260 | 201,439 |
| | 35.35.00 | PIPE SUPPORTS, HANGERS | | | | | | | | | | |
| | | SUPPORT W/ BEAM FOR 3 IN PIPE | | | 2.00 EA | -- | -- | 302 | 21 | 1,556 | 396 | 2,254 |
| | | SUPPORT W/ BEAM FOR 3.5 IN PIPE | | | 44.00 EA | -- | -- | 6,864 | 465 | 34,225 | 8,712 | 49,801 |
| | | SUPPORT W/ BEAM FOR 4 IN PIPE | | | 8.00 EA | -- | -- | 1,285 | 97 | 7,166 | 1,824 | 10,278 |
| | | SUPPORT W/ BEAM FOR 5 IN PIPE | | | 30.00 EA | -- | -- | 4,950 | 365 | 26,871 | 6,840 | 36,661 |
| | | SUPPORT W/ BEAM FOR 14 IN PIPE | | | 4.00 EA | -- | -- | 1,875 | 97 | 7,166 | 1,824 | 10,866 |
| | | SUPPORT W/ BEAM FOR 18 IN PIPE | | | 100.00 EA | -- | -- | 50,000 | 1,620 | 119,329 | 30,375 | 208,704 |
| | | SUPPORT W/ BEAM FOR 20 IN PIPE | | | 6.00 EA | -- | -- | 4,728 | 167 | 12,304 | 3,132 | 20,164 |
| | | PIPE SUPPORTS, HANGERS | | | | | | 79,099 | 2,832 | 208,617 | 63,103 | 340,728 |
| | 35.45.00 | VALVES | | | | | | | | | | |
| | | 6 X 8 IN RELIEF VALVE, CAST IRON, CLASS 250, MANUAL, FLANGE END | | | 2.00 EA | -- | -- | 20,912 | 33 | 2,451 | 624 | 23,987 |
| | | 8 IN GATE VALVE, CS, CLASS 150, MANUAL, WELD END | | | 2.00 EA | -- | -- | 4,800 | 31 | 2,288 | 582 | 7,668 |
| | | 12 IN GLOBE VALVE, CS, CLASS 300, AIR OPERATED, WELD END | | | 2.00 EA | -- | -- | 180,000 | 82 | 4,573 | 1,164 | 185,737 |
| | | 14 IN GATE VALVE, CS, CLASS 300, MANUAL, WELD END | | | 10.00 EA | -- | -- | 145,000 | 289 | 19,600 | 5,040 | 169,640 |
| | | 14 IN CHECK VALVE, CS, CLASS 300, MANUAL, WELD END | | | 2.00 EA | -- | -- | 21,120 | 54 | 3,960 | 1,008 | 26,088 |
| | | 16 IN PRESSURE CONTROL VALVE, CS, CLASS 150, MANUAL, WELD END | | | 2.00 EA | -- | -- | 100,000 | 83 | 4,887 | 1,188 | 105,855 |
| | | 18 IN GATE VALVE, CS, CLASS 150, MANUAL, WELD END | | | 6.00 EA | -- | -- | 76,000 | 221 | 18,264 | 4,140 | 96,404 |
| | | VALVES | | | | | | 549,832 | 733 | 54,002 | 13,746 | 617,580 |
| | 35.46.00 | STAINLESS STEEL VALVES | | | | | | | | | | |
| | | 0.75 IN BALL VALVE, CLASS 600, MANUAL, WELD END | | | 14.00 EA | -- | -- | 2,800 | 89 | 5,115 | 1,302 | 9,217 |
| | | 0.75 IN GATE VALVE, CLASS 600, MANUAL, WELD END | | | 2.00 EA | -- | -- | 870 | 10 | 731 | 188 | 1,587 |
| | | 3.5 IN GATE VALVE, CLASS 150, MANUAL, WELD END | | | 6.00 EA | -- | -- | 18,000 | 70 | 5,127 | 1,305 | 24,432 |
| | | 3.5 IN CHECK VALVE, CLASS 150, MANUAL, WELD END | | | 2.00 EA | -- | -- | 6,000 | 23 | 1,709 | 435 | 8,144 |
| | | 3.5 IN GATE VALVE, CLASS 150, AIR OPERATED, WELD END | | | 2.00 EA | -- | -- | 35,000 | 33 | 2,428 | 616 | 38,046 |
| | | 4 IN VALVE, CLASS 150, MANUAL, WELD END | | | 4.00 EA | -- | -- | 14,000 | 52 | 3,886 | 964 | 18,850 |
| | | 5 IN VALVE, CLASS 150, MANUAL, WELD END | | | 4.00 EA | -- | -- | 22,000 | 73 | 5,374 | 1,368 | 28,742 |
| | | STAINLESS STEEL VALVES | | | | | | 98,470 | 331 | 24,349 | 6,198 | 129,017 |
| | 35.49.00 | MISCELLANEOUS VALVES | | | | | | | | | | |
| | | STAINLESS STEEL TUBING, COMPRESSION FITTINGS, VALVE, SUPPORT, FILTER, REGULATOR | AIR SUPPLY FOR AIR OPERATED/ACTUATED VALVE | | 6.00 EA | -- | -- | 3,600 | 115 | 8,488 | 2,160 | 14,248 |
| | | STEAM TRAP 1" INVERTED BUCKET | | | 2.00 EA | -- | -- | 1,440 | 13 | 943 | 240 | 2,623 |
| | | MISCELLANEOUS VALVES | | | | | | 5,040 | 128 | 9,431 | 2,400 | 16,868 |
| | | PIPING | | | | | | 1,800,267 | 22,225 | 1,637,109 | 416,723 | 3,854,099 |
| | 36.00.00 | INSULATION | | | | | | | | | | |
| | 36.17.03 | PIPE, MINERAL WOOL W/ALUMINUM JACKETING | | | | | | | | | | |
| | | 1 IN THICK, 3 IN PIPE | | | 16.00 LF | -- | -- | 118 | 15 | 1,275 | 128 | 1,520 |
| | | 1 IN THICK, 3.5 IN PIPE | | | 480.00 LF | -- | -- | 3,840 | 246 | 20,258 | 2,032 | 28,130 |
| | | 1 IN THICK, 3.5 IN PIPE | BURIED R/O SUPPLY LINE FROM HYDROGEN PLANT | | 20.00 LF | -- | -- | 160 | 19 | 1,593 | 160 | 1,913 |
| | | 1 IN THICK, 4 IN PIPE | | | 80.00 LF | -- | -- | 722 | 88 | 7,259 | 728 | 8,710 |
| | | 1 IN THICK, 5 IN PIPE | | | 440.00 LF | -- | -- | 4,400 | 260 | 21,471 | 2,154 | 28,026 |
| | | 3 IN THICK, 14 IN PIPE | | | 120.00 LF | -- | -- | 5,701 | 298 | 24,373 | 2,445 | 32,519 |
| | | 3 IN THICK, 18 IN PIPE | | | 3,500.00 LF | -- | -- | 201,460 | 3,801 | 313,318 | 31,434 | 548,211 |
| | | 3 IN THICK, 20 IN PIPE | | | 200.00 LF | -- | -- | 12,684 | 319 | 26,298 | 2,838 | 41,801 |
| | | PIPE, MINERAL WOOL W/ALUMINUM JACKETING | | | | | | 229,066 | 5,045 | 415,844 | 41,721 | 686,630 |
| | | INSULATION | | | | | | 229,066 | 5,045 | 415,844 | 41,721 | 686,630 |
| | 41.00.00 | ELECTRICAL EQUIPMENT | | | | | | | | | | |
| | 41.33.00 | HEAT TRACING | | | | | | | | | | |
| | | 3.5 IN PIPE HEAT TRACING | | | 480.00 LF | -- | -- | 11,498 | 730 | 49,086 | 11,871 | 72,432 |
| | | 3.5 IN PIPE HEAT TRACING | BURIED R/O SUPPLY LINE FROM HYDROGEN PLANT | | 20.00 LF | -- | -- | 479 | 81 | 4,089 | 989 | 5,557 |
| | | 4 IN PIPE HEAT TRACING | | | 80.00 LF | -- | -- | 2,009 | 251 | 18,872 | 4,082 | 22,962 |
| | | 5 IN PIPE HEAT TRACING | | | 440.00 LF | -- | -- | 13,200 | 690 | 48,397 | 11,225 | 70,822 |
| | | CONTROL PANEL | | | 1.00 EA | -- | -- | 8,000 | 38 | 2,983 | 617 | 11,598 |
| | | TRANSFORMER | | | 1.00 EA | -- | -- | 3,000 | 28 | 1,975 | 412 | 5,387 |

