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Light Water Reactor Sustainability Program

Pre-Conceptual Design for Large-Scale Nuclear Integrated Hydrogen Production Facility

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Idaho National Laboratory (INL)
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Pre-Conceptual Design for Large-Scale Nuclear Integrated Hydrogen Production Facility

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Report prepared for the Light Water Reactor Sustainability (LWRS) Program at Idaho National Laboratory (INL) under the direction of Richard Boardman and Tyler Westover. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

LIMITATIONS OF USE

This design report is provided as a guide and feasibility assessment for coupling a large-scale hydrogen production facility with a commercial pressurized water reactor (PWR) nuclear power plant. Site-specific analysis is required to provide the analytical basis for performing this modification. Evaluations within this report are provided for the nuclear plant and hydrogen facilities described in Section 4 and Section 5, respectively. If using a different size or design for the hydrogen production facility and nuclear power plant, the results and conclusions should be carefully analyzed and considered for impact.

VERSION LOG

Version	Issue Date	Sections Modified
0	June 10, 2024	Initial Issuance
1	June 21, 2024	Updated Executive Summary, Project Cost Estimate, and Conclusion

ISSUE SUMMARY AND APPROVAL

This is to certify that this document has been prepared, reviewed, and approved in accordance with Sargent & Lundy's Standard Operating Procedure SOP-0405, which is based on ASQ/ANSI/ISO 9001:2015: Quality Management Systems–Requirements.

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

Abbreviation/Acronym/Initialism	Definition/Clarification
A/E	architect/engineer
AACE	Association for the Advancement of Cost Engineering
ac	alternating current
AFT	Applied Flow Technology
AHJ	Authority Having Jurisdiction
AOV	air-operated valve
ASME	American Society of Mechanical Engineers
AVR	automatic voltage regulator
AWE	alkaline water electrolysis
BES	bulk electric system
BOP	balance of plant
BWR	boiling water reactor
CT	current transformer
CW	cooling water
DAR	Design Attribute Review
dc	direct-current
DOE	United States Department of Energy
EPCM	engineer, procure, construction management
EPRI	Electric Power Research Institute
ESV	emergency shutoff valve
ETAP	electrical transient analyzer program
FAC	flow-accelerated corrosion
FCV	flow control valve
FOAK	first-of-a-kind
FPOG	Flexible Plant Operation and Generation
ft	feet
gpm	gallons per minute
GSU	generator step-up
H_2	hydrogen
HDPE	high-density polyethylene
HELB	high energy line break
HMI	human machine interface
HP	high-pressure
hp	horsepower

Abbreviation/Acronym/Initialism	Definition/Clarification
hr	hour
HSS	hydrogen steam supply
HTE	high-temperature electrolysis
H.V.	high-voltage
HVAC	heating, ventilation, and air conditioning
I&C	instrumentation and controls
IGBT	insulated gate bipolar transistor
INL	Idaho National Laboratory
km	kilometer
kW_{dc}	kilowatt direct current
LAR	License Amendment Request
lbm	pound mass
LP	low-pressure
LTE	low-temperature electrolysis
LV	low-voltage
LWRS	DOE Light Water Reactor Sustainability
LWR	light water reactor
MCR	main control room
MOD	manually operated disconnect
MPT	main power transformer
MS	main steam
MSR	moisture separator reheater
MT	metric tonnes
MV	medium-voltage
MVA	megavolts ampere
MW	megawatt
MW_{dc}	megawatt direct current
MW_e	megawatt electric (alternating current)
MW_t	megawatt thermal
NERC	North American Electric Reliability Corporation
NFPA	National Fire Protection Association
NOAK	Nth-of-a-kind
NPDES	National Pollutant Discharge Elimination System
NPSH	net positive suction head
NRC	United States Nuclear Regulatory Commission
OCA	owner controlled area
OEM	original equipment manufacturer

Abbreviation/Acronym/Initialism	Definition/Clarification
OEM	original equipment manufacturer
OPGW	optical ground wire
P&ID	piping and instrumentation diagram
PA	protected area
PDC	power distribution center
PEM	polymer electrolyte membrane
PEPSE	Performance Evaluation of Power System Efficiencies
PLC	programmable logic controller
PRA	probabilistic risk assessment
PSCAD	Power Systems Computer Aided Design
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PTZ	pan, tilt, zoom
PWR	pressurized water reactor
S&L	Sargent & Lundy, L.L.C.
SCADA	supervisory control and data acquisition
SDP	Standard Design Process
sec	second
SOEC	solid oxide electrolysis cell
TB	Turbine Building
TDH	total developed head
TPE	thermal power extraction
UPS	uninterruptible power supply
U.S.	United States
USD	United States dollars

EXECUTIVE SUMMARY

Nuclear power has been identified as a source of large-scale, carbon-free "clean" steam, with thermal and electrical energy that can be utilized to realize national decarbonization goals. However, nuclear power plants in deregulated markets continue to face economic pressures from inexpensive natural gas and non-dispatchable renewables.

Alternative uses for nuclear plant steam and electricity can provide a potential pathway for improved profitability and long-term operational viability. Carbon-free hydrogen production using steam and electricity through a high-temperature electrolysis (HTE) process is one use case well suited to nuclear power generators.

This report develops a pre-conceptual design for a generic large-scale, 500 MW_{dc} HTE hydrogen production facility coupled with a generic 1,200 MW_e pressurized water reactor (PWR) nuclear power plant.

The pre-conceptual design is comprised of three (3) main parts:

- Nuclear plant integration,
- High-voltage switchyard, and
- Hydrogen production facility.

Nuclear Plant Integration

Based on the thermal and electrical load requirements of the hydrogen facility, the nuclear plant interfaces are developed. Electrically, power is dispatched through a new connection on the high-voltage side of the generator step-up transformers before being distributed to the high-voltage switchyard via transmission line. Mechanically, a relatively small portion (~3%) of nuclear plant steam extracted from the High-Pressure (HP) Turbine exhaust is diverted to boil demineralized water for electrolysis. Separated via a heat exchanger in the nuclear plant protected area, nuclear plant steam is condensed, subcooled, and returned to the main condenser, while the isolated hydrogen process feed steam is sent to the hydrogen facility for electrolysis. Additional interfaces are established between the nuclear plant and hydrogen facility for water-based BOP systems.

High-Voltage Switchyard

A new high-voltage switchyard is developed to support hydrogen facility electrical loads and to step down transmission voltages to the levels required for distribution throughout the hydrogen facility. Monitoring and control is performed by a Supervisory Control and Data Acquisition (SCADA) system with human-machine interface (HMI) in the facility control center.

Hydrogen Production Facility

The hydrogen production facility design consists of the major hydrogen process and balance of plant (BOP) systems. Hydrogen is produced via solid oxide electrolysis cell (SOEC) technology within the electrolyzer modules; each 1.2 MW_{dc} electrolyzer stamp contains a set of hydrogen generation modules. Groups of eight (8) stamps are combined to form 9.6 MW_{dc} blocks; there are fifty-two (52) blocks within the facility.

After leaving the electrolyzers, wet hydrogen is dried and purified to the desired purity, compressed, and sent to the desired offtake, which is a distribution pipeline in this generic design. Supporting systems include water treatment, cooling systems, heat and condensate recovery, and utility gases, as well as various safety and ancillary systems (i.e., HVAC, plumbing, etc.). Also developed within the facility design are the electrical systems, including rectification for direct-current (dc) electrolyzers and distribution for auxiliary loads.

This report also provides considerations for various factors including nuclear plant modification scope, thermal and electrical transients, equipment lead times, and stack replacement frequency.

Project Cost Estimating

Range cost estimates were developed in 2024 United States dollars (USD) for the three (3) focus areas of the pre-conceptual design: nuclear plant integration, high-voltage switchyard, and hydrogen production facility. Nuclear plant integration costs were estimated at approximately $40 million and align with previous S&L reports. High-voltage switchyard costs are estimated at approximately $34 million.

Two (2) hydrogen production facility cost scenarios were developed in this study:

- a near-term *early adopter* site (3-5 years away), and
- an enhanced *large module* electrolyzer design (8-10 years away).

These two (2) scenarios assumed an electrolyzer stamp price of $\$500/kW_{dc}$ and $\$250/kW_{dc}$, respectively. The electrolyzer stamp scope included: electrolysis stacks, topping heaters, component housing, and auxiliary electrical equipment. Rectifier skids were estimated separately. High pressure compression was *not included* in these facility costs to support cost comparison.

The early adopter hydrogen production facility option was estimated to cost approximately $750 million, or $\$1,500/kW_{dc}$. Through future expected electrolyzer stamp design enhancements in module capacity and energy density, a lower-cost large module option was estimated at a range cost of approximately $600 million, or $\$1,200/kW_{dc}$. In both options, uninstalled capital costs account for approximately 60% of the total hydrogen production facility cost.

The cost estimates determined within this report were compared to similar investigations of large-scale nuclear-integrated HTE hydrogen production facilities. These investigations have estimated 2024 USD first-of-a-kind (FOAK) and Nth-of-a-kind (NOAK) HTE hydrogen production facility costs in the range of $\$750\text{-}1,250/kW_{dc}$. The estimates within this report align with previous cost estimates, with small differences attributed to contrasting indirect cost assumptions, electrolyzer block sizes, and modular versus stick-built construction practices.

Further assessments have determined that a number of hydrogen facility design and operational refinements can be implemented to help decrease the estimated hydrogen facility range costs identified herein. By utilizing lean design principles, refining facility operation and maintenance activities, and conducting fundamental risk evaluations as described in Section 6, cost reductions upward of $50 million could be achieved to bring overall hydrogen facility costs to approximately $\$1,100/kW_{dc}$ (~$\$850/kW_{dc}$ in 2021 USD, accounting for historical escalation).

Further cost reduction is envisioned through the continued assessment of design and construction optimizations. This pre-conceptual design illustrates the feasibility of developing a large-scale nuclear-integrated HTE hydrogen production facility.

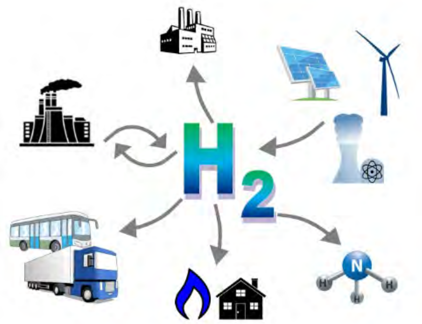
Nuclear-integrated HTE hydrogen production is a valuable asset that can provide vast amounts of carbon-free hydrogen. Given the potential value nuclear-integrated HTE can provide in support of national decarbonization goals, continued efforts should focus on the development of site-specific front-end engineering design studies and cost optimization strategies.

1. BACKGROUND

One of the focuses of the United States (U.S.) Department of Energy's (DOE) Light Water Reactor Sustainability (LWRS) program is to explore avenues that can extend the operation of the U.S. commercial nuclear power plant fleet. Within the LWRS program, the Flexible Plant Operation and Generation (FPOG) Pathway is working to diversify the revenue streams of light-water reactors (LWRs) through the exploration of nuclear plant operation beyond supplying electrical power to the grid. Nuclear power has been identified as a source of large-scale, carbon-free "clean" steam, with thermal and electrical energy that can be effectively utilized to realize national long-term decarbonization goals.

Nuclear power plants are typically operated at full power to provide electrical power to the national grid. In deregulated markets, nuclear power plants face economic pressures from fluctuating electrical demand, inexpensive natural gas, and decreasing prices of wind and solar. Therefore, exploring alternative uses for the clean steam and electricity produced by nuclear plants during these challenging times is critical to improve the viability of long-term nuclear plant operation.

One area of research at the DOE's Idaho National Laboratory (INL) has been focusing on the use of clean steam produced by a nuclear power plant to support the production of hydrogen (H_2) through the emerging technology of high-temperature electrolysis (HTE). The combination of H_2 production, storage, and distribution, through what are known as "H_2 hubs" in support of the transportation, agricultural, and industrial sectors, has been identified as a strategic avenue to support overall decarbonization in the United States.



Electrolysis is the process through which water is decomposed into its oxygen and hydrogen gases via the application of an electrical potential. Research in the field has shown electrolysis to be more efficient at elevated temperatures. The process of HTE leverages this advantage using high-temperature steam as the process fluid for the reaction. The steam is broken down using rectified direct-current (dc) power within a solid oxide electrolysis cell (SOEC) to produce H_2 that can then be compressed, stored, and utilized in a variety of applications.

To inform future discussions and considerations of coupling an existing nuclear plant to a large-scale high-temperature electrolysis hydrogen production facility, INL contracted Sargent & Lundy (S&L) to develop a pre-conceptual design for the development and integration of a 500 MW_{dc} high-temperature electrolysis hydrogen production facility with an existing, generic nuclear power plant. This design is an extension to S&L report SL-016181 [1], which detailed the required modifications and plant impacts of diverting thermal and electrical energy from the nuclear plant to the hydrogen production facility. This current study focuses on the design of the hydrogen production facility itself, with additional refinement of the integration with the nuclear plant and surrounding environment.

2. PURPOSE

The purpose of this report is to develop a pre-conceptual design for a 500 MW_{dc} hydrogen production facility integrated with a generic pressurized water reactor nuclear power plant to assess project cost and feasibility. This work focuses on the hydrogen facility design including hydrogen production, compression, drying, purification, balance of plant systems, and electrical transmission and distribution to the facility. A conceptual integration strategy for the hydrogen facility with both the nuclear plant and surrounding environment is also refined based on the previous pre-conceptual design developed in S&L report SL-016181 [1]. Following development of the hydrogen facility and integration designs, project costs and considerations are described to support future site-specific investigations.

3. ASSUMPTIONS AND INPUTS

3.1. Pre-Conceptual Hydrogen Facility Design and Integration Philosophy

Electrolysis is one of the main technologies of focus for low-carbon hydrogen (H_2) production. Electrolyzer-based hydrogen production facilities can produce a significant volume of clean hydrogen if supplied with a low-emission electric generating source such as a nuclear power plant.

While solid oxide electrolysis cell (SOEC) technology, which is a category of high-temperature electrolysis (HTE), is less mature than some of the competing low-temperature electrolysis (LTE) alternatives such as Alkaline Water Electrolysis (AWE) and Polymer Electrolyte Membrane (PEM), SOECs are able to achieve approximately 30% higher efficiencies when coupled with nuclear power plants due to the nearby presence of a thermal energy source, in addition to the generated electric power.

This generic pre-conceptual hydrogen production facility (H_2 facility) design is specifically developed for HTE to assess the estimated cost, feasibility, and design associated with the large-scale development of the technology at an existing generic pressurized water reactor (PWR) nuclear power plant site.

The H_2 facility is comprised of a variety of process and balance of plant (BOP) systems. Below is a list of the main systems, which are detailed in this study:

- Hydrogen Production Process
    - Electrolysis
    - Compression (low-pressure [LP] and high-pressure [HP])
    - Drying and Purification
    - Heat Recovery
    - Process Steam
- Balance of Plant
    - Water Treatment
    - Cooling Systems
    - Service Water / Fire Protection
    - Electrical Distribution
    - Compressed Gases (instrument air and nitrogen)
    - Plumbing

There are a number of design integration methods for the interface of a HTE H_2 facility with a nuclear plant. The three primary nuclear plant interfaces are: (1) process water, (2) process steam, and (3) electricity.

Figure 3-1 displays the integration strategy that is used as the basis for this design. Nuclear-generated electricity is sent to the H_2 facility to support electrical demands. Separately, demineralized water is boiled before being routed to the H_2 facility for electrolysis.