| Area | Group | Phase | Description | Notes | Quantity | Subcontract Cost | Process Equipment Cost | Material Cost | Man Hours | Labor Cost | Equip Amount | Total Cost |
|----------|----------|----------|--|---|-------------------------------|----------------------------|------------------------|------------------|---------------|------------------|----------------|----------------------------|
| | | 41.33.00 | HEAT TRACING HEAT TRACE ENGINEERING HEAT TRACING | | 1.00 LS | 20,000 | - | 38,184 | 1,795 | 121,381 | 29,196 | 208,740 |
| | | | ELECTRICAL EQUIPMENT | | | 20,000 | | 38,184 | 1,795 | 121,381 | 29,196 | 208,740 |
| | 44.00.00 | | CONTROL & INSTRUMENTATION | | | | | | | | | |
| | | 44.21.30 | LEVEL DEVICES LEVEL TRANSMITTER, RADAR LIQUID LEVEL TYPE, FLANGE MOUNT LEVEL DEVICES | ROSEMOUNT MODEL NO. 5408A15HA1NA1R2AACAAZ | 4.00 EA | - | - | 18,320 | 128 | 8,484 | 650 | 27,454 |
| | | | | | | | | 18,320 | 128 | 8,484 | 650 | 27,454 |
| | | 44.21.40 | PRESSURE DEVICES PRESSURE TRANSMITTER, GAUGE TYPE, WITH 2 VALVE MANIFOLD PRESSURE DEVICES | ROSEMONT MODEL NO. 305191CG1AZA11A1AL2M5D4 | 2.00 EA | - | - | 8,710 | 35 | 2,333 | 179 | 11,222 |
| | | | CONTROL & INSTRUMENTATION | | | | | 8,710 | 35 | 2,333 | 179 | 11,222 |
| | | | | | | | | 27,030 | 163 | 10,817 | 829 | 38,676 |
| | 61.00.00 | | CONSTRUCTION INDIRECT | | | | | | | | | |
| | | 61.15.00 | CRAFT PERSONNEL CRAFT PERSONNEL FOR STARTUP SUPPORT CRAFT PERSONNEL | | 1.00 EA | - | - | - | 800 | 58,064 | 0 | 58,064 |
| | | | CONSTRUCTION INDIRECT | | | | | - | 800 | 58,064 | 0 | 58,064 |
| | | | | | | | | - | 800 | 58,064 | 0 | 58,064 |
| | | | 1 STEAM SUPPLY | | | 1,497,380 | 2,482,000 | 3,635,164 | 42,438 | 3,272,388 | 769,475 | 11,656,406 |
| 2 | | | ELECTRICAL & TRANSMISSION LINE | | | | | | | | | |
| | 21.00.00 | | CIVIL WORK | | | | | | | | | |
| | | 21.17.00 | EXCAVATION FOUNDATION EXCAVATION, COMMON EARTH USING 1 CY BACKHOE EXCAVATION | (1) 345KV CIRCUIT BREAKER FOUNDATION - 25L X 10'W X 2'D | 38.98 CY | - | - | - | 9 | 748 | 165 | 913 |
| | | | | | | | | - | 9 | 748 | 165 | 913 |
| | | 21.19.00 | DISPOSAL DISPOSAL OF EXCESS MATERIAL USING DUMP TRUCK, 4 MIRROUND TRP DISPOSAL | (1) 345KV CIRCUIT BREAKER FOUNDATION - 25L X 10'W X 2'D | 38.98 CY | - | - | - | 4 | 299 | 66 | 365 |
| | | | | | | | | - | 4 | 299 | 66 | 365 |
| | | 21.20.00 | BACKFILL FOUNDATION BACKFILL, SELECT STRUCTURAL FLL BACKFILL | (1) 345KV CIRCUIT BREAKER FOUNDATION - 25L X 10'W X 2'D | 34.16 CY | - | - | 1,093 | 8 | 655 | 145 | 1,894 |
| | | | | | | | | 1,093 | 8 | 655 | 145 | 1,894 |
| | | 21.54.00 | CAISSON 3 FT DIA X 13 FT DEEP CAISSON 5.5 FT DIA X 40 FT DEEP CAISSON 3 FT DIA X 15 FT DEEP CAISSON | FOR 345KV DISC. SW. - EACH CAISSON = 3.4CY X \$1,300 = \$4,420 FOR 345KV STEEL POLES - EACH CAISSON = 35.19 X \$1,300 = \$45,754 FOR (3) 345KV CCVTs - EACH CAISSON = 3.93CY X \$1,300 = \$5,109 EA. | 2.00 EA 6.00 EA 3.00 EA | 8,840 274,404 15,327 | - - - | - - - | - - - | - - - | - - - | 8,840 274,404 15,327 |
| | | | CAISSON | | | 298,571 | | | | | | 298,571 |
| | | | CIVIL WORK | | | 298,571 | | 1,093 | 21 | 1,702 | 377 | 301,743 |
| | 22.00.00 | | CONCRETE | | | | | | | | | |
| | | 22.13.00 | CONCRETE MAT FOUNDATION LESS THAN 5 FT THICK, 4500 PSI CONCRETE | (1) 345KV CIRCUIT BREAKER FOUNDATION - 25L X 10'W X 2'D | 18.52 CY | - | - | 2,685 | 37 | 2,530 | 482 | 5,688 |
| | | | | | | | | 2,685 | 37 | 2,530 | 482 | 5,688 |
| | | 22.15.00 | EMBEDMENT EMBEDMENTS, STAINLESS STEEL EMBEDMENT | (1) 345KV CIRCUIT BREAKER FOUNDATION - 25L X 10'W X 2'D | 4.00 EA | - | - | 100 | 13 | 898 | 24 | 1,022 |
| | | | | | | | | 100 | 13 | 898 | 24 | 1,022 |
| | | 22.17.00 | FORMWORK BUILT UP INSTALL & STRIP FORMWORK | (1) 345KV CIRCUIT BREAKER FOUNDATION - 25L X 10'W X 2'D | 140.00 SF | - | - | 350 | 45 | 3,272 | 369 | 3,991 |
| | | | | | | | | 350 | 45 | 3,272 | 369 | 3,991 |
| | | 22.25.00 | REINFORCING UNCOATED A615 GR60 | (1) 345KV CIRCUIT BREAKER FOUNDATION | 1.30 TN | - | - | 1,556 | 40 | 2,846 | 453 | 4,854 |

| Area | Group | Phase | Description | Notes | Quantity | Subcontract Cost | Process Equipment Cost | Material Cost | Man Hours | Labor Cost | Equip Amount | Total Cost |
|------|----------|----------|---|--|--|-----------------------|---|--|-----------------------------------|---|---|--|
| | | 22.25.00 | REINFORCING UNCOATED A#15 GR69 | --2#L X 10"W X 2'D | 1.39 TN | - | - | 1,556 | 40 | 2,846 | 453 | 4,854 |
| | | | REINFORCING | | | | | 1,556 | 40 | 2,846 | 453 | 4,854 |
| | | | CONCRETE | | | | | 4,691 | 135 | 9,545 | 1,329 | 15,565 |
| | 23.00.00 | | STEEL | | | | | | | | | |
| | | 23.99.00 | STEEL, MISCELLANEOUS STEEL - STRUCTURAL SUPPORT FOR 345KV DISCONNECT SWITCH | FOR 345KV DISC. SW. - EACH SUPPORT = 8,952 LBS X 2 = 16,104 | 16,104.00 LB | - | - | 44,288 | 206 | 18,212 | 5,844 | 68,342 |
| | | | STEEL - STRUCTURAL SUPPORT FOR CCVT | FOR (3) 345KV CCVT - EACH SUPPORT = 450LBS X 3 = 1,350 LBS TOTAL | 1,350.00 LB | - | - | 3,713 | 17 | 1,527 | 490 | 5,729 |
| | | | STEEL, MISCELLANEOUS | | | | | 47,999 | 223 | 19,738 | 6,334 | 74,071 |
| | | | STEEL | | | | | 47,999 | 223 | 19,738 | 6,334 | 74,071 |
| | 41.00.00 | | ELECTRICAL EQUIPMENT | | | | | | | | | |
| | | 41.17.00 | COMMUNICATION SYSTEM COMMUNICATION SYSTEM - CABINET NEMA 4X | WITH METERS & AUX. TELECOMMUNICATION FOR REVENUE METERS | 1.00 LS | - | 50,000 | | 192 | 14,813 | 3,087 | 67,900 |
| | | | COMMUNICATION SYSTEM | | | | 50,000 | | 192 | 14,813 | 3,087 | 67,900 |
| | | 41.31.00 | ELECTRICAL EQUIPMENT, GROUNDING 40 BARE COPPER CONDUCTOR 500 AWG GROUNDING CABLE ROD, GROUND, CONICAL POINT, 5/8" DIA. X 15' LGTH. COPPERCLAS, NOT THREADED 5/8" X 10'-0" COPPER WELD GROUND ROD #2 CU BARE STRANDED GROUND WIRE ELECTRICAL EQUIPMENT, GROUNDING | GROUNDING (6) 345KV STEEL POLES (6) 345KV STEEL POLES | 492.00 LF 1,970.00 LF 18.00 EA 6.00 EA 340.00 LF | - - - - - | - - - - - | 2,001 19,700 4,680 1,050 288 27,609 | 15 102 50 13 3 183 | 1,019 8,649 3,329 886 222 12,307 | 247 1,857 805 215 54 2,977 | 3,357 28,206 8,814 2,152 864 43,093 |
| | | 41.47.00 | PANEL: CONTROL, DISTRIBUTION, & RELAY PROTECTIVE RELAY 50BF BREAKER FAILURE LOCKOUT RELAY 88BF LINE DIFFERENTIAL PROTECTION RELAY 411L/87 LINE DIFFERENTIAL PROTECTION RELAY 311L/87 LINE DIFFERENTIAL LOCKOUT RELAY 86 | RELAY WILL BE MOUNTED IN EXISTING RELAY PANEL RELAY WILL BE MOUNTED IN EXISTING RELAY PANEL RELAY WILL BE MOUNTED IN EXISTING RELAY PANEL RELAY WILL BE MOUNTED IN EXISTING RELAY PANEL RELAY WILL BE MOUNTED IN EXISTING RELAY PANEL | 1.00 LS 1.00 LS 3.00 LS 3.00 LS 1.00 LS | - - - - - | 300 800 30,450 17,910 1,000 | | 26 26 115 115 26 | 1,975 1,975 8,888 8,888 1,975 | 412 412 1,852 1,852 412 | 2,887 3,187 41,190 28,650 3,387 |
| | | | PANEL: CONTROL, DISTRIBUTION, & RELAY | | | | 50,460 | | 307 | 23,700 | 4,940 | 79,100 |
| | | | ELECTRICAL EQUIPMENT | | | | 100,460 | 27,609 | 682 | 50,820 | 11,056 | 190,094 |
| | 42.00.00 | | RACEWAY, CABLE TRAY & CONDUIT | | | | | | | | | |
| | | 42.15.33 | CONDUIT, PVC 4" PVC CONDUIT CONDUIT, PVC | ROUTED UNDERGROUND | 492.00 LF | - | - | 2,706 | 80 | 5,082 | 111 | 7,879 |
| | | | CONDUIT, PVC | | | | 2,706 | | 80 | 5,082 | 111 | 7,879 |
| | | 42.15.37 | CONDUIT, RGS 2" RGS CONDUIT | CONDUIT FOR CT's & CONTROL CABLES ROUTED INSIDE TB | 1,148.00 LF | - | - | 11,423 | 647 | 41,166 | 899 | 53,487 |
| | | | CONDUIT, RGS | | | | 11,423 | | 647 | 41,166 | 899 | 53,487 |
| | | | RACEWAY, CABLE TRAY & CONDUIT | | | | 14,129 | | 726 | 46,238 | 1,009 | 61,366 |
| | 43.00.00 | | CABLE | | | | | | | | | |
| | | 43.10.00 | CONTROL/INSTRUMENTATION/COMMUNICATION CABLE & TERMINATION 24 FIBER OPTIC GROUND WIRE | CABLE FOR LINE DIFFERENTIAL RELAYS ACROSS THE LINE | 2,297.00 LF | - | - | 11,761 | 184 | 12,358 | 2,990 | 27,108 |
| | | | CONTROL/INSTRUMENTATION/COMMUNICATION CABLE & TERMINATION | | | | 11,761 | | 184 | 12,358 | 2,990 | 27,108 |
| | | 43.20.00 | 600V CABLE & TERMINATION 12C #12 AWG SHLD 12C #12 AWG SHLD 4C #10 AWG SHLD | INDICATION CABLE FOR 345KV BREAKER CONTROL CONTROL & INSTRUMENTATION FOR MECH EQUIP TO CONTROL RM CABLES FOR (3) CT's FROM BREAKER TO RELAY ROOM | 1,640.00 LF 328.00 LF 8,862.00 LF | - - - | - - - | 3,605 761 14,305 | 131 28 283 | 6,823 1,785 19,064 | 2,135 427 4,612 | 14,763 2,953 37,981 |

| Area | Group | Phase | Description | Notes | Quantity | Subcontract Cost | Process Equipment Cost | Material Cost | Man Hours | Labor Cost | Equip Amount | Total Cost |
|------|----------|----------|---|--|--|------------------|-----------------------------------|---------------------------|--------------------------|-------------------------------------|-------------------------------|---|
| | | 43.20.00 | 600V CABLE & TERMINATION 4C #8 AWG 600V CABLE & TERMINATION CABLE | CABLE FOR PUMP | 656.00 LF | - | - | 1,975 20,845 32,606 | 47 488 672 | 3,176 32,828 45,186 | 768 7,942 10,932 | 5,919 61,616 68,724 |
| | 44.00.00 | 44.13.00 | CONTROL & INSTRUMENTATION CONTROL SYSTEM HUMAN MACHINE INTERFACE (HMI) | STAND ALONE HMI FOR CONTROL & INDICATIONS OF H2 POWER LINE & STEAM SUPPLY IN THE MCR | 1.00 LS | - | 30,000 | | 128 | 8,150 | 178 | 38,528 |
| | | | CONTROL SYSTEM CONTROL & INSTRUMENTATION | | | | 30,000 30,000 | | 128 128 | 8,150 8,150 | 178 178 | 38,528 38,328 |
| | 51.00.00 | | SUBSTATION, SWITCHYARD & TRANSMISSION LINE | | | | | | | | | |
| | | 51.13.00 | CONDUCTOR & WIRE OPTICAL GROUND WIRE (OPGW) - SHIELD WIRE CONDUCTOR & WIRE | | 10,500.00 LF | - | - | 17,640 17,640 | 58 58 | 3,677 3,677 | 80 80 | 21,397 21,397 |
| | | 51.13.02 | CONDUCTORS CONDUCTOR, 1113 KCMIL, ACSR (2) PER PHASE, BLUEJAY CONDUCTORS | TRANSMISSION LINE CABLE OUTDOOR | 10,500.00 LF | - | - | 53,760 53,760 | 347 347 | 23,302 23,302 | 5,638 5,638 | 82,700 82,700 |
| | | 51.15.27 | CIRCUIT BREAKER 345KV, 3000A, MANUALLY OPERATED DISCONNECT SWITCH, 50 KA SHORT CIRCUIT 345KV, 3000A, HV - CIRCUIT BREAKER CIRCUIT BREAKER | 345KV DISC. SW. | 2.00 EA 1.00 EA | - - | 50,000 257,600 307,600 | | 352 192 544 | 23,604 13,033 36,927 | 1,155 630 1,784 | 75,048 271,263 346,311 |
| | | 51.15.37 | COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT) COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT) COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT) | | 3.00 EA | - | 29,100 29,100 | | 192 192 | 13,033 13,033 | 630 630 | 42,763 42,763 |
| | | 51.15.43 | METERING REVENUE METER METERING | METERS TO BE RATED FOR 345KV TRANSMISSION LINE | 3.00 EA | - | 7,500 7,500 | | 77 77 | 5,213 5,213 | 252 252 | 12,965 12,965 |
| | | 51.15.67 | INSULATOR INSULATOR, POST, CLAMP TOP, 138KV, POLYMER, GRAY, HORIZONTAL MOUNT INSULATOR | (B) 345KV STEEL POLES | 18.00 EA | - | 4,422 4,422 | | 10 10 | 686 686 | 161 161 | 5,249 5,249 |
| | | 51.21.00 | TRANSMISSION TOWER, HARDWARE ASSEMBLY DAMPER, CONDUCTOR, STOCKBRIDGE VIBRATION, 1590 MCM ACSR, 45X7 STRANDING, CODE NAME-LAPWING DAMPER, CONDUCTOR, SPIRAL VIBRATION, 336.4 KCM ACSR, 150 KCM ACSR, 66" LENGTH, COLOR CODE-GREEN CLAMP, CABLE, SUSPENSION U-BOLT, 5A, ALUMINUM ALLOY ROD, ARMOR, SINGLE ARMSUPPORT, 2156 KCM ACSR, 84X19 STRANDS, 0436 DIA. X 109 IN. LONG, 14 RODS PER SET, ALUMINUM ALLOY, PREFORMED TRANSMISSION TOWER, HARDWARE ASSEMBLY | (B) 345KV STEEL POLES (B) 345KV STEEL POLES (B) 345KV STEEL POLES (B) 345KV STEEL POLES | 18.00 EA 12.00 EA 24.00 EA 24.00 EA | - - - - | - - 1,182 1,290 3,318 | | 13 3 3 30 50 | 892 222 222 1,997 3,333 | 216 54 54 483 896 | 1,720 510 1,458 3,771 7,458 |
| | | 51.25.00 | TRANSMISSION TOWER, POLE (STEEL) 85' ENGINEERED STEEL MONOPOLE (H6) TRANSMISSION TOWER, POLE (STEEL) | (B) 345KV STEEL POLES | 6.00 EA | - | 53,544 53,544 | | 46 46 | 3,107 3,107 | 752 752 | 37,403 57,403 |
| | | 51.99.00 | SUBSTATION, SWITCHYARD & TRANSMISSION LINE, MISCELLANEOUS SIGNS AND MARKERS (WARNING, STRUCTURE NUMBER, AERIAL PATROL, ETC.) SUBSTATION, SWITCHYARD & TRANSMISSION LINE, MISCELLANEOUS | (B) 345KV STEEL POLES | 6.00 LT | - | 252 252 | | 20 20 | 1,344 1,344 | 65 65 | 1,661 1,661 |