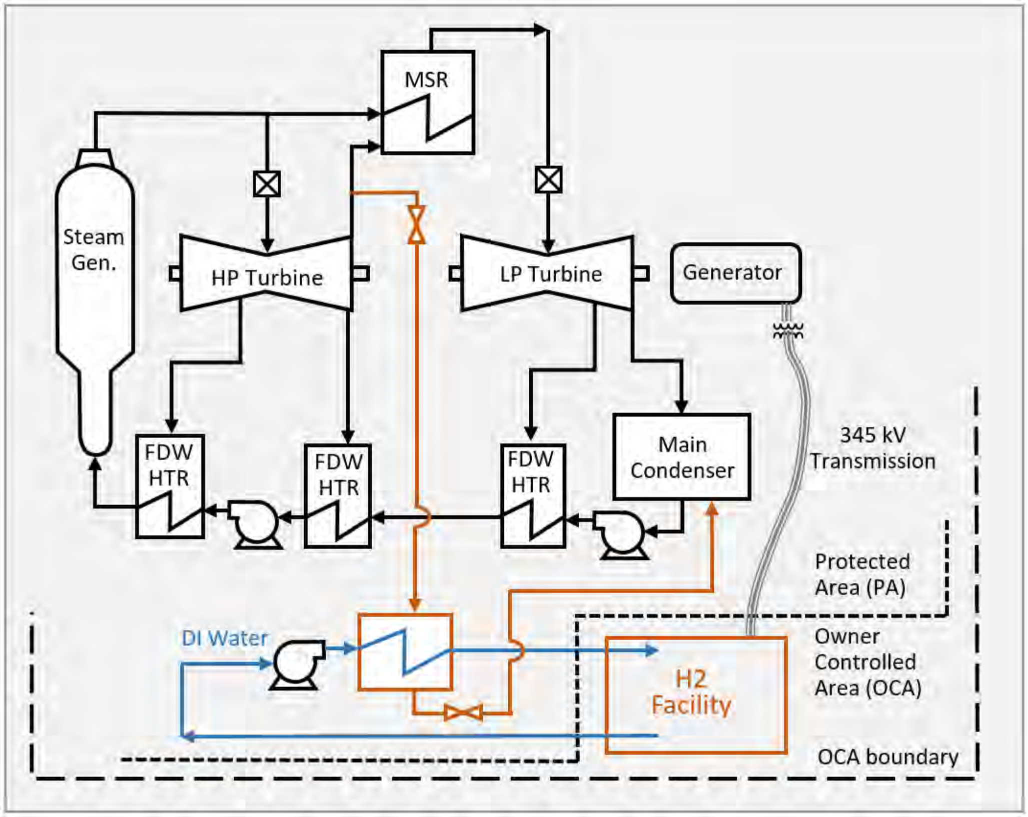


Figure 3-1. Nuclear-Hydrogen Integration Strategy

Demineralized water generated at the hydrogen production facility is sent into the nuclear plant protected area to be heated by a small portion (~3%) of nuclear plant steam extracted from the High-Pressure (HP) Turbine exhaust (i.e., Cold Reheat) and diverted to a reboiler. This extraction steam boils the demineralized water in the reboiler, after which the heated steam is supplied back out of the protected area to the H_2 facility as saturated process steam for electrolysis, while the nuclear plant extraction steam condenses to subcooled water before returning to the nuclear plant main condenser. On the electrical side, ac power is diverted from the high-voltage side of the generator step-up [GSU] transformer to the H_2 facility to support electrolysis (through dc power rectification) and auxiliary plant loads.

This design is expected to be both highly efficient, and one of the more feasible options for existing nuclear power plants. Nevertheless, other nuclear plant connection locations for thermal and electrical energy may be preferable depending on the specific site selected [1].

3.2. Reference Nuclear Power Plant Parameters

Continuing off of previous work documented in S&L report SL-016181 [1], an approximately 1,200 megawatt electric (MW_e) Westinghouse 4-loop PWR is selected as the reference reactor design. In a PWR, high-pressure water passes through the reactor core, where it is heated by thermal energy created by nuclear fission. This "primary" water flows to a steam generator, where it boils feedwater in the "secondary" plant cycle to create steam. This steam then drives a series of turbines that 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 approximately one-third of the United States nuclear fleet employing this type of design, it is an appropriate choice for use as the representative reference plant for this pre-conceptual design. Additionally, a PWR design is preferable over a boiling water reactor (BWR) since the concerns of radioactive steam leakage are comparatively small.

It is assumed for this report that the transmission system interconnection voltage for the reference plant is 345 kV. This is standard for nuclear power plants in the United States.

3.3. Hydrogen Production Facility Interfaces

The various H_2 facility interfaces with the nuclear plant and environment are shown in Figure 3-2. Although process water, process steam, and electricity are primary focuses for this study, additional considerations for controls and BOP systems are also provided.

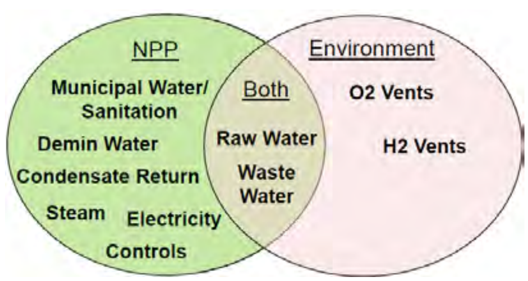


Figure 3-2. H_2 Facility System Interfaces

3.3.1 Thermal Power

For the reference nuclear power plant design, Cold Reheat piping downstream of the high-pressure turbine is the optimal location for steam extraction since it provides good efficiency and minimal adverse impact on existing plant equipment [1]. This extraction location is depicted in Figure 3-1.

Steam extracted from the nuclear power plant's secondary loop is diverted to a steam reboiler (adjacent to the Turbine Building), where it transfers its thermal energy to boil demineralized water. The condensate, after passing through a reboiler and drain cooler, is returned to either the nuclear plant main condenser or heater drain tank. On the other side of the reboiler, demineralized feedwater is vaporized for electrolysis.

Extraction steam and process steam conditions (mass flow rate, temperature, and pressure) were previously calculated in Reference 1 by running a PEPSE heat balance model analysis, assuming no heat recovery for the hydrogen production process. This study refines the PEPSE model based on electrolyzer vendor feed steam requirements and an enhanced hydrogen production process design incorporating heat recovery.

3.3.2 Electrical Power

Similar to the Reference 1 design, electrical energy is diverted from the output of the main generator (downstream of the GSU transformer) to a high-voltage switchyard near the H_2 facility at 345 kV. In the switchyard, high-voltage (H.V.) is dropped to medium-voltage (34.5 kV), before being distributed to users in the facility with step-down transformers (to 13.8 kV, 4.16 kV, and 480 V) as required. A majority of the load is rectified to dc power for electrolysis.

The medium- and low-voltage loads inside the H_2 facility are assessed herein to determine total H_2 facility electrical load in support of equipment sizing and plant impact evaluation.

3.3.3 Water Systems

The water systems interfacing with the nuclear plant include (1) raw water, (2) wastewater, and (3) plumbing. The raw water and wastewater systems may also integrate with the environment, while plumbing systems could tie into city/municipal streams, depending on the selected site. The integration assumptions for the water systems in this design are described below.

3.3.3.1 Raw Water

Raw water provides an input to both the electrolysis process as well as H_2 facility BOP needs for water-based cooling and service water/fire protection. Water consumption depends upon a number of factors including required treated water production, condensate recovery, wet or dry cooling systems, use in service water/fire protection systems, and source composition. Demineralized water production requirements are calculated based on industry experience and vendor specifications. Hydrogen production facility BOP raw water demand is based on the design described in Section 5.1.2. A wet-cooling system design is selected in this study as it is expected to be cheaper than dry-cooling; however, dry cooling may be preferable for sites with limiting water permit requirements.

Evaluating the operational Westinghouse 4-loop PWR designs in the United States, the most common cooling water source is a local lake [5]. In lieu of specific raw water data, this design develops a generic makeup water treatment system comprised of solids removal, degasification, and purification equipment that is expected for a fresh surface water source to meet the H_2 facility needs. Site-specific raw water quality would be necessary for the next phase of design.

In the interest of minimizing capital expense, integration of the H_2 facility raw water system with the nuclear plant raw water intake, preferably downstream of the traveling screens or other debris collection equipment, is expected to be the most economic option for the site layout developed in this report (refer to Attachment L for site layout). For this study, raw water is tapped off the nuclear plant circulating water system, downstream of the main circulating water pumps. The H_2 facility raw water demand is expected to have minimal adverse impact on the circulating water system.

3.3.3.2 Wastewater

In an SOEC H_2 facility with a wet-cooling design, the primary wastewater streams are water treatment reject and cooling tower blowdown. As these waste streams are of similar quality to the analogous reject streams within a nuclear plant, the integration of the H_2 facility wastewater stream with the nuclear plant wastewater treatment and/or discharge systems is expected to be acceptable with site National Pollutant Discharge Elimination System (NPDES) permitting requirements. Nevertheless, contaminant concentration and flows would require site-specific evaluation to confirm acceptability.

3.3.3.3 Plumbing

The hydrogen production facility is expected to have approximately five (5) full-time personnel, including operators and technicians. Standard plumbing amenities including bathrooms, sinks, water fountains, and emergency shower/eyewash stations will be provided, as applicable.

To reduce operational burden and cost, most industrial facilities do not handle their own potable water and sanitary sewage systems. As a result, the hydrogen facility plumbing systems are integrated with the nuclear plant potable water and sanitary sewage systems in this design. Potable water will be pumped from the nuclear plant's potable water system to the H_2 facility. A sewage tank will be supplied along with a lift station for return back to the nuclear plant. The nuclear plant systems are expected to have sufficient margin to support this increased demand.

3.3.4 Controls

It will be important for nuclear plant Main Control Room (MCR) operators to have indication of hydrogen production facility supply parameters and system conditions to evaluate impacts to nuclear plant operations 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 H_2 facility. To facilitate this operation, a dedicated set of operator controls with remote Human Machine Interface (HMI) will be provided in the nuclear plant Main Control Room to allow for control, indication, and alarm of the electrical feeder line and steam supply. Additional indication and controls will be provided local to the nuclear plant equipment added as part of the modification.

The overall monitoring and control of the H_2 facility will be performed by a Supervisory Control and Data Acquisition (SCADA) system with an HMI in the new facility control center and local I/O racks distributed by location, as required. All equipment will be monitored by this control system.

The control and operation of the high-voltage, medium-voltage, and low-voltage power equipment will be provided from Power Distribution Centers (PDCs) in the H.V. switchyard and H_2 facility. Metering of electrical power usage by the electrolyzer system and auxiliary loads will be required. The metering and electric power usage for the electric power system and auxiliary loads will be provided from the switchgears.

The primary controlling interface for the electrolyzer system solution will be an electrolyzer vendor provided Programmable Logic Controller (PLC) which will interface with the SOECs, providing control and data acquisition capabilities. Multiple PLCs may be preferred depending on site layout and operational needs. Wi-Fi dual ethernet communications will provide the primary monitoring and communication for rectifier skids. Operating points from the electrolyzers and rectifiers will be uploaded to the cloud to support facility operator access.

The water treatment system, air compressors, hydrogen compressors, hydrogen purification/drying systems and any other original equipment manufacturer (OEM) supplied equipment will be controlled by OEM supplied PLC's and tied to the H_2 facility main control center.

The H_2 facility will be equipped with all necessary emergency shutdown and purging instrumentation to facilitate complete system controls and safe operations. Instrumentation will also be provided for the monitoring of the hydrogen systems outside of the vendor provided systems. This will include pressure monitoring, temperature monitoring, flow monitoring, and level monitoring. The H_2 facility will also have its own security system (separate from the nuclear plant security system) that will contain standard items such as cameras and gates.

3.3.5 Venting

Oxygen separation during the electrolysis process will require either its utilization or venting. High-purity oxygen is currently inexpensive and abundant. In this design, it is assumed that the oxygen product stream is diluted to a concentration safe for ventilation to atmosphere, as opposed to purified for utilization. Nevertheless, there may be regional high-value product stream applications where the capture and utilization of oxygen is desirable.

Hydrogen venting provisions will also be required to support production startup and shutdown, and in the case of any upset conditions such as relief scenarios. Standards for venting hydrogen must be in accordance with CGA G-5.5, "Standard for Hydrogen Vent Systems", and API 521, "Pressure-relieving and Depressuring Systems", as critical distances and specific data points must be considered to ensure the safety of the process. More detailed studies can be done in detailed engineering and design to ensure that all hydrogen vents are being routed to safe location and do not present safety concerns.

3.3.6 Siting Parameters

3.3.6.1 Separation Distance

Previous S&L report SL-016181 [1] assumed a ½ kilometer (km) minimum separation between nuclear plant safety-related components (and switchyard) and H_2 facility electrolyzers. This separation distance was shown to be viable based on a generic probabilistic risk assessment (PRA) [3].

This study assumes a separation of ½ km between the nuclear plant protected area and the H_2 facility boundary. This fence-to-fence separation is slightly greater than what was previously assessed in SL-016181 [1], therefore the conclusions remain applicable.

Implementing additional preventative (e.g., hydrogen detection, ventilation, and removal systems) and mitigative (e.g., barriers) measures within the H_2 facility, and performing site-specific hazard assessments (e.g., hydrogen explosion overpressures, flammable vapor clouds, heat fluxes from jet fires or fireballs, etc.) may support reduced separation distances. This may be of particular benefit in cases of onsite bulk H_2 storage. Nevertheless, onsite bulk H_2 storage is not considered in this design, and barriers are not included in the design of the hydrogen production facility design. Regulatory Guide 1.91 [4] provides guidance to support co-location of a hydrogen production facility at a nuclear power plant site and should be consulted in performing site assessment.

3.3.6.2 Site Conditions

In order to develop a pre-conceptual design suitable to a wide variety of potential locations within the United States, the following site conditions, shown in Table 3-1 are assumed. These conditions are expected to apply to a large portion of the northern United States.

Table 3-1. Site Conditions

Parameter	Unit	Value
Ambient Temperature	°F	-20 to 110
Site Elevation (1)	ft	<1,000 AMSL
Separation Distance (2)	ft (m)	1,640 (500)

1 Nuclear plant and hydrogen facility are assumed to be at the same grade level.
2 Fence-to-fence distance from nuclear plant protected area to hydrogen production facility boundary.

3.4. Hydrogen Facility Parameters

There are a number of companies developing SOEC electrolyzer designs for large-scale hydrogen production. The design developed in this study is compatible with a standard 1.2 MW_{dc} SOEC electrolyzer “stamp” offering from Bloom Energy [2].

Design parameters for a single stamp are provided in Table 3-2 below. These electrolyzer stamps are intended for outdoor use. Each stamp contains electrolysis stacks, topping heaters, power distribution, component housings, and supporting equipment such as a short-term uninterruptible power supply (UPS) and heat trace.

Table 3-2. Hydrogen Electrolyzer Design Parameters

Parameter	Unit	Value
System Efficiency (1)	kWh/lb [kWh/kg]	17 [37.5]
Electrical Voltage	V_{dc}	800
Electrical Current	A	1500
Feed Steam Mass Flow	lbm/hr [kg/hr]	741 [336]
Feed Steam Temperature	°F [°C]	302 to 392 [150 to 200]
Feed Steam Pressure	psi(g) [bar(g)]	65-80 [4.5-5.5]
H_2 Output Purity	mol% H_2	85%
H_2 Output Mass Flow	lbm/hr [kg/hr]	70.5 [32]
H_2 Outlet Temperature	°F [°C]	212 to 356 [100 to 180]
H_2 Outlet Pressure	psi(g) [bar(g)]	0.36 [0.025]
Ambient Temperature	°F [°C]	-4 to 113 [-20 to 45]

[1] Only includes Bloom Electrolyzer™ system loads and losses.

Hydrogen is produced via 52 SOEC blocks for a total of approximately 500 MW_{dc} hydrogen production (at beginning of life). Each 9.6 MW_{dc} block is comprised of 8 SOEC stamps, for a total of 416 electrolyzer stamps.

A constant production operating profile is selected for the H_2 facility, which would result in approximately 320 metric tonnes (MT) of H_2 produced per day. Although electrolyzer performance degrades over time, constant production can be achieved by increasing electrical power over the life of the stack. Based on vendor degradation models (refer to Section 5.3.2), one 10.5-MW rectifier can support the end of life power requirements of one block, as described in Section 5.1.4.1. At an assumed end-of-life electrolyzer load of 1.3 MW_{dc} per stamp, maximum H_2 facility electrolyzer load is 540.8 MW_{dc}.

The total H_2 facility electrical load is 640 MVA. Direct-current electrolyzer loads comprise 80% to 85% of the total facility load, while facility alternating-current (ac) auxiliary loads (e.g., compression and electrolyzer auxiliaries), losses, and margin make up the remainder.

The total H_2 facility thermal load on the nuclear plant is 107 MW_t, based on heat balance model evaluation which is described in Section 4.1.2 and Attachment A.

After production, the gaseous H_2 will be piped offsite to an undefined end user(s); users could include storage facilities, filling stations, and industrial plants, among other applications. A typical pipeline pressure and purity of 1,500 psig and 99.999% is assumed for this design, although different conditions may be required depending on the application.

Table 3-3 below details the hydrogen production facility design parameters.