| Area | Group | Phase | Description | Notes | Quantity | Subcontract Cost | Process Equipment Cost | Material Cost | Man Hours | Labor Cost | Equip Amount | Total Cost | |
|------|----------|----------|---|-----------------------|----------|------------------|------------------------|----------------|----------------|--------------|----------------|---------------|------------------|
| | | | SUBSTATION, SWITCHYARD & TRANSMISSION LINE | | | | | 344,200 | 132,936 | 1,343 | 90,602 | 10,168 | 577,906 |
| | 61.00.00 | | CONSTRUCTION INDIRECT | | | | | | | | | | |
| | | 61.15.00 | CRAFT PERSONNEL | | | | | | | | | | |
| | | | CRAFT PERSONNEL FOR STARTUP SUPPORT | | | 1.00 EA | - | - | | 550 | 36,988 | 0 | 36,988 |
| | | | CRAFT PERSONNEL | | | | | | | 550 | 36,988 | 0 | 36,988 |
| | | 61.99.00 | MISCELLANEOUS | | | | | | | | | | |
| | | | SET UP TIME | (8) 345KV STEEL POLES | 24.00 EA | - | - | | 86 | 4,439 | 1,074 | 5,512 | |
| | | | AUXILIARY ARMS | (8) 345KV STEEL POLES | 8.00 EA | - | - | | 10 | 686 | 161 | 827 | |
| | | | DRILLING AND FRAMING | (8) 345KV STEEL POLES | 8.00 EA | - | - | | 13 | 888 | 215 | 1,102 | |
| | | | BLOCK & TAGS | (8) 345KV STEEL POLES | 18.00 EA | - | - | | 7 | 443 | 107 | 551 | |
| | | | STEEL ASSEMBLY | (8) 345KV STEEL POLES | 6.00 EA | - | - | | 132 | 8,877 | 2,148 | 11,028 | |
| | | | MISCELLANEOUS | | | | | | | 228 | 15,312 | 3,704 | 19,017 |
| | | | CONSTRUCTION INDIRECT | | | | | | | 778 | 52,300 | 3,705 | 56,804 |
| | | | 2 ELECTRICAL & TRANSMISSION LINE | | | | 298,571 | 474,660 | 261,262 | 4,708 | 324,272 | 45,035 | 1,403,800 |

Appendix J: IP - ENG-001 Design Attribute Review

| Design Attribute Review - Engineering Disciplines | | | |
|---|---|--------------|--|
| Tier 1 | Tier 2 | Placekeeping | Remarks |
| | Does the change: (Affect is defined as add, change, or remove) | | |
| Electrical | | | |
| | 1. Affect electrical components including motors, breakers, fuses, relay, electrical cables, conduits, trays raceways, tubing tracks, skid mounted equipment, large power transformers etc.? (SOER 10-1) | Yes | The protective relays of the H2 transmission line interface with the plant existing generator and GSU transformer relays and logic to isolate the generator/GSU during fault on the line. Therefore, CTs from the HV circuit breaker at the H2 feeder will be brought back to the plant relay room. The reboiler feed pump requires 480 Vac. 125 Vdc is required for the high-voltage breaker control and protective relay circuits. Therefore, the design effects the plant existing breakers, electrical cables, trays, and raceways in the plant. |
| | 2. Affect electrical protective devices or their settings such as fuses, breakers, protective relays, or thermal overloads? | Yes | The design affects the existing protective relays for the generator and GSU transformer. |
| | 3. Affect electrical loads? <ul style="list-style-type: none"> • Affect emergency diesel loading? • Add or remove station battery loading? • Add or remove load to a vital bus? • Add or remove load to a non-vital bus? • Compatible with transformer capacities? • Impact and Station Blackout Loadings or commitments? • Compatible with other associated electrical equipment capacities? • Have the dynamic effects as well as the static effects on bus voltage, current, and setpoints been considered, such as a large motor start, large motor trip, or bus transfer? | Yes | The 480 Vac and 125 Vdc power required for the H2 interface equipment are non-safety related and they will add additional loads to the plant electrical system. |
| | 4. Affect motor driven pump or fan load, horsepower or efficiency? | No | |
| | 5. Affect transformers, breakers, protective devices, the main turbine, and/or generator that could impact the transmission system (studies, protective settings, etc.)? <ul style="list-style-type: none"> • Affect switchyard voltage, switchyard breaker alignment, generator VAR loading? • Affect changes to generator electrical characteristics? • Affect changes to POST TRIP offsite power loading? • Affect status of offsite power voltage regulating devices (e.g. capacitor bank availability)? | Yes | There is no impact to generator VAR loading, which is controlled based on switchyard voltage. The switchyard breaker alignment is not impacted by the addition of the new high-voltage line to the hydrogen plant as the new high-voltage line is protected by a new high-voltage circuit breaker downstream of the tap point. The only additional exposure for the nuclear plant generator and switchyard breakers to trip for a single failure is for a fault on the very short length of conductor bus from the electrical tap point to the new high-voltage breaker. The length of this buswork is designed as short as practical to minimize the additional exposure. The hydrogen production facility is physically and electrically separated from the offsite power feed. Therefore, there is no impact to offsite power loading for the POST TRIP scenario. The hydrogen production facility is physically and electrically separated from the offsite power circuits. The load flow analysis demonstrates the change in the switchyard voltage due to the addition of the 128MWe/570MWe electrical load is negligible. Therefore, the status of offsite power voltage regulating devices is not impacted. |
| | 6. Add structures in a strong electrical field (e.g., near high voltage power lines)? Special grounding may be required. | Yes | The installation of the H2 transmission line is around the GSU transformer and the yard. Therefore, it is near high voltage power line. |
| | 7. Affect electrical cables: <ul style="list-style-type: none"> • Assure that all added cables meet fire retardancy requirements, and if required, EQ requirements? (Reference IEEE 383, IEEE1202, or approved equivalent) • Be compatible with existing electrical insulation and wiring? • Affect ampacity of existing cables? • Affect voltage drop? • Add cables to existing electrical raceways? • Be routed through fire wrapped raceways? • Routed in and/or through manholes? • Meet train separation requirements? | Yes | The cables added in the power block from the design will meet fire retardancy requirements. |
| | 8. Affect ampacity or voltage drop, with consideration for component or system performance? | Yes | Complete system analysis performed on the power feeder between the NPP and the H2 plant for cable ampacity and voltage drop. |
| | 9. Affect current, voltage, or power, with consideration for component or system performance? | Yes | |
| | 10. Affect elevated or degraded supply voltage, with consideration for impact on equipment and components? | Yes | |

| Design Attribute Review - Engineering Disciplines | | | |
|---|--|--------------|--|
| Tier 1 | Tier 2 | Placekeeping | Remarks |
| | Does the change: (Affect is defined as add, change, or remove) | | |
| | 11. If relays are used, are any relay contacts appropriate for the operating voltage? (Also, CONSIDER the impact of low voltage on CONTACT operation and coil pickup/drop out.) | Yes | |
| | 12. Affect containment penetration protection? | No | |
| | 13. Affect UL (or equivalent) listings? | No | |
| | 14. Affect raceways (including seismic analysis)? | Yes | New cable added will be routed in the plant existing raceways. |
| | 15. Affect the station grounding or lightning protection system? | Yes | Electrical equipment installed in the PA or the yard will be connected to the switchyard grounding. |
| | 16. Affect electromagnetic interference between new/existing equipment and electromagnetic coupling interactions between circuits? (Reference EPRI 102323 and NRC RG 1.180) | No | |
| | 17. Affect motor selection, including requirements for torque, voltage, frequency, and insulation class? | No | |
| | 18. Affect plant communication system including phones, paging, cell phones, radio systems, etc? | No | |
| | 19. Affect SSC protected by the cathodic protection system or freeze protection / heat tracing? | Yes | Underground piping will require heat tracing and outdoor components will require freeze protection. Exposed metals may also require cathodic protection. The nuclear plant will supply the power required for these measures. |
| | 20. Affect environmental conditions in areas containing EQ qualified equipment? | No | |
| | 21. Affect heat load calculations including Control Room, Battery Room, etc? | No | |
| | 22. Affect normal/emergency lighting including potential obstructions to light paths? | Yes | Lighting within the Turbine Building and in the yard near the H2 interface equipment may be affected. More lighting would be required. |
| Instrument and Controls (I&C) | | | |
| | 1. Affect any instrumentation and controls including controllers, actuators, transducers, indicators, transmitters, gauges, other instruments, system interlocks, start trip signals, annunciators, set points or margins, ranges, accuracy, time constants, response time, location, associated tubing, skid mounted equipment, wiring, control logic, etc. because of modifications or installation of new SSCs? | Yes | A standalone HMI for control, indications and alarm of the H2 power line and steam supply installed in the MCR, utilizing existing Fiber Optic backbone in the plant to communicate between the HMI and H2 interface equipment / protection panel. |
| | 2. Affect critical characteristics of instrument or control equipment including voltage, power to an instrument, current, pressure, temperature ratings, switch development, coil or contact on a switch or relay associated with an instrument, critical dimensions or materials, instrument range, accuracy, Setpoint or tolerance, replacement of analog devices with digital devices, etc.? | No | |
| | 3. Affect indicating instruments, controls and alarms used for operation, testing or maintenance, type of instruments, installed spares, range or measurement, calibration, accuracy, response time, and location of indication. | Yes | Existing alarms may be modified through the addition of H2 steam supply and electric feeder equipment. New indication, controls, and alarms will also be added for this equipment. |
| | 4. Affect instrument piping, tubing, or supports? | No | |
| | 5. Affect I&C setpoints, setpoint margin and/or setpoint calculations? | No | |
| | 6. Affect requirements for measurement and test equipment, or test equipment accuracy evaluations? | No | |
| | 7. Have the instruments been properly selected for the application? (i.e. range, accuracy, time response, pressure/ temperature rating, etc.) | No | |
| | 8. Require alarms for off-normal conditions? | Yes | |
| | 9. Are there requirements for remote and/or local operation? | Yes | See detail in question 1. |
| | 10. Are there requirements for manual and/or automatic operation? | No | |
| | 11. Are there calibration and maintenance requirements for the instruments? | No | |
| | 12. Are there requirements for testing (e.g. permanent test features, indication, restoration, connections)? | No | |
| | 13. Affect response characteristics of any existing instrumentation? | No | |
| | 14. Are there requirements for electro-magnetic Interference (EMI) / Radio Frequency Interference (RFI), including adding equipment to existing plant configuration and/or need to address solid state vulnerability to RFI? | No | |
| | 15. Affect software and programming/programmable settings of digital or electronic equipment? | No | |
| | 16. Affect digital equipment upgrades? (Ref: EPRI TR 102348, GL 95 02, and EPRI TR 107339) | No | |
| | 17. Could a transient result if the equipment is bumped? | No | |
| | 18. Affect grounding of the instrument signal loop and/or power source? | No | |
| | 19. Affect the air supply, fail position, regulator type, stroke or action of a valve or damper associated with an instrument? | No | |
| | 20. Affect an instrument loop action or wiring associated with an instrument loop? | No | |
| | 21. Are there requirements for power supplies, or modification affects loading on instrument loops? | No | |
| | 22. Are there requirements for special post installation setup? • Setting of gain for full power that may be unstable at low power? • Tuning of a controller to account for a new control valve trim? | No | |

| Design Attribute Review - Engineering Disciplines | | | |
|---|--|--------------|---|
| Tier 1 | Tier 2 | Placekeeping | Remarks |
| | Does the change: (Affect is defined as add, change, or remove) | | |
| | 23. Affect acceptance criteria for data such as pressure, flow, temperature, etc. used for calculations, or measurement and test equipment uncertainty? | No | |
| | 24. Affect the cyber security program or affect digital assets such as communication pathways, computer equipment, networks, systems, data transmission, modems, etc.? | Yes | The design includes digital relays that will require review. |
| | 25. Affect Reg Guide 1.97 equipment? | No | |
| Mechanical | | | |
| | 1. Affect mechanical SSCs, including tanks, pumps, valves, heat exchangers, piping, supports, skid mounted equipment, etc. and attachments because of modifications or installation of a new SSCs? | Yes | Tie-ins to existing steam & drains piping, installation of reboiler/s, demin pump/s, demin tank/s, and isolation & control valves. |
| | 2. Are there requirements for ASME, ASTM and ANSI standards applicable to the design? | Yes | Reboiler/s designed to ASME code. |
| | 3. Affect design limits (i.e., pressure, temperature, limits on number of various temperature/pressure cycles required by ASME to be considered) to be placed on the hydraulic properties of a system or component? | No | |
| | 4. Are there requirements for vibration, stress, shock, and reaction forces? | Yes | Stress requirements for piping, reaction loads on Hx nozzles. Steam piping will need to meet requirements for stress and reaction forces. |
| | 5. Does the design involve piping subject to vibration or piping near to/ connected to rotating equipment? If so, the design should consider impacts on branch lines and other connected equipment (i.e. 2-1 taper welds, piping support design, vibration analysis, etc.). | Yes | Demin pump discharge piping will need to consider vibration in its design. |
| | 6. Affect cantilevered branch lines created by new installations or by re-configuration or removal of existing piping? | No | |
| | 7. Affect class II/I conditions associated with non-safety class piping? | No | |
| | 8. Affect the frequency forcing function created by rotating equipment such as a pump, fan or compressor (e.g. change in speed, number of cylinders, etc.)? If so, the post-modification testing should monitor surrounding piping and tubing for excessive vibration to be evaluated for additional support if necessary. | No | |
| | 9. Affect equipment or components in locations prone to inducing low stress/ high cycle fatigue failures? ASSESS the potential for high cycle fatigue caused by: <ul style="list-style-type: none"> • Changes in the system structural frequency content, • Changes in operating speeds of rotating equipment or operating speeds, • Changes in hydraulic control systems, • Changes in system flow characteristics, e.g. flow velocities, • Changes in system flow control and pressure drop devices | No | |
| | 10. Require freeze protection or does the modification affect existing freeze protection? | Yes | Demin water lines and associated equipment may require freeze protection. |
| | 11. Affect normally stagnant non-isolable RCS branch lines (e.g. length, size, and configuration)? If so, the guidance provided in EPRI Document MRP-146 Revision 1, Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines" and EPRI MRP-146S, Supplemental Guidance, shall be considered in implementing the plant change. | No | |
| | 12. Does the modification need to consider hydraulic requirements such as PUMP net positive suction heads, allowable pressure drops, allowable fluid velocities and pressures, valve trim requirements, packing/seal requirements? | Yes | Pump sizing, hydraulic analysis of piping, valve trim considerations for level control to condenser. |
| | 13. Affect any piping erosion (cavitation, impingement, abrasive wear, etc.), or corrosion (FAC, general corrosion, etc.) concerns? | Yes | Evaluate flow conditions between reboiler and condenser connections for FAC. |
| | 14. Affect any pipe stress, pipe support, thermal expansion, seismic movement, or hydraulic analysis? | Yes | Stress analysis for piping mods, pipe supports for steam/drains piping. |
| | 15. Affect a potential for causing hydraulic transients or water hammer that can have damaging impact on piping or plant operation? | Yes | When bringing the external loop into service potential exists to flow high pressure steam through a cold pipe. |
| | 16. Affect any mechanical setpoints, setpoint margins, and/or setpoint calculations? (e.g. relief valve settings). | Yes | The reboiler/s will require pressure relief. Feed pump discharge may also require a relief valve for pump protection. |
| | 17. Are there requirements to provide vents, drains, and sample points to accommodate operational, maintenance and testing needs? | Yes | MS system piping changes, steam piping to H2 island, etc. |
| | 18. Are there code requirements to provide overpressure protection or thermal relief? | Yes | The reboiler/s will require pressure relief. Feed pump discharge may also require a relief valve for pump protection. |
| | 19. Affect line pressure, differential pressure, or temperature at which a valve functions? | Yes | Applies to new piping runs to new external closed loop. |

| Design Attribute Review - Engineering Disciplines | | | |
|---|---|--------------|---|
| Tier 1 | Tier 2 | Placekeeping | Remarks |
| | Does the change: (Affect is defined as add, change, or remove) | | |
| | 20. Affect loading on HVAC systems or ventilation flow during or after installation? <ul style="list-style-type: none"> Continually energized equipment has been added to a room. Changes to equipment that will increase the heat load in a room during post-accident conditions. Changes in system flows of cooling water or chilled water that may reduce existing cooling flow rates to HVAC units. Changes to wall and floor penetrations, doors, barriers that could short circuit air flow and limit cooling/heating to specific areas. Consider both temporary conditions during installation as well as final configurations. Changes to the Control Room, Fuel Building, Auxiliary Building, and BWR Turbine Building boundaries that could affect the ability of the HVAC to provide pressurization and filtration requirements. | No | |
| | 21. Affect quantities, storage, or location of chemicals that may impact Control Room Habitability issues? | No | |
| | 22. Affect loading on any other support system such as instrument air, service air, circulating water, fire water, demineralized water, or other system? | Yes | Demin water is assumed to be supplied from offsite. New AOVs will affect loading on station instrument air system. |
| | 23. Affect insulation? | Yes | New piping will be insulated. |
| | 24. Are there requirements for independent means of pressure relief? | Yes | Reboiler/s will require pressure relief. |
| | 25. Affect the assigned system design pressure or temperature? | Yes | New piping added to plant, increasing extracted mass flow. |
| | 26. Affect a gas-to-fluid system interface that may ALLOW gas intrusion? If so, the design shall be revised to preclude or mitigate the gas intrusion. | No | |
| | 27. Does the design provide means to ensure full pipes (high point, etc.), if required due to the assumptions of the pressure drop, NPSH, water hammer, or pump gas binding analyses? When installing or modifying piping, is the piping system properly sloped and are sufficient vent valves installed to prevent gas accumulation? (Reference Generic Letter 2008-01) | Yes | Piping design will have to consider gas accumulation. |
| | 28. Affect HEAT exchangers, such as INCREASE fouling, tube vibration, erosion? | Yes | Installation of new reboiler/s. |
| | 29. Does the modification need to consider utilizing cathodic protection for new underground SSCs? | No | |
| | 30. Affect Hydrogen (H2) piping? If so, THEN welded joints are preferred, especially where leakage cannot be tolerated or are in areas difficult to INSPECT. Back-welding of threaded fittings should be considered and compression fittings should not be used in a system or areas subject to cyclic stresses. (Reference ASME B31.12, "Hydrogen Piping and Pipeline, NFPA 55 2013 Edition, NUREG/CR-3551, NUREG-1364 for further guidance). | No | |
| | 31. Affect systems that connect or discharge to the main condenser? If so, modification should consider potential impacts to condenser internals when normally closed lines are allowed to discharge continuously (i.e. erosion of tubes, deflectors, baffles, shell, etc.). | Yes | Installing new connection for continuous drain into condenser. Condenser nozzles will need to be considered to ensure the condenser walls can handle the forces of new piping. |
| | 32. Affect the design, performance or operation of pumps? | Yes | New pump for demineralized water feed to the reboiler. |
| | 33. Affect operation of a valve or the sequence in which the valves are operated so that thermal binding or pressure locking is possible? | No | |
| | 34. Affect plant barriers including doors, walls, floors, special barriers, etc. that perform primary containment boundary, secondary containment boundary, Control Room boundary, flood, HELB, fire, Halon, CO2, security, depressurization, missile protection, ventilation, or other barrier functions used to support plant evaluations? | Yes | Routing cables into the MCR through Control Room boundary. Also routing piping out of the Turbine Building. |
| | 35. Affect containment (PWR)/ primary containment (BWR) design requirements, including: <ul style="list-style-type: none"> Adding or removing components in containment? Change the amount of exposed aluminum in containment? Change the amount of exposed zinc in containment? Introduce materials into containment that could affect sump performance or lead to equipment degradation (ref. GSI-191)? Decrease free volume of containment? Require addition or modification of a containment penetration boundary? Repair, replace or install coatings inside of primary containment, including installing coated equipment? | No | |
| | 36. Affect high/moderate energy line break analysis? | Yes | Impact evaluated in report. |
| | 37. Affect time critical operator actions? | Yes | Control room operators may need to evaluate transients and impacts to plant equipment/procedures. |
| | 38. Affect reactivity management or core design? | Yes | Modification will affect final feedwater temp. Faulted condition of the H2 plant could cause a thermal transient in the FW flow. Additional reactivity management activities required for large-scale design. |
| | 39. Affect nuclear safety analysis? | No | Bounded by FW malfunction. |