Table 3-3. Hydrogen Production Facility Design Parameters

Parameter	Unit	Value
Hydrogen Production Capacity (1)	MT/day	320
Operating Profile	------	Constant Production
H_2 Facility Stamp Count	------	416
H_2 Facility Block Count	------	52
Electrolyzer Nameplate Power (Beginning of Life) (2)	MW_{dc}	499.2
Electrolyzer Nameplate Power (End of Life) (2)	MW_{dc}	540.8
Facility Auxiliary Loads (3)	MVA	82
Total Electrical Power	MVA	640
Total Thermal Power	MW_t	107
H_2 Offtake Method	------	Pipeline
H_2 Offtake Pressure	psi(g)	1500
H_2 Offtake Purity	% H_2	99.999

1 Production Capacity based on 32 kg of H_2/hr from a standard 1.2 MW_{dc} Bloom Electrolyzer [2].
2 Electrolyzer nameplate based on 1.2 MW_{dc} (beginning of life) and 1.3 MW_{dc} (end of life, assumed) stamp loads.
3 A power factor of 0.9 is assumed for facility auxiliary loads. Electrolyzer auxiliary loads are included in this value.

4. NUCLEAR POWER PLANT DESIGN

4.1. Design

The nuclear power plant integration design in this report is based on the pre-conceptual design developed under SL-016181 [1]. The design of that report has been refined by:

- Using hydrogen equipment vendor data
- Tabulating hydrogen facility electrical loads
- Developing balance of plant (BOP) systems within the H_2 facility
- Incorporating hydrogen process heat and condensate recovery into design

This section revisits the nuclear plant integration and describes an updated pre-conceptual design for the thermal, electrical, and ancillary interfaces between the nuclear power plant and H_2 facility.

The design of the H_2 facility and high-voltage switchyard is described in Section 5.

4.1.1 Description of Modification

The utilization of nuclear plant steam for preheating of the electrolysis process water is one of the primary benefits of co-locating an HTE hydrogen production facility at an existing nuclear plant. Steam extraction is taken at the crossunder (Cold Reheat) piping in the MS system using two (2) extraction lines, one on each side of the HP turbine to avoid turbine imbalances. Manual isolation is provided on both carbon steel extraction lines before they combine into a common header inside the Turbine Building (TB). After routing out of the TB, the header branches back into two (2) lines to supply steam to two (2) independent reboiler trains (tube side), used to boil hydrogen process water for high-temperature steam electrolysis. Each line is equipped with a station instrument air controlled flow control valve (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 piping and instrumentation diagram (P&ID) provided in Attachment B shows the arrangement of steam extraction for this design. The two independent loops help to improve gradual startup of the system and enable partial hydrogen production during maintenance.

Hydrogen steam supply (HSS) equipment will be located in the protected area, adjacent to the TB, and is comprised of the following components: steam reboilers (2), drain coolers (2), reboiler feed pumps (2), and a pressurized demineralized water expansion tank (1). Along with these components are reboiler feed level control valves, controlled using station instrument air routed from header in the TB, process steam (to electrolyzers) pressure control valves, as well as relief, check, and isolation valves as applicable. A physical layout of this equipment is provided in Attachment D. Control of the mechanical and electrical equipment is provided through an H_2 interface control panel, located in the Main Control Room. A relay panel houses the protective relay components for the HSS equipment, in the nuclear plant Relay Room. Section 4.1.4 provides details pertaining to control capabilities and Main Control Room interfacing.

After passing through the reboilers, nuclear plant steam condenses and further cools in a drain cooler before returning to the main condenser or heater drain tank. Condenser return is deemed preferable for this design, but both options are considered in Attachment A and Attachment C. Stainless steel piping is used for the condensate return lines. Prior to reaching the condenser, flow is controlled through air-operated level control valves, which have tie-ins to the station instrument air system and control signal cables routed from their respective reboiler drain coolers.

The H_2 facility has its own water treatment system used for generating demineralized water used for electrolysis. After pre-heating (using heat recovery from the electrolyzer hydrogen product stream) in the H_2 facility, the demineralized water is piped to the HSS equipment in the protected area for boiling. Stainless steel piping is direct-buried at a suitable depth and routed between the hydrogen and nuclear plants. The demineralized water is first sent to a pressurized expansion tank, before splitting into two (2) trains. In each train, a feed pump drives flow through the drain cooler, to the shell side of the reboiler. The drain coolers help to preheat the reboiler feed water and cool the reboiler drain water, improving cycle efficiency. Demineralized water flow rate into the drain cooler is controlled using a level control valve, actuated using plant instrument air. The control signal is provided from a water level transmitter on the shell side of the reboiler.

Carbon steel process steam piping is routed from each reboiler through a self-contained backpressure regulating valve before combining back into a header and passing through the protected area boundary to the H_2 facility. Drains and steam traps are provided to remove condensate from the line. Insulation and heat tracing are added to piping and outdoor equipment where applicable based on expected environmental conditions.

Reboiler chemistry is maintained using blowdown connections routed to a station drain. The ability to sample reboiler blowdown enables plant personnel to ensure radioactivity has not inadvertently contaminated the flow of steam to the H_2 facility.

Raw water is extracted downstream of the nuclear plant circulating water pumps for H_2 facility use in the water treatment and cooling water systems. Wastewater from the H_2 facility is returned to the nuclear plant and combined with existing waste streams in the discharge structure. Potable water and sanitary waste systems are also integrated with the nuclear plant systems. All of these systems are connected via direct-buried HDPE lines, and equipped with booster pumps, isolation, and flow control, as applicable.

The 345 kV transmission line (H_2 feeder) for the H_2 facility is tapped into the line between the nuclear plant's GSU transformer's high-voltage bushing and the switchyard. The transmission line has two manually operated disconnect (MOD) switches and one 345 kV circuit breaker at the beginning of the line. The H_2 feeder is ~0.5 km long with the revenue meter at the beginning of the line. The end of the line inside the H.V. switchyard for the H_2 facility will be terminated at a 345 kV motor operated disconnect switch on the 345 kV bus. Two step-down power transformers, step the power down from 345 kV to 34.5 kV, the primary winding will be connected to the 345 kV bus by 345 kV dead tank circuit breaker and MOD switch. The secondary winding of each transformer will be connected to an outdoor 34.5 kV bus. There is a total of thirteen 34.5 kV breakers, eight of these breakers will feed step-down transformers 34.5 kV/13.8 kV, one will feed service transformer and four spares.

The transmission line to the H_2 facility 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 plant existing GSU transformer differential relays will cover the new high-voltage breaker at the H_2 feeder within their zone of protection. Interface with the existing plant tripping scheme (using the existing GSU transformer differential relays) is required in order to be able to trip the high-voltage breaker to the H_2 facility.

A conceptual site plan showing the interfaces between the H_2 facility, nuclear plant, and environment is provided in Attachment L.

4.1.2 Mechanical Design

4.1.2.1 Selection of Nuclear Plant Steam Dispatch Location

The heat balance diagrams in Attachment A illustrate the expected plant operating conditions considering (1) no thermal extraction, (2) 107MW$_t$ extraction with condensate return to condenser, and (3) 107MW$_t$ extraction with condensate return to heater drain tank. The modeling accounts for thermal and hydraulic losses in the system, as described in Attachment A and Attachment C, respectively. The final process steam supply conditions the H_2 facility boundary are 350,000 lbm/hr and 83 psig at saturated conditions, in accordance with the requirements from the ASPEN hydrogen process modeling described in Section 5.1.1.2.

The preferred location of extraction is Cold Reheat downstream of the HP turbine exhaust and upstream of the moisture separator reheaters (MSRs). This steam extraction location provides sufficient thermal energy to heat up reboiler feed water to the targeted steam conditions, while minimizing adverse impacts on plant efficiency.

4.1.2.2 Selection of Nuclear Plant Drain Return Location

The preferred location selected to return the condensed drain flow is the main condenser. This location allows sufficient energy removal from the cycle steam, while minimizing nuclear power plant impacts. Return to the heater drain tank is also a viable option; both locations are considered in the modeling performed in Attachment A and Attachment C.

4.1.2.3 Thermal Analysis

A PEPSE heat balance model of the reference nuclear plant was used to determine the impact on the plant under normal H_2 facility operation. Based on the electrolyzer requirements at the H_2 facility, 107-MW$_t$ extraction is required. Attachment A provides heat balance diagrams illustrating process parameters at various location in the thermal extraction system.

Table 4-1 details key thermal extraction system parameters.

Table 4-1. Summary of Important System Parameters for 107-MW_t Extraction

Parameter	Unit	Extraction Level		Total Δ for 2 Trains
		0 MW_t	107 MW_t	
Reactor Thermal Power	MW_t	3659	3659	-
Generator Output	MW_e	1239.6	1214.8	-24.8 MW_e
Final Feedwater Temperature	°F	447.6	447.6	0.0°F
Main Steam Flow	Mlb/hr	16.28	16.28	0.00%
Cold Reheat Flow	Mlb/hr	12.73	12.70	-0.24%
Thermal Extraction Flow	lb/hr	0	395,000	-
Extracted Steam Fraction of Cold Reheat Flow	%	0	3.11	3.11%
Remaining Steam to MSRs	Mlb/hr	12.73	12.31	-3.30%
Hot Reheat Flow	Mlb/hr	11.26	10.86	-3.55%
Heater Drain Forward Temperature	°F	339.7	336.7	-3.0°F
HP FWH Cascading Drain Flow	Mlb/hr	1.39	1.38	-1.01%
LP FWH Cascading Drain Flow	Mlb/hr	2.42	2.37	-1.90%
Heater Drain Tank Pressure	psia	185.5	178.9	-6.6 psi

[1] Cascading drain conditions are averaged. Individual feedwater heater drain lines may have higher variations in conditions.
[2] Changes from 0 MW_t to 107 MW_t are calculated based on PEPSE model outputs. There may be slight differences in the tables due to truncation of values.
[3] Values for 107 MW_t thermal power extraction are based on the condensate return to condenser case. Values for the return to heater drain tank case may differ slightly.

4.1.2.4 High Energy Line Break (HELB)

Existing nuclear power plants are required to be protected from plant hazards such as HELB. Each plant's licensing basis defines HELB criteria, which state the conditions required to define a high-energy system based on operating temperature and/or pressure limits. If a plant is licensed to a temperature *and* pressure, both the minimum temperature and the minimum pressure criteria must be met for the system to be defined as a high-energy system. Conversely, if a plant is licensed to a temperature *or* pressure, only one of the criteria needs to be met for the system to be defined as a high-energy system. The temperature and pressure limits are defined as 200°F and 275 psig. Based on the PEPSE heat balance in Attachment A, maximum operating conditions are expected to be approximately 375°F and 169 psig. Therefore, if a plant is licensed for HELB considering the temperature *and* pressure, the location of the extraction piping that feeds the H_2 steam reboiler would not meet the criteria and would be exempt from consideration from the HELB program. Conversely, if a plant is licensed to a temperature *or* pressure, the piping would meet the criteria for consideration into the HELB program and the following discussion would apply.

Some plants analyze HELBs in the TB for impact on essential equipment. Any piping additions should be routed in such a way as to be separated from any equipment that may be important to safety or station operation. Any piping additions inside the TB due to the pipe routing to the H_2 reboiler will be significantly smaller than the main steam lines inside the TB; therefore, the impact of a HELB in the new piping is expected to be bounded by mass and energy release rates for existing piping. New piping routed outside the TB should also be assessed for HELB impact.

Station HELB programs are not expected to be impacted by this modification. However, station specific review will be required.

4.1.2.5 Evaluation of Plant Transients

Introduction of a hydrogen production facility to the existing nuclear power plant could cause operational transients, which will need to be addressed. Specifically, the startup or shutdown of the H_2 production facility needs to be evaluated to ensure there are no adverse effects on the operation of the existing nuclear power plant. Plant response to various faulted conditions is described in Section 4.1.4.3. Electrical transients are described in Section 4.1.3.8.

Table 4-1 above provides a summary of key parameters for 107-MW_t thermal extraction. Additional details are included in Attachment A.

As seen in Table 4-1, the 107-MW_t thermal extraction from Cold Reheat requires approximately 395,000 lbm/hr (~197,500 lbm/hr per train) of steam, corresponding to approximately 3.1% of total cold reheat flow. Normal startup of the H_2 production facility 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 of the total cold reheat flow (~1.6% per train) and reduces the hot reheat flow to the LP turbines by approximately 3.6% (per train). These changes result in a 24.8-MW_e reduction in main generator output, which represents approximately 2.0% 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 much greater than the level of steam extraction described.

Similarly, for normal shutdown (shutting one reboiler train at a time) of the H_2 facility, 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 H_2 facility, a transient involving shutting down of two reboiler trains at the same time could be expected.

4.1.2.5.1 Water Hammer/Steam Hammer Considerations

During the detailed design of the thermal steam extraction system, the potential for water hammer or steam hammer must be addressed. These phenomena could occur if steam or water flow rapidly stops; this condition is typically addressed by selecting appropriate valve closing times.

4.1.2.5.2 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. Reactivity impacts are expected to be negligible since final feedwater flow and temperature to the steam generators remain virtually unchanged under this ~3% steam flow extraction scenario. Sudden perturbations resulting from events at the H_2 facility should not exceed the capabilities of the normal nuclear power plant controls system response.

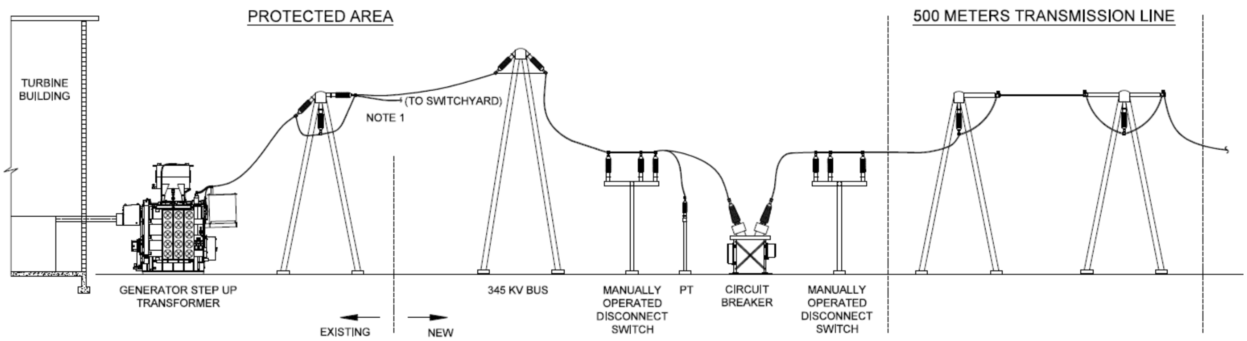
From a mechanical design perspective, the largest impact to the nuclear plant will be a loss of steam demand from the H_2 facility, which would result in a similar plant controls systems response to that which occurs when loss of generator load occurs. In the case of an approximately 3% load rejection, the nuclear plant 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. Isolation and control values are provided on the process lines to and from the nuclear plant and H_2 facility, which will allow isolation of the HSS system while keeping the nuclear plant operational. Operators will follow their indications to take actions appropriately using alarm response or other plant operating procedures.

4.1.3 Electrical Design

The H_2 facility requires 540.8 MW_{dc} power (end of life) for the electrolysis process and approximately 82 MVA for auxiliary loads (including power factor correction). Incorporating losses, the total electrical power required is approximately 640 MVA. The H_2 facility high-voltage switchyard is ~0.5 km from the nuclear plant protected area, therefore power will be supplied to the high-voltage switchyard from the nuclear plant via a 345 kV transmission line.

4.1.3.1 Selection of Nuclear Power Plant Electrical Dispatch Location

The electrical physical layout diagram in Figure 4-1 illustrates the preferred electrical system tie-in point, which is the high-voltage side of the nuclear plant main GSU transformer. The electrical feed to the H_2 facility consists of a high-voltage circuit breaker, two manually operated disconnect switches, and an ~0.5 km high-voltage transmission line. For a total apparent power rating of approximately 640 MVA transmitted to the H_2 facility, the current rating of the high-voltage equipment must be in the range of approximately 763 A to 1600 A, considering a nominal transmission system voltage in the range of 230 kV to 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.



Reference: SL-016181 [1].