| Design Attribute Review - Engineering Disciplines | | | |
|---|---|--------------|--|
| Tier 1 | Tier 2 | Placekeeping | Remarks |
| | Does the change: (Affect is defined as add, change, or remove) | | |
| | 40. Affect foreign material that would require cleaning to prevent degradation of downstream components? What cleaning methods are to be used? What cleanliness criteria are required? | No | Modifications to the MS and CN flowpath, including the condenser hotwell. Normal FME practices. |
| | 41. Affect thermal performance including steam flows, feed water flows, condenser performance, heat exchanger performance, or circulating water? | Yes | Impact evaluated in report. |
| Structural | | | |
| | 1. Affect piping routing, component location, support location, support load, support type, etc.? | Yes | Pipe supports required. |
| | 2. Affect stress calculations of pipe supports or whip restraints? | Yes | Stress calculations for piping. |
| | 3. Affect snubbers, a process parameter in a line that contains a snubber, or personnel access to any safety related snubber? | No | |
| | 4. Affect the loading or require changes to existing equipment foundations? | No | No impact on existing foundations. New foundations will be required for transformers, demin tank/s, demin pump/s, and reboiler/s. |
| | 5. Affect wall stress calculations for pressurized concrete cubicles or structures (PWR)? | No | |
| | 6. Require a floor or wall loading analysis? | Yes | The addition of new piping and supports within the Turbine Building will require floor/wall loading analyses. |
| | 7. Affect supports, hangers, or foundations or add weight to or between existing supports, hangers, embedment, or foundations during installation or post installation? | Yes | Supports required for new piping. Also foundations required for demin water tank, hydrogen steam supply equipment, and electrical equipment. |
| | 8. Require core drills, expansion anchors, or re-bar cuts? | Yes | Pipe supports within the Turbine Building will likely require expansion anchors. |
| | 9. Affect an external or internal missile hazard, or an existing missile barrier? | No | |
| | 10. Affect wind and storm loading on external structures? | No | |
| | 11. Affect dynamic requirements such as live loading, vibration, and shock/impact? | No | |
| | 12. Require masonry wall analysis/ evaluation? Consider the following: <ul style="list-style-type: none"> • Modification will add a masonry wall. • Modification will delete a wall, floor or ceiling affecting a masonry wall. • Modification will locate safety-related components/systems near a masonry wall. • Modification will attach to or route safety-related systems/components through a masonry wall. | No | |
| | 13. Affect permanent radiological shielding or temporary shielding? | No | |
| | Heavy Loads / Lifting and Rigging | | |
| | 14. Affect load handling systems (cranes, hoists, lifting devices, lift points) including their load path limits? | Yes | H2 interface equipment will require the use of cranes, hoists, etc. for installation. |
| | Seismic Qualification / Review | | |
| | 15. Affect seismically qualified equipment or affect seismic boundaries? (Including currently seismically qualified components, new components requiring seismic qualification, or existing components required to be seismically qualified.) | No | |
| | 16. Require clearance review for seismic movement? | No | |
| | 17. Affect raceways in seismic areas of the plant? | No | |
| | 18. Are there requirements for seismic mounting/orientation? | No | |
| | 19. Affects spans between two separate seismic areas/buildings? (The effect of the relative movement must be addressed). | No | |
| | Flood Protection | | |
| | 20. Affect potential flooding sources to a flood zone and thereby increase the direct and/or indirect flooding vulnerability of essential equipment? Check for proximity of piping not subject to HELB to piping subject to pipe whip from HELB. | Yes | New demineralized water tank/s. Flood analysis will need to be reviewed against the addition of the tank/s. |
| | 21. Affect existing flood barriers or flood mitigation features providing unanalyzed pathway for flooding to propagate? | No | |
| | 22. Affect new penetrations or openings through existing flood barriers? | No | |
| | 23. Affect plant drainage/backfill requirements? | No | |
| | 24. Affect essential equipment or supporting systems where it would be susceptible to flooding? (Flooding conditions may also impact Environmental Qualification.) | No | |
| | 25. Affect new plant construction and/or infrastructure modifications or changes to site geology/topography that could potentially alter the site's geo-hydrological characteristics (ground water flow, direction, pressure, etc.)? | No | |

| Design Attribute Review - Programs Engineering | | | |
|--|--|--------------|---|
| Tier 1 | Tier 2 | Placekeeping | Remarks |
| | Does the change: (Affect is defined as add, change, or remove) | | |
| | | | |
| 10 CFR 50 Appendix J | | No | |
| ASME Code | | No | |
| Boric Acid | | No | |
| Buried Components | | Yes | New buried HDPE piping. |
| Coatings | | Yes | Carbon steel components will be coated. |
| Environmental Qualification (EQ) | | No | |
| Fire Protection, Appendix R, and NFPA D805 | | Yes | Add cables in the power block will add more combustible loads to different fire zones. Location of H2 Interface Enclosure and Demin Tank outside will require review from fire brigade to ensure access is not restricted. |
| FLEX | | Yes | New H2 interface equipment and the H2 plant addition may affect existing FLEX management. FLEX strategies will need to be reviewed for impact. |
| Flow Accelerated Corrosion (FAC) | | Yes | New piping added to MS and SD systems. |
| Heat Exchangers (HX) | | Yes | New heat exchanger being added to the plant. Will be added to the Hx program. |
| License Renewal and Aging Management | | No | |
| Maintenance Rule | | No | |
| Material Compatibility | | Yes | Piping and fabrication of pipe supports will require welding. |
| MOVs, AOVs, Relief Valves, and Check Valves | | Yes | New manual valves, air-operated valves, and check valves included in the design. AOV's may be added to the program. |
| North American Electric Reliability Corporation (NERC) | | Yes | The protective relays of the H2 transmission line will interface with the plant existing generator and GSU transformer differential relays to cover the new HV Breaker within their zone of protection. There is no adverse impacts to generation, transmission operator's protective system. |
| Nuclear Electric Insurance Limited (NEIL) | | Yes | Insurance for modification will be required. |
| Obsolescence | | No | |
| Station Blackout (SBO) | | No | |
| Steam Generators | | No | |
| Thermal Fatigue | | No | |
| Vessel Internals | | No | |
| Welding | | Yes | Piping and pipe supports will require welding. |

| Design Attribute Review - Stakeholders | | | |
|--|--|--------------|---|
| Tier 1 | Tier 2 | Placekeeping | Remarks |
| | Does the change: (Affect is defined as add, change, or remove) | | |
| Chemistry/ Environmental | | No | |
| Dry Fuel Storage (DFS) | | No | |
| Emergency Plan | | No | |
| Industrial Safety | | Yes | Routing steam out of Turbine Building. Dispatching large electrical load at high voltage to new location. New high voltage power lines required for design. |
| Information Technology | | No | |
| Licensing | | No | |
| Maintenance | | Yes | |
| Non-Destructive Examination (NDE) | | No | |
| Operations | | Yes | New equipment added to plant with interface in the MCR. Operator training will be required for the operation of the new HMI associated with the H2 power line and steam supply. Operator will interface with standalone HMI for the control, indication and alarm associated with the H2 power line and steam supply. |
| Plant Computer | | Yes | Information may be fed into plant computer based on site-specific design. |
| Probabilistic Risk Assessment (PRA) | | Yes | PRA impacted by modification. Siting of H2 plant can impact CDF. |
| Radiation Protection / ALARA Program | | No | |
| Refueling Equipment & Reactor Assembly | | No | |
| Security | | Yes | Steam piping will breach the Protected Area boundary. Installation of H2 interface enclosure and demineralized water tank may impact security line-of-sight, pathways, etc. |
| Supply Chain | | Yes | Equipment will need to be procured with Supply Chain input. |
| System Engineering | The applicable system engineering(s) should be included as stakeholder(s). | Yes | MS and SD system engineers should be involved as stakeholders. |
| Training | | Yes | New equipment being added to the plant, along with interface in the MCR. |
| Transmission | | Yes | New high-voltage transmission lines are required to be installed, in accordance with NERC reliability standards. |
| Work Planning | | Yes | Installation will be implemented through Work Planning. |

Appendix K: Control System Implementation

K-1. HIGH-LEVEL DESIGN BASIS

K-1.1 Purpose

The purpose of this document is to identify and document the high-level control system requirements associated with the 500 MW_{nom} HTEF. This design basis is limited to the cold reheat steam extraction only and the associated controls for the hydrogen production steam extraction. The use of HP steam would require additional control system modifications to the nuclear plant which are more involved and could be addressed in a separate report.