Figure 4-1. Electrical Feeder Physical Layout within Nuclear Scope

4.1.3.2 Electrical Design and Equipment within Nuclear Power Plant Boundary

The 345 kV transmission line will be tapped to the line between the nuclear plant GSU transformer's high-voltage bushing and the switchyard. The H_2 transmission line routes over a transmission tower to a 345 kV circuit breaker and its two manually operated disconnect switches for line protection/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 nuclear protected area or nuclear plant switchyard, depending on spatial availability in the protected area. To span the ~0.5 km plant separation distance, the H_2 transmission line will be routed over six (6) transmission towers. At the high-voltage switchyard, there are two (2) two winding step-down transformers rated for 345 kV-delta/34.5 kV-wye, 205/250/340MVA ONAN/ONAF/ONAF, 10% nominal impedance H-X. The 34.5 kV windings are resistance-grounded. Within the H_2 facility are eight (8) two-winding step-down transformers rated for 34.5 kV-delta/13.8 kV-wye, (2) 66/83/110 MVA, (4) 55/68/90 MVA and (2) 28/34/45 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 H_2 electrolyzers. H_2 facility equipment is described in Section 5.1.3 and 5.1.4.

Revenue meters are installed in different locations depending on the nuclear plant. Some plants locate revenue meters inside the TB, while others locate them outside after the GSU transformer or in the switchyard. Therefore, the nuclear plants 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 H_2 feeder, along with issues that can affect the location of the connecting point in relation to the meters (such as GSU transformer power losses) to ensure the H_2 facility is connected behind-the-meter.

4.1.3.3 Transmission Line Control and Protection

The control and indication of the H_2 power line can be performed locally at the equipment or from the Main Control Room. The high-voltage circuit breaker and two manually operated 345-kV disconnect switches will have indications only in the Main Control Room. Protective relays associated with the new high-voltage circuit breaker will be installed in the nuclear power plant Relay Room.

It is assumed that the revenue meters for the new H_2 transmission line will be located outdoors close to the associated 345-kV breaker(s).

4.1.3.4 Power Requirements for Hydrogen Steam Supply Equipment

Hydrogen steam supply 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.

4.1.3.5 Switchyard Arrangement and Offsite Power

The existing switchyard breaker alignment is not impacted by the addition of the new high-voltage line to the H_2 facility, as the new line is protected by a new high-voltage circuit breaker downstream of the tap point. The new H_2 feeder has no effect on the switchyard voltage, breaker alignment, generator AVR loading, or the status of offsite power voltage regulating devices.

The H_2 facility is physically and electrically separated from the offsite power circuits. Therefore, there is no impact to offsite power sources or plant safety loads.

4.1.3.6 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 H_2 facility electrical tie-in. The model was developed based on typical electrical parameters for the nuclear power plant main power circuit, actual electrolyzer loads, and required H_2 facility auxiliary loads. The ETAP model consists of the following components:

- Thevenin equivalent source representation of the high-voltage transmission system
- Nuclear power plant synchronous generator
- Nuclear power plant main GSU transformer
- 0.5-km high-voltage transmission line to the H_2 facility high-voltage switchyard
- High-voltage switchyard and H_2 facility step-down transformers
- Medium-voltage switchgear buses for the H_2 facility
- Electrical auxiliary loads at the H_2 facility

The step-down transformers supplying the H_2 facility are specified as a two-winding unit to supply 640 MVA to the H_2 facility.

A short-circuit analysis was performed in ETAP to determine estimated equipment short-circuit ratings and aid in sizing the high-voltage switchyard step-down transformers. The two (2) main power transformers were modeled as 205/256/340MVA 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 10% nominal impedance between the H-X windings (with ±7.5% tolerance) on the 205 MVA self-cooled base of the secondary windings allows for the use of 56 kA, 34.5 kV circuit breaker and 46-kA, 13.8 kV medium-voltage switchgear at the H_2 facility.

The ETAP model shows that the addition of the H_2 facility has a negligible impact on the existing nuclear plant equipment. The H_2 facility loads are primarily rectifiers supplying dc power to the electrolyzers (approximately 85% 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 H_2 facility 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 nuclear power plant main generator. The ETAP model shows the H_2 facility contributes less than 1.3 kA of short-circuit current at 345 kV, compared to approximately 40 kA from the transmission system and approximately 7 kA from the nuclear plant.

The ETAP model was also used to perform a load flow and voltage drop analysis to evaluate sizing of the electrical equipment. The load flow analysis shows the 340 MVA top rating of the main power transformers is sufficient to carry the full load of the H_2 facility. The voltage drop across the 0.5 km high-voltage transmission line is not significant. For the 500 MW_{dc} H_2 facility, a two conductor bundle, such as a 2-1113 kcmil Bluejay ACSR or higher depending 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 main power transformers do not require an on-load tap changer if the transmission voltage is maintained within approximately a ±2.5% bandwidth. This would be applicable to nuclear power plants that operate per a voltage schedule and nuclear plants that require strict voltage regulation, for offsite power per NUC-001 (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 ±5%, ±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 main power transformers will provide additional flexibility for locations where the transmission system operating voltage may vary over a wider range and for locations where the H_2 facility may operate while the nuclear plant is in a refueling outage.

For the H_2 facility, capacitor banks are employed on the medium-voltage (13.8kV) switchgear powering the auxiliary loads to provide power factor correction. The medium-voltage switchgears powering the SOEC rectifier skids do not require capacitor banks since the rectifier skids already have built-in power factor correction. In the ETAP model, a 12 MVAR capacitor bank is applied on both of the 13.8 kV switchgear power auxiliary loads. The application of these capacitor banks ensures the power factor at the 345 kV line tap is approximately 0.9 lagging.

4.1.3.7 Protective Relaying Design

The electrical tie-in of the H_2 facility has a significant impact on the nuclear power plant protective relaying scheme. The relay and protection diagram in Attachment I 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 nuclear plant 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 H_2 facility.

The high-voltage transmission line to the H_2 facility is protected by redundant microprocessor-based line-current differential (87L) relays. This scheme requires six (6) 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 nuclear plant generator remains stable should a fault occur on the transmission line. To ensure stability of the nuclear plant 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 are tripped or the generator circuit breaker (if the nuclear plant is equipped with generator circuit breaker) in the event of a failure of the new high-voltage circuit breaker.

The H_2 facility high-voltage switchyard main power transformers are 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 high-voltage Power Distribution Center (PDC) in the high-voltage switchyard.

It is important to note that with this arrangement of the protection scheme, the only additional exposure of the nuclear plant generator to 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 the additional exposure. There is no impact to the reliability of the offsite power circuits.

Table 4-2 below shows the required trip logic for different fault locations following electrical tie-in of the H_2 facility.

Table 4-2. 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 H_2 facility	New high-voltage circuit breaker New high-voltage step-down transformer circuit breaker	Existing high-voltage switchyard circuit breakers Generator circuit breaker (if equipped)
H_2 facility transformer	New high-voltage step-down transformer circuit breaker inside the H_2 facility 34.5 kV circuit breakers in the H_2 facility 13.8 kV breakers in the H_2 facility	New high-voltage circuit breaker

4.1.3.8 Electrical Transient Analysis

An electrical transient analysis was performed to evaluate the impacts of a trip of the H_2 facility load on the existing nuclear plant generator using Power Systems Computer Aided Design (PSCAD) software. 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 nuclear plant synchronous generator, including the AVR and governor control models
- The nuclear plant main GSU transformer
- The 0.5 km high-voltage transmission line to the H_2 facility high-voltage switchyard
- High-voltage switchyard and H_2 facility step-down transformers
- Lumped loads to represent the loading at the H_2 facility

The PSCAD model was used to simulate a trip of the H_2 facility 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 H_2 facility, the excess power from the nuclear plant generator is injected into the transmission system. The model shows that for a 640 MVA electrical load, the nuclear plant generator remains stable for both faulted and unfaulted trips of the H_2 facility. During an unfaulted trip of the line, the generator exhibits a slight increase in mechanical speed (<0.02%), followed by damped oscillations. The mechanical transient decays within 10 seconds. After the H_2 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 H_2 facility 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 like 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 nuclear plant to the nearby H_2 facility without impacting the stability of the nuclear plant generator during a loss of load. The additional runs show that the H_2 facility 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 H_2 facility, either with or without a fault. Note that this model is based on typical nuclear power plant and transmission system data, which may not be representative of the available capacity for all U.S. nuclear sites.

4.1.3.9 Bulk Electric System Regulatory Impacts

The high-voltage transmission line supplying the H_2 facility 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 4-3 provides a summary of the applicable NERC Reliability Standards. Note that the nuclear plant is already subjected to the following standards.

Table 4-3. 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 Protection 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.

4.1.4 Instrumentation and Controls Design

4.1.4.1 Operator Control Capabilities

The nuclear power plant supplies two principal components for the high-temperature steam electrolysis process: (1) cold reheat steam from the HP turbine exhaust, and (2) 345-kV electrical power. Just like any plant system, it will be important for the nuclear plant Control Room operators to have indications of the H_2 facility supply parameters and system conditions, to effectively evaluate the contributions to nuclear plant operation and perform the necessary actions such as start and stop of steam supply and electrical power to the H_2 facility.

A dedicated set of operator controls with remote HMI in the nuclear plant Main Control Room will be provided to allow for control, indication, and alarm of the hydrogen power line and steam supply; these controls will be electrically and functionally isolated from nuclear power plant controls. Existing plant fiber optic infrastructure will be used to communicate between the HMI and associated equipment. The operator should be trained in operating the power and steam supplies from the nuclear plant Main Control Room using the new standalone HMI. A special procedure(s) will be developed for this operation.

Additional indication and controls will be provided local to the HSS equipment.

4.1.4.2 Available Process Parameters for Monitoring

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

- Electrical power consumption on the plant computer system
- Diverted steam flow on the plant computer system
- HSS equipment trouble alarm in Main Control Room
- Hydrogen production facility trip or fire alarm in Main Control Room

4.1.4.3 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. Below is a summary of potential failure modes of the installed thermal and electrical extraction components and a brief description of the plant and/or operations response to ensure that the plant can be maintained in a safe condition.

- Extraction Steam leak going to reboiler – Response depends on the severity and location of leak. With two trains of reboilers, the leak could be isolated to the affected train allowing the second train to operate. H_2 facility steam supply would be halved. If the leak is located such that both trains must be isolated, then hydrogen production would stop. If isolation is not possible, manual trip of the nuclear plant would occur, similar to the response to an unisolable MS line leak. The addition of a remote, manually operated valve (motor- or air-operated) at the extraction point would allow for online construction of parts of the steam extraction line and would facilitate positive isolation in the event of a steam leak in the extraction line.
- Process Steam leak going to H_2 Facility – As described in Section 4.1.2.5, the line would be isolated and hydrogen production would stop. Electrical power would still be provided to the H_2 facility to support controlled electrolyzer shutdown and the required facility auxiliaries. The nuclear power plant turbine-generator would pick up the additional load. Either the turbine admission valve would throttle down or more power would be supplied to the grid, depending on demand.
- Reboiler Drain valve fails closed – This should not occur since the valve is set to fail open. However, if this event were to occur, 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 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. H_2 facility steam supply would be halved.

- Reboiler Drain valve fails open – Level in the affected reboiler would drop and potentially steam would 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. H_2 facility 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 would be equal to or greater than the steam conditions. The amount of condensation would be controlled by the H_2 facility demand. The condensate level would be controlled by the condensate drain valves. With normal operation of the reboiler feed water supply, the plant would continue to operate normally.
- Extraction Steam supply valve fails closed – With two Extraction Steam supply and reboiler trains, a closed valve will only affect one train. Level in the affected reboiler level would fall; the condensate drain line would control level by closing. The affected train could be isolated, allowing the second train to operate. H_2 facility steam supply would be halved.
- Rapid trip of H_2 facility – Steam demand would cease, the process feed water level on the hydrogen-side of the reboiler would increase, and the feed 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 extraction steam supply to the reboiler would be rerouted to the LP turbines. Either the turbine admission valve would throttle down or the generator would pick up the additional load. The electrical transient would be more significant; this response is described in Section 4.1.3.8. Electrolyzer Uninterruptible Power Supplies (UPSs) would provide the power required for safe, controlled shutdown of electrolyzers; emergency shutdown may be required for extended loss of power.
- Short in high-voltage line – Overcurrent protection, as discussed in this report, would trip the H_2 facility. The electrical transient response would be similar to the rapid trip of the H_2 facility as described above.
- Open in high-voltage line – An open in the high-voltage line would trip the H_2 facility. The electrical transient response would be similar to the rapid trip of the H_2 facility as described above.

4.1.5 Design Attribute Review

When performing an engineering change in accordance with industry Standard Design Process (SDP) Engineering procedure IP-ENG-001, the responsible engineer completes the Design Attribute Review (DAR), which is a series of questions that aids in identification of impacted disciplines, stakeholders, and programs. The previous pre-conceptual design in SL-016181 [1] developed a sample DAR. That evaluation remains applicable and is summarized in this section. Specific design attributes may be applicable on a plant or design specific basis when performing a similar modification, therefore the below criteria are provided as an example for guidance only.

4.1.5.1 Electrical

- This conceptual design covers the installation of ~0.5 km of 345 kV transmission line between the GSU transformer and H_2 facility high-voltage switchyard. A 345 kV high-voltage circuit breaker, two associated disconnect switches, and potential transformers (PTs) will be installed in the nuclear plant protected area or existing nuclear plant switchyard, depending on available space around the GSU transformer. Inside the H_2 facility high-voltage switchyard will be two (2) main power transformers, stepping down from 345 kV to 34.5 kV, each with one (1) 345-kV circuit breaker and one (1) 345-kV disconnect switch. Also, two (2) outdoor 34.5 kV buses with thirteen (13) 34.5 kV breakers each will be installed. In the H_2 facility, nine (9) 34.5-kV breakers will be connected to step down transformers. Eight (8) will step the power down from 34.5 kV to 13.8 kV to feed the respective 13.8-kV switchgear and one (1) will feed a service transformer to step the voltage down from 34.5 kV to 480 V for the auxiliary loads.
- The control/indications of the 345-kV circuit breaker and indication only for the breaker-associated disconnect switches for the H_2 transmission line are from the Main Control Room. All the required protective relays for the H_2 power line are located in the plant Relay Room. The local control and monitoring for the electrical equipment associated with the H_2 steam line, such as pump motors, are from the Main Control Room. A standalone human-machine interface (HMI) for control and indications of the H_2 power line and steam supply is available in the Main Control Room, using plant existing fiber optic infrastructure to communicate between the HMI and associated equipment.
- CTs at the H_2 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 alternating-current 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 H_2 facility 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 transmission line towers 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 fire requirements or raceway capacity.
- The load flow analysis demonstrates the change in the switchyard voltage due to the addition of the 640 MVA electrical load is negligible. As such, 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 H_2 facility, 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 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 like 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.

4.1.5.2 Instrumentation and Controls (I&C)

- The use of digital controls is an integral component of the proposed coupling of an H_2 facility with a nuclear plant. Standard Design Process (SDP) IP-ENG-001 directs that any nuclear plant 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 nuclear plant. 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 H_2 facility 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 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.

4.1.5.3 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, heat exchangers, pumps, tanks, 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.
- 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, 2-1 socket weld profiles, etc., 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 H_2 facility. Nozzle reaction loads require evaluation of 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 above ground piping and tanks.
- Piping installed by this modification includes saturated steam and saturated water and should, therefore, 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 reboilers and pressurized demineralized water tank 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 H_2 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 (introducing steam into a cold pipe, etc.). 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 H_2 facility 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 needs to be evaluated.
- New piping routed outside the TB should also be assessed for HELB impact.

4.1.5.4 Structural

- Pipe supports are required for steam and drains piping, including pipe supports to route steam piping 0.5 km to the H_2 facility.
- Foundation designs are required for HSS equipment, transformers, disconnect switches, circuit breakers, etc.

4.1.5.5 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 addition of heat exchangers, relief valves, check valves, and air-operated valves require addition to those programs.
- 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 H_2 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.
- HELB programs are not expected to be impacted by this modification, but should be reviewed on a station-specific basis.

4.1.5.6 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 being 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 installation of HSS equipment within the protected area. These items affect line-of-sight and lighting in the area.
- Security will be required as a stakeholder for the modification due to 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 26-inch steam piping from within the station protected area out to the H_2 facility constitutes a three-dimensional pathway as defined in NEI 09-05. Per 10 CFR 73.55(i)(5)(iii), this requires protection using a physical barrier, intrusion detection equipment, or security observation at a frequency sufficient to detect exploitation.

  Site Security may also take actions to accommodate the additional personnel and vehicles needed onsite if the H_2 facility happens to be located within the Owner Controlled Area.

4.1.6 Additional Considerations

The previous S&L nuclear plant integration pre-conceptual design report SL-016181 [1] detailed various design considerations, including different extraction steam locations, different heat exchanger and material selections, net metering, and decreased plant separation distances. For these details, please refer to that report.

The following subsections describe some additional key considerations for this design.

4.1.6.1 Licensing

The licensing impacts of a 500MW$_{dc}$ HTE hydrogen production facility coupled with a Westinghouse 4-loop PWR nuclear power plant were previously evaluated in SL-017513 [8] through the development of a generic 10 CFR 50.59 evaluation. In that evaluation, it was concluded that a License Amendment Request (LAR) is not expected to be required for the modification due to the limited scope of nuclear plant impacts and the anticipated acceptability of explosive hazard results at a plant separation distance of 500 m. Nevertheless, a formal 10 CFR 50.59 evaluation would need to be performed on a project and site specific basis. If a site does not have an existing hazard analysis within their licensing basis, or if equipment vendors indicate transient responses differing from the generic evaluation, a LAR may be required.

Since the design assumptions in this report are equivalent or conservative with respect to the generic 10 CFR 50.59 evaluation, the conclusions of the previous 10 CFR 50.59 evaluation are upheld for this design.

4.1.6.2 Electrical Power Dispatch Limitations

Under S&L design report SL-016181 [1], ETAP sensitivity analysis was performed to determine the maximum power that can be transmitted from the nuclear power plant to the hydrogen production facility without impacting the stability of the nuclear plant generator during a load rejection event. In that evaluation, the ETAP model was developed using typical plant and transmission system data with a sufficiently robust grid. That evaluation concluded that the H_2 facility load could be increased up to the maximum output power rating of the nuclear plant generator (i.e., the total nuclear plant rated capacity, with consideration for the steam demand for high-temperature steam electrolysis) without causing the generator to become unstable following a trip of the high-voltage heeder line to the hydrogen production facility.

Although the conclusions of this evaluation remain valid for the design developed in this report, ETAP analysis will be required on a site specific basis. The transmission system data used in the previous evaluation may not be representative of the available capacity for all U.S. nuclear plants, which could impact site-specific conclusions. Additionally, thermal power requirements for an H_2 facility of this size will increase significantly and thermal transient analysis would be required to assess plant response and the potential for a plant trip.

4.2. Major Equipment

Equipment sizing is presented in the following sections based on the thermal and electrical analyses discussed in Section 4.1.2 and Section 4.1.3, along with analysis performed in Attachment C. 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 cost optimization. Further refinements to the design can be performed based on the site-specific requirements to minimize the cost of nuclear plant auxiliary equipment and connection commodities.

4.2.1 Reboiler Sizing

Performance parameters for the steam reboiler/drain cooler set are determined using the PEPSE analysis provided in Attachment A. Sizing information for input to reboiler vendors is provided considering 107-MW_t thermal power extraction in Table 4-4 below.

Table 4-4. Reboiler/Drain Cooler Set Sizing Parameters for 107-MW_t Power Extraction

Connection Location	Mass Flow Rate (1)		Temperature		Pressure	
Steam Supply from Cold Reheat	395,000	lbm/hr	~361	°F	~154	psia
Drain to Main Condenser	395,000	lbm/hr	200	°F	by Vendor	
Demineralized Water Supply	350,000	lbm/hr	178	°F	145	psia
Steam Supply to H_2 Production Facility	350,000	lbm/hr	344	°F	125	psia

[1] Flow rate values represent the total extraction and process steam flows. This design utilizes two (2) reboiler/drain cooler trains, therefore ½ flow should be used in the sizing of a two-train system.

4.2.2 Piping and Component Sizing Summary

Integrating the H_2 facility with the existing nuclear plant requires sizing of the various pipelines, which is performed based on the 107-MW_t thermal extraction. Steam pipe sizes are determined in Attachment C Appendix i and ii, and water pipe sizes are determined in Attachment C Appendix iii and iv.

The results of pipe sizing are summarized as follows:

- **Extraction steam piping to the steam reboilers (Attachment C Appendix i)**

  Two, 16-inch pipes were connected to the cold reheat pipes on either side of the HP turbine for extraction. Each of these lines was STD schedule carbon steel, 40 feet long. These lines joined to a 22-inch, STD schedule carbon steel header that was 200 feet long. After routing out of the Turbine Building, the header once again split into two, 16-inch, STD schedule carbon steel lines that spanned 20 feet each until reaching their respective steam reboilers. Maximum steam velocity was ~130 feet per second (ft/sec). A design pressure of 200 psig and design temperature of 400°F envelop observed conditions.

- **Process steam piping to electrolyzers (Attachment C Appendix ii)**

  Pipe size of 18-inch, STD schedule carbon steel, 50 feet long were connected to the outlets of the shell side of the two reboilers, before joining to a header and routing out of the nuclear plant protected area to the H_2 facility. The header is 26-inch, STD schedule carbon steel, 1710 feet long. Maximum steam velocity experienced in the lines was ~131 ft/sec. A design pressure of 150 psig and design temperature of 400°F envelop observed conditions.

- **Reboiler feed water piping (Attachment C Appendix iii)**

  From the H_2 facility to the nuclear plant, 1720 feet of 6-inch, STD schedule carbon steel is modeled, with a maximum velocity of ~8 ft/sec and a maximum pressure of 137 psia, before routing into the pressurized surge tank. A design pressure of 150 psig and design temperature of 275°F envelop observed conditions, including an additional 50% in pump head rise to shutoff conditions. Stainless steel piping was used for the actual design.

  Two tank outlets then split flow to either of the two reboiler trains. Reboiler feed pump suction piping is modeled as 40 feet of 6-inch, STD schedule carbon steel piping. Pump discharge lines are 4-inch, STD schedule carbon steel pipe, 240 feet long, with a maximum velocity of ~9 ft/sec. A design pressure of 75 psig for suction piping, 250 psig for discharge piping (including 50% margin for pump shutoff), and design temperature of 275°F overall envelop observed conditions. Stainless steel piping was used for the actual design.

- **Drain piping from the reboiler to the main condenser (Attachment C Appendix iv)**

  The drain pipe size of 6-inch, STD schedule carbon steel, 220 feet long was modeled, resulting in a maximum water velocity of approximately 4.5 ft/sec. Design pressure of 200 psig and design temperature of 250°F were selected to envelop the drain conditions. Stainless steel piping was used for the actual design.

The results of pump, valve, and tank sizing are summarized as follows:

- **Reboiler feed water pump (Attachment C Appendix iii)**

  The pump sizing is based on the nominal flow rate of 360 gallons per minute (gpm), along with the nominal carbon steel pipe characteristics, resulting in a required pump total developed head of approximately 260 feet, requiring approximately 29 horsepower (hp).

- **Pressurized demineralized water surge tank (Attachment C Appendix iii)**

  The surge tank sizing is based on a maximum water volume expansion of approximately 7% between minimum and maximum water temperatures. Including 100% margin in the expansion volume, the required usable surge tank volume is about 426 gallons.

- **Drain control valve size (Attachment C Appendix iv)**

  The drain control valve sizing results in the following requirements:

Drain flow:	197,500 lbm/hr (~410 gpm)
Valve differential pressure:	~152.7 psid
Valve inlet pressure:	~154.6 psia

  Note that due to a very high valve differential pressure, there is a high potential for valve flashing/cavitation, which must be considered when specifying the drain control valve for severe duty, as well as an internal baffle plate to protect condenser internals.

All results provided in this section are specific to the draining of condensate to the main condenser. If the heater drain tank is selected as the preferred drain location, results will change and an additional pump will be required. Discussion of this alternate option, and the sizing of the additional pump, can be found in Attachment C.

4.2.3 Major Equipment List

The major equipment required to implement the thermal integration within the nuclear plant scope of the modification is summarized in Table 4-5 below. This listing is not intended to be all-inclusive, but instead 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, conduit, etc., must also be considered. Materials needed for piping supports, transmission towers, etc., are also excluded from the equipment list below, but are built into the cost estimate developed in Attachment M and summarized in Section 6.

Table 4-5. Major Equipment for Nuclear-Hydrogen Integration Design

No.	Item	Quantity	Description/Notes
Mechanical (Thermal)			
1	Steam Reboiler	2	Refer to Section 4.2.1 for sizing information
2	Drain Cooler	2	
3	Pressurized Demineralized Water Tank	1	500-gallon capacity @ 50 psig
4	Reboiler Feed Pump	2	360 gpm @ 260 ft TDH (approximately 29 hp)
5	4” Air-Operated Level Control Valve	2	
6	6” Air-Operated Level Control Valve	2	
7	14” Steam Dispatch Air-Operated Flow Control Valve	2	
8	16” Non-Return Valve	2	
9	16” Steam Manual Isolation Valves	10	Double isolation at both crossunder tie-ins, after header, and isolation to reboilers
10	18” Self-Contained Backpressure Regulating Valve	2	
11	18” Steam Manual Isolation Valves	6	Isolation at reboilers and PCVs
12	26” Steam Manual Isolation Valves	1	
Mechanical (Balance of Plant)			
1	Raw Water Feed Pump	1	1,400 gpm @ 130 ft TDH
2	Wastewater Feed Pump	1	380 gpm @ 270 ft TDH
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
4	Coupling Capacitor Voltage Transformer (CCVT)	3	345 kV/120 V
5	Protective Relay 50BF	1	
6	Communication System	1	Cabinet NEMA 4X with meters and Aux. telecommunication for revenue meters
7	Standalone HMI	1	Located in the Main Control Room
8	Breaker failure relay (50BF)	1	
9	Breaker Failure Lockout relay 86BF	1	
10	Line Differential Protection Relay 411L/87	1	
11	Line Differential Protection Relay 311L/87	1	
12	Line Differential Lockout Relay 86	1	
13	Revenue Meter	3	
14	1113 kcmil Bluejay ACSR with OPGW Shield Wire	13,500 ft	Transmission line cable outdoor

5. HYDROGEN PRODUCTION FACILITY DESIGN

5.1. Design

The nuclear plant and H_2 facility design scopes are delineated at the boundaries of the H_2 facility and high-voltage switchyard for the mechanical and electrical connections. This cut-off is expected to allow the H_2 facility and switchyard designs to be largely isolated from nuclear regulatory requirements which are more stringent and add cost throughout the duration of engineering, design, and construction.

Section 4 covers the items within nuclear plant scope. This section will detail the remainder of the project, with focus on the hydrogen production facility and high-voltage switchyard. A general arrangement drawing of the H_2 facility and high-voltage switchyard is provided in Attachment J and Attachment K, respectively. H_2 facility process flow diagrams are shown in Attachment E.

5.1.1 Hydrogen Production Process

The H_2 production process starts with electrolysis, where steam (supplied from the nuclear plant via the reboilers for this high-temperature steam electrolysis application) is split into hydrogen and oxygen. The hydrogen product stream exits the electrolyzers at high temperature, low pressure, and a high water content (15% molar fraction of water). Heat transfer, compression, and drying/purification are needed to reach the desired conditions for offtake (see Table 3-3). The oxygen product stream is not utilized in this design and is direct vented to atmosphere after dilution within the SOEC stacks.

5.1.1.1 Electrolysis

As described in Section 3.4, the reference electrolyzer for this study is compatible with a standard 1.2 MW_{dc} Bloom Energy SOEC electrolyzer [2]. These stamps were grouped into blocks based on rectifier capabilities. Eight (8) stamps per block was identified as an appropriate selection for this design that can reduce equipment quantities in support of a consolidated facility footprint. A total of 52 SOEC blocks (416 total stamps) will be needed to meet the 500 MW_{dc} (499.2 MW_{dc} exactly) beginning of life load dedicated to electrolysis. Electrolyzers commonly degrade throughout their life. Vendors can recommend increasing power consumption to maintain hydrogen production or maintain power consumption at reduced hydrogen production rates. Preference for this site is to maintain hydrogen production levels and design the supporting electrical equipment for the SOECs with margin to accommodate degradation. The rectifiers for this design are sized to accommodate this margin through an assumed end of life electrolyzer load of 1.3 MW_{dc} per stamp. Rectifier selection is discussed further in Section 5.1.4.1.

Bloom electrolyzers are intended for outdoor use; as site ambient temperatures fall below the minimum design temperature of the electrolyzers (see Table 3-1 and Table 3-2), winterization provisions will be required.

Table 3-2 provides the feed steam normal operating flow rate (741 lbm/hr) for a single stamp. With margin for greater maximum flow rates, the thermal integration systems are designed for a total flow of 350,000 lbm/hr. On the discharge side of the electrolyzers, diluted oxygen will be vented to atmosphere. The wet H_2 exits the SOEC at only 0.36 psig and requires cooling, compression, and drying to reach the conditions necessary for offtake.

The SOECs require an external supply of H_2 for startup, shutdown, and idle conditions. This H_2 can be sourced from dried H_2 product (via onsite storage or vehicular transport) or from the H_2 pipeline offtake. For this study, it is assumed that the H_2 pipeline used for product offtake could also be used for startup and shutdown. During hot idle conditions, dried H_2 located in the H_2 buffer vessel downstream of the dehydration system could be used. Given these sources of H_2, there will be no need for onsite H_2 storage. External H_2 supply conditions for selected projects would be stipulated by the electrolyzer vendor selected.

5.1.1.2 Heat Removal and Recovery

There are many sources of waste heat within the H_2 facility. It is not economical to recover most of these sources. Some of these sources include SOEC condensate drains and oxygen vents. Condensate recovery flows are relatively small (compared to process flows), and oxygen vents are typically diluted throughout the ventilation process, reducing the temperature to the point where heat recovery is no longer practical.

Given the compression cooling requirement for the process H_2 product stream (specific to the reciprocating low-pressure compression technology selected for this design) and the hot outlet temperature (100-180°C), heat recovery from that source can yield substantial process efficiency improvements if used to preheat the treated water to the reboiler as well as support compressor cooling requirements. As a result, heat exchangers are selected at this location to support both of these functions.

As shown in Attachment E, this design implements two heat exchangers in parallel, directly downstream of the electrolyzers. The heat exchangers use treated water to absorb H_2 product stream waste heat before sending the process feedwater to the nuclear plant for boiling. This preheating lowers the nuclear plant thermal power extraction required to support high-temperature steam electrolysis and increases the overall efficiency of the process.

On the hot side, the SOEC H_2 product is cooled to approximately 120°F. This results in a significant amount of condensate removal, which is sent back to the water treatment system for reuse in the process stream, while at the same time improving H_2 product purity and providing the necessary cooling prior to low-pressure compression.

On the cold side, near-ambient temperature demineralized water is heated from approximately 78°F to 178°F during the summer and 50°F to 113°F in the winter. This preheating significantly reduces the nuclear plant steam extraction requirements, improving plant efficiency.

Operating conditions for the heat recovery design were calculated by developing an Aspen HYSYS process model as seen in Figure 5-1. Heat exchanger equipment selection is described in Section 5.2.1.1.

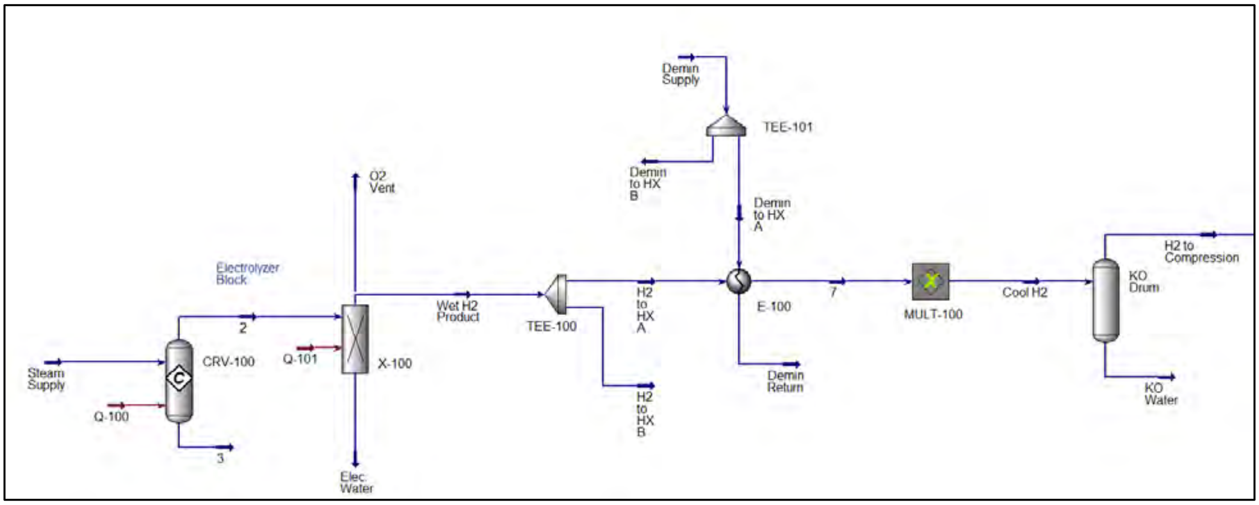


Figure 5-1. Aspen Model

Table 5-1 provides the hydrogen heat recovery parameters used for heat exchanger selection.