The intent of the below design basis is the following:

1. Identify the control system considerations to be implemented in the plant so end users can determine whether to use existing instrumentation and controls (I&C) or employ a digital control system.
2. Identify operational considerations for how operators shall enable the dispatch of steam to the hydrogen generation “island”.
3. Provide the control system design basis of the system which allows more detailed functional requirements to be developed.

K-1.2 Design Basis

K-1.2.1 Operating Controls and Monitoring

- a. The nuclear plant operator shall manually initiate the activation of the steam extraction portion of the HTEF (warmup and normal operation).
- b. The nuclear plant operator shall have the capability to monitor and control the steam extraction portion of the HTEF and the associated field equipment (i.e., pumps and valves).
- c. The nuclear plant operator shall be alerted to abnormal operating conditions within the steam extraction portion of the HTEF.
- d. The nuclear plant operator controls shall be easily accessible to the operator and provide for automatic and manual operation.
- e. The operator controls may be either dedicated controls per controlled component or graphic soft controls which are a part of a digital control system.
- f. The nuclear plant operator shall have the capability of initiating a warmup cycle for the steam extraction portion of the HTEF.

K-1.2.2 Warm-up

- a. A means to initiate and control the warming of the steam extraction portion of the HTEF may be performed via a small warmup line or by modulating the steam extraction valve.
- b. For automatic warm-up controls within a digital control system, a warm-up rate and target temperature shall be employed with the warm-up initiation implemented by the nuclear plant operator.
- c. Following a system warm-up or shutdown, the system shall have the capability to maintain standby conditions with the components in the warmed condition and ready state.

K-1.2.3 Drains

- a. The control of the system piping drains within the steam extraction portion of the HTEF shall be either manual (local), manual (control room), or a part of the control system.

K-1.2.4 Permissive Interlocks

- a. A permissive interlock shall be part of the controls to permit the opening of the steam admission valve for the HTEF portion of the steam extraction.
- b. The interlock shall be a function of nuclear power such as nuclear instrumentation system power or the reactor coolant system delta temperature power.
- c. The permissive interlock shall be maintained and if the plant conditions are no longer met the steam extraction valve associated with the HTEF shall rapidly close.
- d. A separate permissive interlock may exist for system warm-up and standby operations.

K-1.2.5 Operator Graphics

- a. An operator visual representation shall be available to the operator which presents process measurements and depicts the control elements associated with the system (e.g., fluid lines, pumps, and valves).
- b. The visual representation may be either a computer graphic or a control board mimic.
- c. Computer graphics shall use the “Systems Engineering Human-System Interface Display Implementation Guidelines” provided in WNA-DS-04213-GEN, (Reference 4) for the development of graphic displays.

K-1.2.6 Design Basis Transients

- a. The controls associated with the steam extraction portion of the HTEF shall not negatively impact the nuclear steam supply system design basis transients identified in the plant USAR.

K-1.2.7 Chapter 15 USAR Impacts

- a. The controls associated with the steam extraction portion of the HTEF shall not negatively impact the transient analysis events analyzed in the plant USAR (typically Chapter 15 analysis).

K-1.2.8 Existing Plant Controls

- a. The nuclear plant existing control systems shall not be negatively impacted nor require an upgrade for the steam extraction portion of the HTEF.
- b. The nuclear plant existing control systems may require some control system tuning to accommodate the conditions associated with the steam extraction portion of the HTEF.

K-2. CONTROL SYSTEM CONSIDERATIONS

K-2.1 Considerations for Control System Implementation

Careful consideration should be given to the control system when implementing the steam extraction and reboiler controls. If the plant has an older analog control system, it could be possible to implement the design, but it can present some limitations and challenges. Incorporating the controls into the existing analog system would require significant space on the main control board to implement a hard-wired Human-System Interface (HSI). Whereas a digital system can incorporate all necessary controls into a single touchscreen display, which would require much less main control board real estate. Implementing Boolean logic within analog control systems typically requires the use of relay logic circuits that require significant cabinet space. The digital control system can perform the same logic with a greatly reduced footprint. The digital control system also provides the flexibility to easily make modifications without requiring physical wiring changes. If the plant has an existing digital control system, the design could be implemented on that system, or a new dedicated digital system could be used.

The control system chosen for implementation will need to interact with the following components:

- Steam Extraction Flow Control Valve
- Steam Extraction Flow Control Valve Interlock Solenoid

- Steam Extraction Flow Transmitter
- Reboiler Level Control Valve
- Reboiler Level Control Valve Interlock Solenoid
- Reboiler Level Transmitter
- Drain Receiver Level Control Valve
- Drain Receiver Level Control Valve Interlock Solenoid
- Drain Receiver Level Transmitter
- Reboiler Outlet Pressure Transmitter
- Reboiler Feed Pump Breaker
- HTEF Breaker
- HTEF Power Meter

The below component descriptions are for one reboiler loop. The details should be considered for two reboiler loops.

K-2.1.1 Steam Extraction Flow Control Valve, Interlock Solenoid and Flow Transmitter

This control is manual only. In an analog control system, it will require a manual loader (potentiometer) to throttle the valve and an analog meter to display steam flow to the reboiler to be added to the main control board. The manual loader and steam flow indications can be implemented on graphics in a digital control system.

A new stem flow transmitter and associated analog input will need to be added to the control system.

A turbine trip status from the nuclear plant will need to be wired into the steam extraction flow control valve interlock solenoid to immediately close the valve on a turbine trip.

Reboiler Level Control Valve, Interlock Solenoid and Level Transmitter

This control is manual or automatic closed loop level control. In an analog control system, it will require a manual/automatic station and an analog meter to display reboiler level to be added to the main control board. The manual/automatic station and reboiler level indications can be implemented on graphics in a digital control system.

A new reboiler-level transmitter and associated analog input will need to be added to the control system.

A digital output from the control system will need to be wired into the reboiler-level control valve interlock solenoid to immediately close the valve on a reboiler high-level condition.

A high-level alarm and low-level alarm will need to be added to the plant alarm system. The alarms can be presented graphically in a digital control system.

K-2.1.2 Reboiler Feedpump

This control is manual on/off control of the reboiler feedpump. In an analog control system, it will require start and stop buttons and running and stopped indications for the pump. These controls can be implemented on graphics in a digital control system.

A digital output from the control system will need to be wired into the reboiler feed pump controls to immediately stop the pump on a reboiler high-level condition.

A pump trip alarm will need to be added to the plant alarm system. The alarm can be presented graphically in a digital control system.

K-2.1.3 Drain Receiver Level Control Valve, Interlock Solenoid and Level Transmitter

This control is manual or automatic closed-loop level control. In an analog control system, it will require a manual/automatic station and an analog meter to display drain receiver level be added to the main control board. The manual/automatic station and reboiler level indications can be implemented on graphics in a digital control system.

A new drain receiver level transmitter and associated analog input will need to be added to the control system.

A digital output from the control system will need to be wired into the drain receiver level control valve interlock solenoid to immediately open the valve on a drain receiver high-level condition.

A low-level alarm will need to be added to the plant alarm system. The alarm can be presented graphically in a digital control system.

K-2.1.4 Miscellaneous Indications

A new reboiler outlet pressure transmitter and associated analog input will need to be added to the control system. In an analog control system, it will require an analog meter to display reboiler outlet pressure to be added to the main control board. The pressure indication can be implemented on graphics in a digital control system.

A new HTEF Power consumption transmitter and associated analog input will need to be added to the control system. In an analog control system, it will require an analog meter to display HTEF Power consumption be added to the main control board.

K-2.1.5 Common Component Descriptions

The below component descriptions are common across the two reboiler loops.

K-2.1.6 HTE Electrical Dispatch

This control is manual on/off control of the HTEF Electrical dispatch breaker. In an analog control system, it will require close and open buttons and closed and open indications for the breaker. These controls can be implemented on graphics in a digital control system.

A breaker trip alarm will need to be added to the plant alarm system.

K-2.1.7 Miscellaneous Alarms

A new HTE plant trip or fire input will need to be added to the analog control system. A HTE General alarm will need to be added to the plant alarm system.

Implementation using a new or existing digital control system will require significantly less impact. The required control board space can be greatly reduced by implementing the controls on graphics on a single HSI.