Table 5-1. Hydrogen Heat Recovery Exchanger Design Data

Parameter	Units	Process Side	Water Side
Inlet Temperature (Summer/Winter)	°F	302	78 / 50
Outlet Temperature (Summer/Winter)	°F	120	178 / 113
Inlet Pressure	psig	0.36	70
Maximum Pressure Drop	psid	0.10	15

5.1.1.3 Compression

There will be two parts of hydrogen compression. Initially low-pressure (LP) compression will receive H_2 from the production system assuming a 0.2 psi pressure drop or less and deliver H_2 to the purification and dehydration system at 435 psig. High-pressure (HP) compression will occur downstream of the hydrogen purification and dehydration unit to meet the 1,500 psig required for pipeline offtake.

Table 5-2 details the hydrogen compression parameters for the two parts of compression.

Table 5-2. Hydrogen Compression Parameters

Parameter	Units	Low-Pressure Compression	High-Pressure Compression
Suction Pressure	psig	0.15	435
Suction Temperature	°F	120	104
Discharge Pressure	psig	435	1,500
Discharge Temperature	°F	100	100

The compressors are assumed to be non-lubricated, reciprocating type machines to avoid the requirement of oil removal downstream of the compressors. Lubricated machines can be investigated, especially for the first stage given that purification is located downstream. However, non-lubricated compressors are common in hydrogen applications with high-purity offtake gas requirements and are the basis of the study here. Interstage and after cooling, as needed, is integrated into the compression skids, and cooling water supply is provided by the cooling water system. Compression equipment selection is described in Section 5.2.1.2.

5.1.1.4 Drying and Purification

The SOECs are not provided with purification/drying systems. At an electrolyzer outlet purity of 85 mol% H_2 and 15 mol% steam (per Table 3-2), a purification/drying system is needed downstream of the low-pressure compression to reach the required H_2 purity of 99.999% for offtake. These purification/drying systems will contain gas filters, adsorbers, regeneration gas heaters, regeneration gas coolers, regeneration gas separator, regeneration gas compressor, and other associated piping and control equipment. The system will have three (3) dryer beds each, one in operation and two in cooling/regeneration mode.

5.1.1.5 Offtake

This pre-conceptual design scope is focused on the H_2 facility. Downstream of high-pressure compression, H_2 will be sent offsite via pipeline to the desired user(s). Alternate offtakes include a pipeline for natural gas blending, onsite truck filling station, or remote onsite storage. Detailed design considerations associated with offtake are not developed in this pre-conceptual design report but will be needed for any site considering large-scale H_2 production.

5.1.2 Balance of Plant (BOP)

Various systems are required within the H_2 facility to support continuous H_2 production, including water treatment, cooling water, fire protection, utility gases, and condensate recovery. These systems are detailed further in this section. Other supporting systems include plumbing (see Section 3.3.3.3) and building heating, ventilation, and air conditioning (HVAC).

Control systems are briefly discussed in Section 3.3.4 and Section 5.1.4.5. Electrical systems are described in Section 5.1.3 and 5.1.4.

Given the high-purity feed stream requirements for electrolysis, a sizable water treatment system is required to produce the required treated water. This system must be integrated with the nuclear plant and the environment for raw water sourcing and wastewater reject.

Large mechanical equipment (e.g., compressors) require significant cooling capacity. A wet-cooling design is selected; therefore, a cooling water system is developed.

While it is not always advisable to extinguish hydrogen fires with fire water systems as it is for other flammable gases, it is necessary to provide fire a water-based fire protection system to protect indoor spaces such as the administration building. Fire water can also be used to keep adjacent equipment cool during a hydrogen fire. During detailed design, hydrogen safety systems will be developed in further detail, with the requisite emergency shutoff valves (ESVs), ventilation, leak detection, and hydrogen fire detection equipment.

Utility gases (nitrogen and instrument air) will be required for equipment purging and control. Nitrogen purging will be intermittent; nitrogen will be stored onsite at high pressure.

5.1.2.1 Water Treatment

The water treatment system is needed for the production of treated water to meet the quality requirements for electrolysis. The raw water source will typically be used to provide representative water quality data to support the selection of water treatment equipment. In lieu of specific raw water data, this report assumes that the following components will be included in the makeup water treatment system to support the treatment of a surface freshwater source:

- Solids contact clarifiers to remove seasonal suspended solids
- Sludge thickener to concentrate suspended solids prior to dewatering
- Filter presses to produce a dewatered cake suitable for landfill disposal
- Multi-media filters to further remove suspended solids prior to reverse osmosis
- Two-pass reverse osmosis systems to remove sufficient dissolved solids
- Oxygen scavenger dosing system to ensure dissolved oxygen is removed

This system is conservatively designed to cover the majority of surface freshwater sources. Site-specific water quality information could reduce the equipment required to meet demineralized water quality requirements. Furthermore, for smaller hydrogen production facilities, there may be potential to integrate the water treatment system with existing nuclear plant demineralized water treatment system.

This system is expected to produce a few tons of solid waste per day, which will be removed from the site via truck and disposed of at a landfill. The reverse osmosis reject will be combined with other H_2 facility wastewater streams including filter backwash and cooling tower blowdown, prior to being sent back to the nuclear plant for possible treatment and discharge. Sampling and analysis of this new wastewater may be required based on nuclear plant wastewater programs and procedures. The site NPDES permit will likely require revision to account for the additional wastewater flows and any water quality impacts. Regulatory and procedural impacts will need to be assessed on a site specific basis.

The H_2 facility is supplied with additional raw water for cooling tower makeup, service water, and fire water. The quality requirement for these systems is less stringent than for the process water and is therefore subject to partial treatment prior to distribution within the facility.

5.1.2.2 Cooling Water

A cooling water (CW) system will be supplied for the cooling of the hydrogen compressors and dehydration system. The system will be located within the new H_2 facility and will consist of cooling water pumps and a 9-cell mechanical draft cooling tower. The CW system will have a make-up stream using water from the water treatment system as needed. The system will also have blowdown to maintain an appropriate number of cycles of concentration. Chemical treatment of the cooling water is expected as a part of this system.

The cooling towers will be arranged in a single line, parallel with the prevailing summer wind direction. This arrangement provides the most efficient cooling solution, allowing the plume to rise high enough to not interfere with the surrounding plant. Cooling water will be routed to an underground header and stub up to the individual users to reduce insulation and supports.

5.1.2.3 Fire Protection

A new fire protection system including pumps, a main header loop, hydrants, and building fire systems will be designed in accordance with NFPA 850, “Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations”, and all other applicable NFPA standards and local codes as well as any requirements of the Authority Having Jurisdiction (AHJ). A risk analysis per NFPA 850 is required. The fire protection water supply will be provided from the same surface water source as described in Section 3.3.3.1, and stored in a Fire Protection and Service Water Tank.

ESVs and relief valves will be provided in the hydrogen system to prevent and mitigate fire hazards. Additionally, per NFPA 2, “Hydrogen Technologies Code”, minimum setback distances from bulk gaseous storage systems (hydrogen storage blocks) will be followed, and firewalls will be included to further separate these systems from other equipment in the plant, as required. Currently the plant is designed to use offsite stored hydrogen for SOEC startup and shutdown. While idling the SOEC will consume Hydrogen from the buffer vessel located before high-pressure compression. This buffer vessel is sized below the minimum requirement for NFPA 2 setback distance to be applicable. H_2 gas detection and flame detection systems will be located as appropriate throughout the hydrogen production facility. Any indoor areas with hydrogen piping or equipment will have detection and appropriate ventilation per code.

5.1.2.4 Utility Gas Systems

The new H_2 facility will require instrument air for control valves, emergency shutoff valves, and other equipment. The hydrogen electrolyzers use instrument air system for pneumatic valves. The instrument air system shall include compressor(s), dryer(s), a wet air receiver, an instrument air receiver tank, and instrument air piping.

The new H_2 facility will require nitrogen for purging hydrogen systems. While purging will be infrequent, the quantity of nitrogen required for purging makes onsite generation and storage the most economical solution for the nitrogen system. Nitrogen will be used to blanket condensate sumps in the event of an SOEC upset. It will also be used to purge the electrolyzer, process compressors, dehydration system, and any interconnecting hydrogen process piping. Nitrogen generators will use instrument air to produce low-pressure nitrogen. This low-pressure nitrogen product will be boosted and stored in high-pressure nitrogen vessels to be used when an upset occurs. When purging is required, the high-pressure nitrogen will be stepped down to a lower pressure to be used in these systems.

For gaseous H_2 systems, venting must occur in accordance with CGA G-5.5 at an adequate distance above grade and any adjacent equipment, building, or other structure. Vent diameters will be sized to achieve high enough exit velocities for proper dispersion. A recommended high discharge velocity would be 500 ft/s. The properties of hydrogen make it common for flames to occur at the end of vent stacks. Discharge pressures greater than 15 psig must be evaluated for supersonic compressible flow effects that can lead to aspirating air and possible stack fires. Back pressure at the relief discharge shall not exceed 10% of the pressure relief device set pressure. Vents shall have vent caps to prevent rain accumulation while diverting the gas upwards and vents must be grounded.

In accordance with the guidelines set by NSS 1740.16, “Safety Standard for Hydrogen and Hydrogen Systems”, venting hydrogen with mass flow rates greater than 0.5 lb/s (0.226 kg/s) will require flaring. If flaring, pilot ignition, flameout warning systems, and means to purge the vent are all required.

5.1.2.5 Condensate Recovery

Condensate generated from the steam supply, SOECs, compression cooling, and purification/drying skid are combined and sent to a condensate recovery sump. The condensate is then sent to the water treatment clear well for further processing before being reintroduced in the electrolyzer feed stream. This will help to reduce wastewater and raw water makeup flows.

5.1.3 High-Voltage Switchyard

The 345 kV transmission line (H_2 feeder) for the H_2 facility will be terminated at a 345 kV Motor Operated Disconnect switch on a 345 kV bus (4” A), inside the H.V. switchyard. The H.V. switchyard is designed with reliability and maintenance flexibility in mind to ensure the continuous and safe transmission of electricity to meet the H_2 facility power requirements. The H.V.

switchyard design distributes the required power to the H_2 facility via two (2) two winding step-down Main Power Transformers (MPTs) rated for 345 kV-delta/34.5 kV-wye, 205/257/340MVA ONAN/ONAF/ONAF. Each of the MPTs are connected to the 345 kV bus by 345 kV dead tank circuit breaker and MOD switch. The two transformers are connected in parallel to the 345 kV bus. The H.V. switchyard is configured for one of the MPTs to be able to power half the SOEC blocks (26) and roughly half the auxiliary loads, if the other MPT is out for maintenance. Load reconfiguration with engineering evaluation shall be performed for this condition.

The MPTs step the power down to 34.5 kV to supply a 34.5 kV bus. The 34.5 kV bus will be 2-5" AL schedule 40/phase, connected to the MPT secondary winding by two (2) disconnect switches in parallel. There are two (2) bus tie line disconnect switches between the two (2) 34.5 kV buses, which can be closed to energize both buses from a single MPT, if required. There are six (6) 34.5 kV outdoor breakers on each bus feeding the following power transformers, and one (1) 34.5 kV outdoor breaker shared between both buses feeding the service transformer. These breakers and their associated loads are described below:

- Breaker #1 – Two winding, Delta-Wye 110 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 1A, inside the H_2 facility and powering SOEC blocks. Power cables (2-1/C/phase-1000kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #2 – Two winding, Delta-Wye 90 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 1B, inside the H_2 facility and powering SOEC blocks. Power cables (2-1/C/phase-1000kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #3 – Two winding, Delta-Wye 90 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 1C, inside the H_2 facility and powering SOEC blocks. Power cables (2-1/C/phase-1000kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #4 – Two winding, Delta-Wye 45 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 1D, inside the H_2 facility and powering auxiliary loads. Power cables (1/C/phase-500kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #5 – Spare Breaker
- Breaker #6 – Spare Breaker
- Breaker #7 – Two winding, Delta-Wye 500 kV service transformer (34.5 kV/480V), located outside the H.V. PDC, inside the high-voltage switchyard. Power cables (1/C/phase-500kcmil) between 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #8 – Two winding, Delta-Wye 110 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 2A, inside the H_2 facility and powering SOEC blocks. Power cables (2-1/C/phase-1000kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.

- Breaker #9 – Two winding, Delta-Wye 90 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 2B, inside the H_2 facility and powering SOEC blocks. Power cables (2-1/C/phase-1000kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #10 – Two winding, Delta-Wye 90 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 2C, inside the H_2 facility and powering SOEC blocks. Power cables (2-1/C/phase-1000kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #11 – Two winding, Delta-Wye 45 MVA step-down transformer (34.5 kV/13.8 kV), located outside PDC 1D, inside the H_2 facility and powering auxiliary loads. Power cables (1/C/phase-500kcmil) between the 34.5 kV breaker and the transformer will be routed underground direct buried.
- Breaker #12 – Spare Breaker
- Breaker #13 – Spare Breaker

The control and protection of the equipment inside the H.V. switchyard is managed from a walk-in H.V. Power Distribution Center (PDC) inside the switchyard. The PDC is prefabricated and equipped with the following:

- 480 Vac distribution panel for lights, HVAC, and transformer auxiliary power
- Lighting distribution panel feeds all outdoor lighting in the H_2 facility
- 345 kV MOD switches, 345 kV breakers, and MPTs control and protection panel
- 34.5 kV breakers control and protection panel

An automatically operated manual transfer switch will be installed outside the PDC connected to the normal auxiliary power source in the H.V. switchyard from the service transformer 480 V output to the 480 V utility power (or diesel generator). The switch transfers to the utility power source when the service transformer is out.

Eight (8) lightning protection rods with down conductors will be installed in the H.V. switchyard to safeguard personnel and protect the electrical system from lightning strikes. Three surge arrestors will be connected to the 345 kV bus to protect the switchyard equipment from overvoltage transients, lightning strikes, and switching surges. One of the surge arrestors will be installed close to the incoming 345 kV line; the other two will be installed close to the 345 kV breakers.

The H.V. switchyard will have security cameras and lighting though out the yard. Security cameras will be connected to the H_2 facility control center.

A layout of the high-voltage switchyard is provided in Attachment K.

5.1.4 Electrical Distribution

The electrical distribution inside the H_2 facility will consist of the following:

- Medium-voltage 13.8 kV switchgears to power the rectifier skids and large auxiliary loads
- Medium-voltage 4.16 kV switchgears to power medium size auxiliary loads
- Low-voltage 480 V switchgear and distribution panels to power SOEC ac auxiliaries and other small auxiliary loads

The electrical power distribution inside the H_2 facility uses several PDCs and step-down power transformers located outside the PDCs and fed from 34.5 kV breakers.

The configuration of the electrical distribution in the facility consists of following:

- Six (6) PDCs (PDC-1A/2A/1B/2B/1C/2C), each with the following electrical equipment:
    - 13.8 kV Switchgears powered by a step-down transformer (34.5 kV/13.8 kV) located outside the PDC, to feed rectifier skids to power SOEC blocks
    - 480 V Switchgears powered by a step-down power transformer (13.8 kV/480 V) located outside the PDC, to feed the SOEC block auxiliary loads (heat tracing and Uninterruptible Power Supply [UPS])
    - 480 V distribution panels to feed the auxiliary loads inside each PDC and power transformer located outside the PDCs
- One (1) PDC-1D, containing the following electrical equipment:
    - Two-13.8 kV Switchgears with bus tie breaker between them, each powered by a step-down transformer (34.5 kV/13.8 kV) located outside the PDC, to feed low-pressure and high-pressure hydrogen compressors
    - Two-4.16 kV switchgears with bus tie breaker between them, each powered by a step-down transformer (13.8 kV/4.16 kV) located outside the PDC, to feed applicable H_2 facility auxiliary loads
    - Two-480 V switchgears with bus tie breaker between them, each powered by a step-down transformer (4.16 kV/480 V) located outside the PDC, to feed applicable H_2 facility auxiliary loads.
    - Two-480 V distribution panels which feed H_2 facility auxiliary loads
    - 125VDC battery with battery charger
    - 125VDC distribution panel

The 125 VDC battery/battery charger shall provide sufficient ampere-hour rating at 80% of rated load for the specified duration for instrumentation, control, and monitoring circuits required for startup/shutdown and normal operation. The 125VDC power inside PDC-1D will be used for breaker control and logic protection in the H_2 facility and the H.V switchyard. Therefore, 125 Vdc power cables will be routed from PDC-1D to the other PDCs, including the high-voltage PDC in the H.V. switchyard.

Control and protection of power cables feeding the rectifier skids and H_2 facility auxiliary loads will be from the switchgears and distribution panels inside the PDCs.

The electrical distribution system single-line diagram is provided in Attachment H.

5.1.4.1 Rectifier Skid

Rectifiers are based on Insulated Gate Bipolar Transistor (IGBT) technology that guarantees a ripple-free DC current as well as low grid harmonic generation and complete power factor control.

The SOEC architecture is physically laid out in 1.2 MW_{dc} stamps. The rectifier configuration, as shown in Figure 5-2 below, will power eight (8) stamps per rectifier skid. This will demand step down transformers and rectifiers skids dispersed throughout the site local to the electrolyzers.

The SOEC block requires 800VDC/12000A power feed at beginning-of-life (based on values in Table 3-2). Medium-voltage 13.8 kV power fed from the PDCs will supply the required power to the rectifier skids to power the SOEC blocks. Power feeds from medium-voltage switchgears will supply power to five winding step-down transformers on the rectifier skids to energize the SOEC rectifiers. Each rectifier skid contains a 10.5 MVA step down transformer, medium-voltage switchgear, four (4) air cooled rectifiers, power factor correction, and harmonic filters.

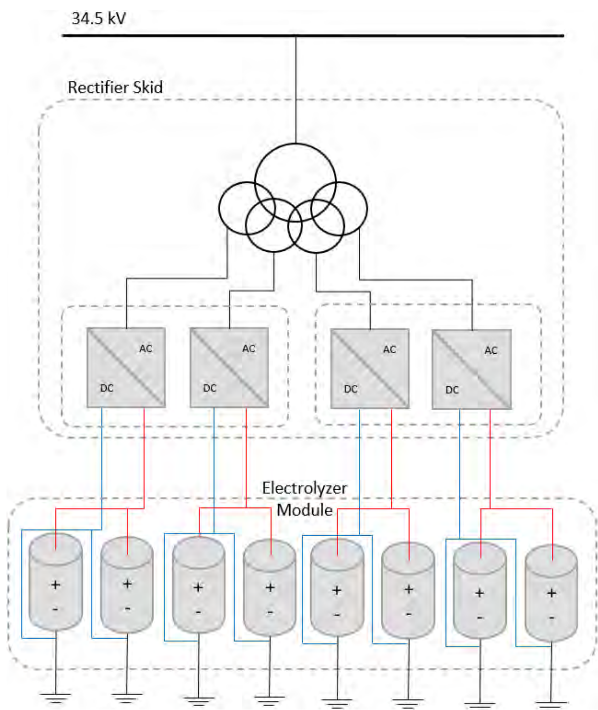


Figure 5-2. Rectifier Skid Power Flow

Per NFPA 497, "Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas", all electrical equipment and enclosures within a 15-foot radius of potential H_2 leak points will be rated Class 1, Division 2, Group B (except for a 3-foot radius around venting points which will be classified as Class 1, Division 1, Group B). All electrical equipment including the raceways and cables required in hazardous areas will be installed in strict accordance with the latest revisions of the NEC "Hazardous (Classified) Locations", Articles 501 for Class 1 locations. Intrinsically safe or non-incendiary designs are acceptable, as are explosion proof enclosures for use in hazardous areas per Article 504.

5.1.4.2 Electrical Short-Circuit and Load Flow/Voltage Drop Analysis

An ETAP electrical power system model was prepared to evaluate the power flow and short-circuit impacts of the H_2 facility electrical tie-in and the electrical distribution inside the H_2 facility. This model is the same as described in Section 4.1.3.6. The resulting impacts within the H_2 facility scope are described below.

The short-circuit analysis model shows that a 10% nominal impedance between the H-X windings (with ±7.5% tolerance) on the 205 MVA self-cooled base of the secondary windings allows for the use of 56 kA, 34.5 kV circuit breaker, and 46-kA, 13.8 kV medium-voltage switchgear at the H_2 facility.

The voltage drop analysis performed with the ETAP model shows that the H_2 facility step-down transformer does not require an on-load tap changer if the transmission voltage is maintained within approximately a ±2.5% bandwidth. The voltage at the medium-voltage buses and low-voltage buses are within acceptable limits, as shown below:

- 13.8 kV buses: 97.8% of bus rated voltage
- 4.16 kV buses: 95.0% of bus rated voltage
- 480V buses: 93.6% of bus rated voltage

The minimum acceptable running voltage at any medium-voltage bus (13.8 kV, 4.16 kV) is 90% of bus rated voltage. The same criterion applies to the main 480V switchgear buses. This corresponds to about 94% of motor rated voltage and will prevent motor and motor starter voltages from falling below their limiting values (90% of 460V).

Medium-voltage buses supplying transformers should have a minimum voltage that is adequate to allow for the voltage drop in the transformer, and still maintain 90% of bus rated voltage at the 480V switchgear buses. This value is typically about 93% of the bus rated voltage.

5.1.4.3 Protective Relay Design

The H_2 facility will house eight (8) step-down power transformers (1A/2A, 1B/2B, 1C/2C & 1D/2D) which will step the voltage from 34.5kV to 13.8kV, two (2) step-down transformer (1DD & 2DD) which will step the voltage from 13.8 kV to 4.16 kV and six (6) step-down transformers (1AA/2AA, 1BB/2BB & 1CC/2CC) which will step the voltage from 13.8 kV to 480V. These transformers, with their associated medium and low-voltage switchgear buses supplied by these transformers inside the H_2 facility are protected by transformer differential relays (87T) and lockout relays (86). Overcurrent relays (50/51) are employed on the feeders on the 13.8 kV and 4.16 kV medium-voltage switchgears. Transformer differential relays (87T), lockout relays and the overcurrent relays will be mounted inside their associated switchgears, inside the PDCs. The low-voltage feeders from distribution panels are protected by their associated circuit breakers.

The electrical system relay and protection diagram is shown in Attachment I.

5.1.4.4 Grounding Grid

The H_2 facility and H.V. switchyard will require an outdoor grounding system to provide an adequate electrical path for the safe flow of ground fault currents and the rapid dissipation of lightning surges to reduce potential gradients in the H.V. switchyard and the H_2 facility to values the average person can withstand without injury.

The outdoor grounding system consists of a grid of ground cable, bare copper 500 kcmil encircling and interconnecting the Administration Building, equipment frames, equipment neutrals, metal structures, SOEC blocks, power rectifier skids, power transformers, PDCs, outdoor circuit breakers, and piping in the high-voltage switchyard and H_2 facility.

In addition to the cable grid, copper-clad steel ground rods will be located throughout the area and connected to the grid. The grounding cable will be buried in moist earth between 24-30 inches below grade. Also, the H_2 facility ground grid will be joined to the nuclear plant grounding system by means of a ground conductor and overhead static wires on the transmission line, since the distance between the power plant and the H_2 facility is less than a mile.

5.1.4.5 Control Center

The H_2 facility will have a control center located in the Administration Building, where H_2 facility electrical and mechanical equipment can be controlled and monitored. The control of the high-voltage equipment located inside the H.V. switchyard, such as the 345kV MOD switches, 345 circuit breakers and 34.5 kV breakers and their associated auxiliary loads will be from the H.V. PDC inside the H.V. switchyard. The control of 13.8 kV circuit breakers, 4.16 kV breakers, and 480V breakers will be locally from switchgears and distribution panels, inside PDCs. Monitoring the status of all circuit breakers and MOD switches will be provided at the control center. Also, control and monitoring of the electrical equipment in rectifier skids and SOEC auxiliary electrical equipment will be provided in the control center.

5.1.4.6 Security System

The H_2 facility and the high-voltage switchyard will be required to have a security system to protect the facility from unauthorized access, theft, vandalism, and other security threats. Physical barriers will be in place, including a fence around the H_2 facility and around the high-voltage switchyard with access gates to manage and monitor entry points to the facility. Surveillance video cameras (fixed and Pan, Tilt, Zoom [PTZ] cameras) will be positioned strategically throughout the H_2 facility and high-voltage switchyard to provide continuous monitoring and recording of activities. The computer security system will be located in the control center in the Administration Building and will be powered by a UPS.

5.1.4.7 Outdoor Lighting

Outdoor lighting in the H_2 facility and the high-voltage switchyard will be designed to provide safety, security, and personnel accessibility around the H_2 facility and high-voltage switchyard. Outdoor lighting will use LED lights with power consumptions between 50-100 watts. Recommended outdoor lighting levels for industrial plants are based on data published by the Illuminating Engineering Society. Outdoor lights should stay on all the time and under any conditions. Therefore, the lights will be powered by the service transformer or the alternative utility power source, so outdoor lights will stay on in the event of power loss from the nuclear plant or main power transformers.

5.1.4.8 Utility Power Line

The H_2 facility will require an alternative power source to maintain power for general lighting and outdoor lighting, when the main transmission line supplying the H_2 facility is out or the H.V. switchyard is out. Therefore, a 480 V utility power line will supply the alternative power source, with termination on an automatic transfer switch in the H.V. switchyard. The normal power source on the automatic transfer switch will be supplied from the service transformer in the H.V. switchyard; power will transfer to the 480V utility power source only when the service transformer is deenergized, in order to maintain facility lighting.

5.1.4.9 Power and Control Cables Routing

The power cables routed between the 34.5 kV breakers in the H.V. switchyard and the H_2 facility step-down transformers (outside the H_2 facility PDCs) will be direct buried underground. The power cables from 13.8 kV switchgears (inside the PDCs) to the rectifier skids can be routed in power cable trench or direct buried underground. Power cables between high-voltage/low-voltage switchgears and the mechanical equipment will be routed in cable trenches. All control and instrument cables between mechanical equipment/switchgears and the control center will be routed in conduits underground. The DC power cables between rectifier skids and SOEC blocks will be direct buried underground.

5.2. Major Equipment

5.2.1 Equipment Sizing

Multiple vendors were contacted to find the best solution for an H_2 facility of this scale. The majority of the equipment at this site is not unique to the industrial environment. Water treatment, cooling water, utility gas, and water systems used standard product offerings to meet the demands of the H_2 facility. Equipment that required special considerations from vendors were the heat exchangers used for heat recovery and the H_2 product compressors.

5.2.1.1 Hydrogen Heat Recovery Exchangers

Hydrogen product exits the SOECs at the low pressure of 0.36 psig. To avoid the possibility of air being introduced into the product steam, this product must be fed to the inlet of the low-pressure compressors above atmospheric pressure (0 psig). In addition to the low allowable pressure drop, the product has to be cooled to at least 120°F. At these temperatures water condenses out of the product stream and must be removed. Typically, a knockout drum would be used to remove these droplets from the hydrogen product stream, creating additional pressure drop. The high flow and low pressure drop present a challenge to typical heat exchangers design like a shell and tube or plate and frame heat exchanger.

A finned tube heat exchanger is proposed for this design given the purity of the product stream (steam and hydrogen only) and the need for integrated water knockout within the heat exchanger. This design provided the lowest pressure drop path and efficiently transferred the required heat to the demineralized feedwater supplied to the nuclear plant for boiling.

5.2.1.2 Hydrogen Compressors

Compressing low pressure (0.36 psig) hydrogen up to 1,500 psig presents another unique challenge. Low-pressure H_2 gas has a very low density and the H_2 molecule is relatively small compared to most gases processed by compressors, therefore the selected compression technology requires a tight seal to avoid leakage.

Two oil-free compression solutions were considered for this study. Option 1 was liquid ring LP compression with reciprocating HP compression. Option 2 used reciprocating compressors for both LP and HP compression. Liquid ring compressors allow for wetter, higher temperature inlet product gas and can absorb any condensate formed during compression. Reciprocating compressors require drier, lower temperature inlet product gas but can achieve higher compression ratios and operate more efficiently without a seal water system.

Based on comparison of vendor quotes and technical information, Option 2 was selected for this design since it was economical, had a smaller footprint, and reduced the amount of interconnecting piping. While liquid ring compression is an attractive option for smaller scale applications, it did not appear to scale up to the flow rates required for this application.

Screw compression is another alternative option. The quantity of compressors for this option would be in between the liquid ring and reciprocating options. However, given the initial low pressure of this application and high compression ratio, a wetted screw compressor is recommended for this application. Wetted compression will require oil removal, increasing the cost of this option with additional equipment. Nevertheless, screw compression should be considered in future studies for these LP compression applications.

5.2.2 Major Equipment List

The major equipment required for the hydrogen production facility and high-voltage switchyard are summarized in Table 5-3 and Table 5-4 below. This listing is not intended to be all-inclusive, but instead to provide a high-level understanding of the major equipment needed in the H_2 facility design. Depending on site-specific design and configuration, additional commodities and support infrastructure must also be considered; these are included in the cost estimate developed in Attachment M.

A detailed mechanical equipment list for the H_2 facility equipment is provided in Attachment F. A Utility List is provided in Attachment G.

Table 5-3. Major Equipment for Hydrogen Production Facility Design

No.	Item	Quantity	Description/Notes
Mechanical (Process)			
1	SOEC Electrolyzer Blocks	52	8 x 1.2 MW_{dc} SOEC Stamps; beginning of life load
2	Hydrogen Heat Recovery Exchanger	2	
3	LP Hydrogen Compressor	4	
4	Hydrogen Adsorbers	4	
5	Hydrogen Buffer Vessel	1	
6	HP Hydrogen Compressors	2	Excluded from cost estimate
Mechanical (Balance of Plant)			
1	Water Treatment System	1	
2	Treated Water Storage Tank	1	1 Hour Storage Capacity
3	Treated Water Pumps	2	
4	Effluent Water Collection Tank	1	1.5 Hour Storage Capacity
5	Effluent Water Pumps	2	
6	Block Condensate Sump Pumps	24	
7	Fire Protection/Service Water Tank	1	
8	Service Water Pumps	2	
9	Fire Protection Pumps	2	
10	Sanitary Sewage System Lift Station	1	
11	Potable Water Buffer Tank	1	
12	Air Compressors	2	
13	Wet Air Receiver	1	
14	Air Compressor Dryers	2	
15	Instrument Air Receiver	1	
16	Nitrogen Generator	1	
17	Nitrogen Booster	1	
18	Nitrogen Receiver	1	
19	Nitrogen Pressure Vessels	3	
20	Cooling Tower Cells	9	
21	Cooling Tower Basin Heaters	9	
22	Cooling Water Supply Pumps	2	
23	Condensate Recovery Sump Pumps	2	
24	Admin Building HVAC	1	Assuming 1,500 ft^2 Building (5 Occupants)

Table 5-3. Major Equipment for Hydrogen Production Facility Design

No.	Item	Quantity	Description/Notes
Electrical Distribution			
1	Rectifier Skids	52	10.5 MVA Power Transformer
2	Two windings, Delta-Y Power Transformer, 34.5kV/13.8kV	2	110 MVA Rating
3	Two windings, Delta-Y Power Transformer, 34.5kV/13.8kV	4	90 MVA Rating
4	Two windings, Delta-Y Power Transformer, 34.5kV/13.8kV	2	45 MVA Rating
5	Two windings, Delta-Y Power Transformer, 13.8kV/480V	2	3 MVA Rating
6	Two windings, Delta-Y Power Transformer, 13.8kV/480V	4	2.5 MVA Rating
7	Two windings, Delta-Y Power Transformer, 13.8kV/4.16V	2	4 MVA Rating
8	Two windings, Delta-Y Power Transformer, 4.16kV/480V	4	2 MVA Rating
9	Electrolyzer PDC	6	
10	Facility Auxiliaries PDC	1	
11	13.8 kV Switchgear (3000A), 1-incomer (3000A), and 6 breakers (800A)	9	Non Arc Resistance Metal Clad
12	480V Switchgear (2000A), 1-incomer (2000A), and 6 feeders (800A)	6	
13	13.8 kV Switchgear (3000A), 1-incomer (3000A) and 4 breakers (800A)	4	Non Arc Resistance Metal Clad
14	480V Switchgear (2000A), 1-incomer (2000A), and 10 feeders (800A)	4	
15	4.16 kV Switchgear (1200A), 1-incomer (1200A) and 8 breakers (1200/200/150/100A)	3	
16	480V Switchgear (3000A), 1-incomer (3000A), Bus Tie (3000A), and 4 feeders (800A)	3	
17	480V Switchgear (3000A), 1-incomer (3000A), and 4 feeders (800A)	4	
18	125VDC Vented Lead Acid Batteries (200A) and Battery Charger	1	
19	13.8kV Single insulated Copper Conductor size 500 kcmil or AWG	43,000 ft	Direct buried single conductors from PDCs to Rectifier skids, main power.
20	600V, 3/C # 500 AWG or kcmil	15,000 ft	Grounding cable
21	480V Cathodic Protection Rectifier	3	2 kVA Rating
22	20KVA UPS System	1	For Security System
23	13.8kV Capacitor Bank	2	12 MVAR Rating