K-3. Functional Requirements

The purpose of the thermal power extraction control system is to maintain a steady supply of steam to the HTEF. The thermal power extraction control system will extract cold reheat steam from the cross-under piping between the high-pressure turbine and moisture separator reheaters. To provide isolation between the HTEF and the nuclear power plant, the steam extracted from the nuclear power plant will be supplied to two reboiler loops to provide high-quality steam to the HTEF. Each reboiler loop will have a reboiler feed pump and a demineralized water storage tank. The control system will control all components required to provide the steam extraction from the nuclear power plant and the steam supply to the HTEF.

K-3.1 Functional Description

K-3.1.1 Control System Functions

The control system provides the means to start or stop thermal dispatch from the nuclear plant by opening or closing the flow control valves from the cold reheat piping to the two reboiler loops.

The control system provides the interface for starting and stopping the reboiler feed pumps.

The control system provides the capability for energizing and de-energizing power supplied to the HTEF.

The control system provides process values used to evaluate the performance of the thermal and electrical extraction systems.

The control system provides alerts and alarms of the HTEF.

The control system provides two-level control loops in each reboiler loop. One for the reboiler level and one for the drain receiver level.

Nuclear Plant Steam Extraction

The nuclear plant steam extraction is controlled by one flow control valve in each reboiler loop. The valve can be opened to any position to account for the necessary steam supply to the reboiler. A turbine trip interlock shall cause the valve to close, isolating the steam extraction.

Reboiler Feed Pump Control

The reboiler feed pumps can be manually started or stopped by the nuclear plant operator. The pump will trip when the level in the reboiler exceeds a high-level trip setpoint.

Reboiler Level Control

The purpose of the reboiler level regulator is to maintain the reboiler level at its setpoint. There are two reboiler loops. The requirements listed here are for one loop. The other loop is identical.

[Requirement K-3.1.1-2: There shall be an algorithm for the following required proportional integral (PI) transfer function:

$$K_{5.1} + \frac{1}{\tau_{5.1}s}]$$

where

$K_{5.1}$ is the controller proportional gain

$\tau_{5.1}$ is the controller integral time constant.

Drain Receiver Level Control

The purpose of the drain receiver level regulator is to maintain the drain receiver level at its setpoint. Each reboiler loop has its own drain receiver. The requirements listed here are for one loop. The other loop is identical.

[Requirement K-3.1.1-2: There shall be an algorithm for the following required PI transfer function:

$$K_{8.1} + \frac{1}{\tau_{8.1}s}]$$

where

$K_{8.1}$ is the controller proportional gain

$\tau_{8.1}$ is the controller integral time constant.

K-3.2 INTERLOCKS AND PERMISSIVES

K-3.2.1 Turbine Trip Interlock

[Requirement K-3.2.1-1: A turbine trip shall generate an interlock causing the nuclear plant steam dispatch flow control valves to go closed.]

K-3.2.2 Reactor Power Interlock

[Requirement K-3.2.1-2: power below a specified level shall generate an interlock causing the nuclear plant steam dispatch flow control valves to go closed. Reactor power can be measured from the nuclear instrumentation or the reactor coolant system average temperature.]

K-3.2.3 Reboiler High Level Interlock

[Requirement K-3.2.1-3: When the level in the reboiler exceeds the high-level interlock, the reboiler feedpump shall trip and the reboiler level control valve shall close.]

K-3.2.4 Drain Receiver High-Level Interlock

[Requirement K-3.2.1-4: When the level in the drain receiver exceeds the high-level interlock, the drain receiver level control valve shall open.]

K-3.3 I/O Interfaces

| Signal Name | Signal Type | Number of Signals |
|--|----------------|-------------------------|
| Reboiler Level | Analog Input | 2 (1 per reboiler loop) |
| Drain Receiver Level | Analog Input | 2 (1 per reboiler loop) |
| Reboiler Outlet Pressure | Analog Input | 2 (1 per reboiler loop) |
| Steam Extraction Flow | Analog Input | 2 (1 per reboiler loop) |
| HTEF Electrical Power Consumption | Analog Input | 2 (1 per reboiler loop) |
| Reactor Power | Analog Input | 1 |
| Reboiler Level Control Demand | Analog Output | 2 (1 per reboiler loop) |
| Drain Receiver Level Control Demand | Analog Output | 2 (1 per reboiler loop) |
| Steam Extraction Flow Control Demand | Analog Output | 2 (1 per reboiler loop) |
| Reboiler Feed Pump Running | Digital Input | 2 (1 per reboiler loop) |
| Reboiler Feed Pump Stopped | Digital Input | 2 (1 per reboiler loop) |
| HTEF Breaker Closed | Digital Input | 1 |
| HTEF Breaker Open | Digital Input | 1 |
| HTEF Trip or Fire | Digital Input | 1 |
| Reboiler Level Control Valve Interlock | Digital Output | 2 (1 per reboiler loop) |
| Drain Receiver Level Control Valve Interlock | Digital Output | 2 (1 per reboiler loop) |
| Reboiler Feed Pump Start | Digital Output | 2 (1 per reboiler loop) |
| Reboiler Feed Pump Stop | Digital Output | 2 (1 per reboiler loop) |
| HTEF Breaker Open | Digital Output | 1 |
| HTEF Breaker Close | Digital Output | 1 |
| HTEF Alarm | Digital Output | 1 |

K-3.3.1 Ranges

| Signal | Range |
|----------------------|--------|
| Reboiler Level | 0-100% |
| Drain Receiver Level | 0-100% |

| | |
|----------------------------------|------------|
| Reactor Power | 0-100% |
| Reboiler Outlet Pressure | TBD PSI |
| Steam Extraction Flow | TBD lbm/hr |
| HTE Electrical Power Consumption | TBD MW |

K-3.4 Control Interfaces

K-3.4.1 Manual/Auto (M/A) Interface

Steam Extraction Flow Control M/A Station

[Requirement K-3.4.1-1: Capability to manually control the steam extraction flow shall be provided.]

[Requirement K-3.4.1-2: The following features shall be provided:

- Manual valve control
- Indication of valve position demand.]

Reboiler Level M/A Station

[Requirement K-3.4.1-3: Capability to manually control the reboiler level shall be provided.]

[Requirement K-3.2.1-4: The following features shall be provided:

- Ability to switch between automatic and manual
- Indication of valve position demand (automatic and manual)
- Indication of reboiler level
- Ability to change the level setpoint
- Indication of setpoint.]

Drain Receiver M/A Station

[Requirement K-3.4.1-5: Capability to manually control the drain receiver level shall be provided.]

[Requirement K-3.4.1-6: The following features shall be provided:

- Ability to switch between automatic and manual
- Indication of valve position demand (automatic and manual)
- Indication of drain receiver level
- Ability to change the level setpoint
- Indication of setpoint.]

K-3.4.2 On/Off Controls

HTE Power Feed Control

[Requirement K-3.4.2-1: Capability to control the power feed shall be provided.]

[Requirement K-3.4.2-2: The following features shall be provided:

- Ability to energize/de-energize power supplied to the HTEF.
- Indication of HTE breaker status (Open and Closed).]

Reboiler Feedpump Control

[Requirement K-3.4.2-3: Capability to control the reboiler feedpump shall be provided.]

[Requirement K-3.4.2-4: The following features shall be provided:

- Ability to start/stop the reboiler feedpump.

Indication of reboiler feedpump status (running and stopped).]

K-3.5 Indications

K-3.5.1 Steam Extraction Flow

[Requirement K-3.5.1-1: There shall be indication of steam extraction flow in the MCR.]

K-3.5.2 Reboiler Outlet Pressure

[Requirement K-3.5.2-1: There shall be indication of reboiler outlet pressure in the MCR.]

K-3.5.3 HTEF Power Consumption

[Requirement K-3.5.3-1: There shall be indication of HTEF Power consumption in the MCR.]

K-3.6 Alarms and Annunciators

K-3.6.1 Reboiler Feed Pumps

[Requirement K-3.6.1-1: The following conditions shall actuate an alarm:

Pump trip

- Reboiler feedpump tripped due to level greater than reboiler level trip setpoint.
- Pump trip due to motor overload.]

K-3.6.2 Reboiler

[Requirement K-3.6.2-1: The following conditions shall actuate an alarm:

High Level

- Reboiler level greater than the high alarm setpoint

Low-Level

- Reboiler level less than the low alarm setpoint.]

K-3.6.3 Drain Receiver

[Requirement K-3.6.3-1: The following conditions shall actuate an alarm:

High Level

- Reboiler level greater than the high alarm setpoint

Low-Level

- Drain receiver level less than the low alarm setpoint.]

K-3.6.4 HTEF Alarm

[Requirement K-3.6.4-1: The following conditions shall actuate an alarm:

- HTEF trip or fire
- HTEF Breaker Trip
- HTEF Equipment trouble.]

K-4. References

1. WNA-PS-00016-GEN, Rev. 8, “Standard Acronyms and Definitions”, Westinghouse Electric Company LLC.
2. SOW-19894, Rev. 0, “Statement of Work, Integration of Digital Control Systems of Nuclear Power Plants and Hydrogen Production Plants”, Idaho National Laboratory.
3. Report SL-016181, Rev. 1, “Nuclear Power Plant Pre-Conceptual Design Support for Large-Scale Hydrogen Production Facility”, Nov. 18, 2022, Sargent & Lundy
4. WNA-DS-04213-GEN, Rev. 1, “GI&C Control & Information Systems Engineering Human-System Interface Display Implementation Guidelines”, Westinghouse Electric Company LLC.