Table 5-4. Major Equipment for High-Voltage Switchyard Design

No.	Item	Quantity	Description/Notes
1	Two windings Delta-Y Main Power Transformer 345kV/34.5 kV	2	340 MVA Rating
2	345kV H.V. Dead Tank Circuit Breaker (1200A)	2	
3	345kV Disconnect Switch (89-T) (1200A)	2	
4	345kV Disconnect Switch (89-L) (1200A)	1	
5	34.5kV Vacuum Circuit Breaker (3000A)	13	
6	3-phase Disconnect Switch (6000A)	2	
7	230kV MCOV STA CL	3	
8	24.4kV MCOV STA CL	2	
9	34.5kV 38-Line Switch (2000A)	38	
10	Lightning Protection Rods with Poles	50	
11	480V Automatic Transfer Switch	1	
12	Outdoor lights and light poles	35	
13	Pan, Tilt and Zoom (PTZ) Security Cameras with Installation Poles	35	
14	PDC	1	
15	345 kV Motor Operated Disconnect Switch, Circuit Breaker, and Main Power Transformers Control & Relay Panel	1	Includes: - Four (4) 87/487 Differential Relays - Four (4) Lockout Relays - Two (2) 311/87 Relays - Two (2) 411/87 Relays - Two (2) 50/51 Relays
16	Two Windings, Delta-Y Service Power Transformer, 34.5kV/480V	1	500 kVA Rating
17	34.5kV Circuit Breaker Control & Relay Panel	1	Includes: - Eight (8) Differential Relays - Eight (8) Lockout Relays

5.3. Additional Considerations

5.3.1 Equipment Lead Times

One of the major factors influencing project schedule is equipment lead times. Long lead time items should be considered early in the project lifecycle in order to proactively engage procurement engineering to avoid scheduling bottlenecks.

Table 5-5 provides a list of expected long lead time components for the overall project scope, based on S&L vendor data as of 2024. Lead times are subject to change based on vendor, location, and supply chain conditions. Specific vendor lead times should be solicited on a project-specific basis to avoid unforeseen schedule impacts.

Table 5-5. Long Lead Time Components

Component	Indicative Lead Time (months) (1)
Steam Reboilers	12-14
Rectifier Skids	12-14
Hydrogen Heat Recovery Exchangers	12-14
Circuit Breakers	12-16
Hydrogen Compressors	12-18
SOEC Electrolyzer Stamps	18-30
Drying/Purification Skid	24-36
Main Power Transformers	36+

[1] Lead times are based on 2024 S&L vendor data and are subject to change based on supply chain conditions at the time of procurement. Specific vendor lead times should be solicited on a project-specific basis to avoid unforeseen schedule impacts.

5.3.2 Operating Profile and Stack Replacement Frequency

As the SOEC stacks operate they begin to degrade in efficiency. SOECs can be operated in a constant production profile, maintaining H_2 output at higher power consumption, or a constant power profile, resulting in decreased H_2 production over time. For this study a constant production stack operating profile was selected.

Efficiency losses due to SOEC degradation have been limited to an approximately 8% increase in power consumption (1.2 MW_{dc} to 1.3 MW_{dc}) while maintaining initial hydrogen production. This limit is built into the standard sizes of transformer/rectifier units. To prevent exceeding this limit, a replacement plan was developed. For this H_2 facility, stack replacement would begin at the start of the third year of operation (24 months after facility commissioning). Stack replacement is assumed to take one week per stamp, during which time the associated block would be out of service. Stacks would be replaced at a frequency of eight (8) stamps per month for the duration of H_2 facility operation (replacement strategy may change toward the end of facility operation). In the years following initial replacement, average stack degradation would spike; however, this replacement plan results in a peak average stamp power consumption of approximately 1.3 MW_{dc}, which remains within selected rectifier capabilities and therefore will not significantly impact H_2 production during that time. Following this first-replacement spike, average electrolyzer efficiency will converge to an efficiency above 99% of rated efficiency.

Different electrolyzer vendors and designs will have different stack degradation curves. Therefore, the replacement plan described for this generic H_2 facility may differ for site-specific projects. Additionally, operation and maintenance costs associated with this stack replacement frequency were not evaluated and should be considered when selecting an approach.

5.3.3 Variable Operating Profile

While H_2 production is assumed constant, year-round for this design, this may not be the most economic operating strategy. A daily or seasonal variable operating strategy may be more profitable for owners based on geographic conditions and market structure. Site-specific economic analysis should be performed to determine the preferred production strategy.

5.3.4 Hydrogen Production Scaling

This 500 MW_{dc} hydrogen production facility pre-conceptual design is developed with the intent of leveraging economies of scale cost reduction due to the number of electrolyzer stamps and the size of facility equipment. Nonetheless, scaling down the hydrogen production facility for smaller applications would result in a cost scaling effect (although not exactly linear) for the major hydrogen process equipment, electrical distribution, and nuclear steam integration. Conversely, the electrical transmission system and much of the balance of plant equipment/facilities (e.g., water treatment, cooling, and control systems) would see minimal cost reduction driven by size reduction as opposed to quantity reduction. These sensitivities to scale should be evaluated when developing hydrogen production facilities of a different scale.

6. PROJECT COST ESTIMATE

6.1. Basis of Estimate

6.1.1 Scope

The development of an accurate cost estimate for a nuclear-integrated hydrogen production facility requires a detailed understanding of hydrogen equipment and facility specifications, vendor price estimates, and indirect costs associated with the project construction and development. This report develops the following cost estimates:

(1) nuclear plant integration,

(2) high-voltage hydrogen switchyard,

(3a) hydrogen production facility (early adopter option), and

(3b) hydrogen production facility (large module option).

The two hydrogen production facility options represent different points along the technology adoption curve. The early adopter option is representative of a project three to five (3-5) years away, whereas the large module option represents a project eight to ten (8-10) years away.

All cost figures are in 2024 United States dollars (USD). For a complete overview of the methodology and breakdown of cost estimating for these estimates, refer to Attachment M.

6.1.2 Estimate Classification

The Association for the Advancement of Cost Engineering (AACE) has developed a classification system for assessing the expected accuracy of cost estimates [7]. Based on the maturity level of project definition deliverables and the use of this report as a pre-conceptual guide, these cost estimates fall into Class 5. Following the methodology described by this class and the level of estimate detail, the accuracy of these estimates is expected to vary between -30%/+50%. The actual value depends on the risk and suitability of assumptions associated with each cost item. Site-specific studies are required to improve these assumptions and increase estimate accuracy. Vendor estimates should be included on a site-specific basis.

The purpose of these estimates is to allow potential owners to understand the magnitude of capital costs required for the development of a 500 MW_{dc} HTE hydrogen production facility at an existing PWR nuclear power plant nuclear plant. This study provides a quantifiable reference for engineering, installation, and turnover/procurement costs for a project of similar magnitude. This study can be used to inform site-specific feasibility studies and assess the capital necessary to pursue nuclear-integrated hydrogen at the scale investigated.

6.1.3 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 said goods and services, meaning contracts and purchase orders are written on the owner's letterhead. There are no markups by the EPCM contractor on any of the purchase orders or construction contracts.

These cost estimates are 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 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 H_2 facility costs estimates and other relevant cost estimates as a basis. The below equipment pricing inputs to this estimate were obtained from vendor quotations unless otherwise noted:

- Rectifier Skids
- Hydrogen Heat Recovery Exchangers
- Hydrogen Compressors
- Cooling Towers
- Distribution Control Center

SOEC electrolyzer stamp prices were provided as a fixed allowance ($\$500/kW_{dc}$ and $\$250/kW_{dc}$ for the early adopter and large module designs, respectively) by INL, based on expected future cost reduction potential over the next 10 years. The overall electrolyzer stamp cost allowances include process equipment costs anticipated to fall under electrolyzer vendor scope. This includes the electrolysis stacks, topping heaters, component housing, and supporting equipment such as short-term UPS and heat trace. Rectifiers are not included in the electrolyzer cost.

The early adopter scenario is representative of a near term (3-5 years away) project. This does not represent a first-of-a-kind (FOAK) cost. The large module scenario represents an evolved electrolyzer stamp design with larger, higher energy density electrolyzer modules to reduce equipment quantities and support facility footprint consolidation. Further cost reduction potential is anticipated for Nth-of-a-kind (NOAK) facilities beyond the large module option.

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 4-5, Table 5-3, and Table 5-4, as well as supporting components and commodities as required. Capacity-factored or equipment-factored cost estimates do not use quantities of materials for cost estimation.

6.1.4 Cost Items

To further segment project costs, items were categorized into direct, indirect, and contingency costs; escalation costs were not included. Direct costs include labor, materials, subcontract, construction equipment, and process equipment costs, and encompass those activities directly tied to the addition of new permanent equipment. To support project construction and labor efforts, indirect costs were also considered. A buffer for unanticipated issues is covered through an assumed 20% contingency costs. This contingency is applied to all items except for the electrolyzer process equipment cost.

Each of these categories are described in greater detail in Attachment M.

6.1.5 Excluded Items

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. Some of the additional costs that the Owner should consider include:

- Site Facilities and Services for Owner's Personnel, Construction Management, and Start-Up & Commissioning
- Land acquisition, Rights of Way, and Access Road Costs
- Project Development Costs
- Spare Parts
- Legal and accounting fees
- Per diem/Travel expenses for Owner's Personnel
- Applicable taxes
- Insurance
- Project financing
- Schedule acceleration/delays and associated costs

Additionally, high-pressure compression is excluded from this cost estimate for comparison purposes to previous research. If included in the hydrogen production facility costs, high pressure compression would add approximately $15 million in direct costs, as described in Attachment M.

6.2. Cost Estimate Summaries

6.2.1 Nuclear Power Plant Integration

An overview of the direct, indirect, and contingency costs for the nuclear power plant integration scope of the project is provided below in Table 6-1.

The nuclear plant integration is estimated to cost (in 2024 USD) approximately $39.5 million, or $79/kW$_{dc}$. This cost estimate aligns very closely with the previous 500 MW$_{dc}$ integration design cost (in 2022 USD) of $39 million, or $78/kW$_{dc}$, from S&L report SL-016181 [1].

Table 6-1. Cost Summary for Nuclear Power Plant Integration

Description	Cost (2024 USD)
Labor	5,023,448
Material	4,814,211
Subcontract	903,951
Construction Equipment	842,204
Process Equipment	3,198,508
Total Direct Cost	14,782,322
Additional Labor	1,985,000
Site Overheads	3,807,700
Other Construction Indirects	7,385,000
Project Indirects	5,042,900
Total Indirect Cost	18,220,600
Contingency on Labor	3,080,800
Contingency on Material	1,354,700
Contingency on Subcontract	242,300
Contingency on Construction Equip.	242,500
Contingency on Process Equip.	671,700
Contingency on Project Indirects	1,008,600
Total Contingency Cost	6,600,600
Total Cost	**$39,603,522**
Standardized Cost	**$79/kW$_{dc}$**

The previous S&L report SL-016181 [1] also assessed a smaller hydrogen production facility and reduced separation distances; the report found a cost reduction of approximately 20% (to $31 million) by reducing separation distances from 500 m to 250 m, and a nearly 40% cost decrease (to $25 million) by decreasing the hydrogen production capacity to 100 MW$_{dc}$. The costs for this previous report are in 2022 USD. Both of these sensitivities are still expected to apply for this updated design.

6.2.2 High-Voltage Switchyard

An overview of the direct, indirect, and contingency costs for the high-voltage switchyard scope of the project is provided below in Table 6-2. The H.V. switchyard is estimated to cost approximately \$33.5 million, or \$67/kW$_{dc}$ (in 2024 USD).

Table 6-2. Cost Summary for High-Voltage Switchyard

Description	Cost (2024 USD)
Labor	1,153,839
Material	3,235,306
Subcontract	525,550
Construction Equipment	190,194
Process Equipment	14,750,000
Total Direct Cost	19,854,889
Additional Labor	465,000
Site Overheads	605,800
Other Construction Indirects	4,739,000
Project Indirects	2,364,100
Total Indirect Cost	8,173,900
Contingency on Labor	544,500
Contingency on Material	794,900
Contingency on Subcontract	123,000
Contingency on Construction Equip.	46,400
Contingency on Process Equip.	3,624,100
Contingency on Project Indirects	472,800
Total Contingency Cost	5,605,700
Total Cost	**\$33,634,489**
Standardized Cost	**\$67/kW$_{dc}$**

The previous S&L report SL-016181 [1] did not develop a cost estimate for the high-voltage switchyard. Nevertheless, at reduced sizes, the normalized switchyard cost is expected to decrease nonlinearly. At 100 MW$_{dc}$, the switchyard is expected to cost \$10-15 million (60-70% cost reduction), or about \$100-150/kW$_{dc}$ due to equipment quantity and size reductions.

6.2.3 Hydrogen Production Facility

An overview of the direct, indirect, and contingency costs for the hydrogen production facility is provided below in Table 6-3. To assess the sensitivity to electrolyzer costs and other items influenced by economies of scale and learning effects, two cases were analyzed: (1) an early adopter scenario representative of a near-term project three to five (3-5) years away, and (2) a large module scenario representative of a project eight to ten (8-10) years away, with additional efficiencies in electrolyzer design and workforce. In both cases, high pressure compression costs are excluded to support cost comparison for similar studies.

As shown in Table 6-3, the hydrogen production facility is estimated to have a range cost (in 2024 USD) of approximately \$750 million (\$1,500/kW_{dc}) for the early adopter scenario, and approximately \$600 million (\$1,200/kW_{dc}) for the large module option.

Table 6-3. Cost Summary for Hydrogen Production Facility

Description	Cost (2024 USD)	
	Large Module (\$250/kW Electrolyzer)	Early Adopter (\$500/kW Electrolyzer)
Labor	42,755,913	42,755,913
Material	23,918,728	23,918,728
Subcontract	7,623,264	7,623,264
Construction Equipment	8,037,824	8,037,824
Process Equipment	277,429,446	402,229,446
Total Direct Cost	359,765,175	484,565,175
Additional Labor	17,002,200	17,002,200
Site Overheads	22,450,300	22,450,300
Other Construction Indirects	79,098,200	96,383,000
Project Indirects	53,468,800	57,735,000
Total Indirect Cost	172,019,500	193,570,500
Contingency on Labor	20,123,300	20,123,300
Contingency on Material	5,876,800	5,876,800
Contingency on Subcontract	1,783,800	1,783,800
Contingency on Construction Equip.	1,961,200	1,961,200
Contingency on Process Equip.	40,958,000	44,415,000
Contingency on Project Indirects	10,693,800	11,547,000
Total Contingency Cost	81,396,900	85,707,100
Total Cost	**\$613,181,575**	**\$763,842,775**
Standardized Cost	**\$1,226/kW_{dc}**	**\$1,528/kW_{dc}**

As shown in Table 6-4, uninstalled capital expenditure (capex) comprises approximately 60% of the project cost. The major drivers of this cost are mechanical and electrical equipment. Although electrolyzer costs are projected to significantly decrease (as indicated through the assumed reduction from \$500/kW$_{dc}$ to \$250/kW$_{dc}$ between the two scenarios evaluated), other major components such as low pressure compressors, drying and purification equipment, rectifier skids, and transformers are more technologically mature and do not possess the same learning benefits. While this challenges further cost reduction, these areas should be the major focus for future efforts given the major impact on both capital and installation costs.

Table 6-4. Standardized Hydrogen Production Facility Costs

Description	Cost (\$/kW$_{dc}$)	
	Large Module	Early Adopter
Electrolyzer Stamps [(1)]	250	500
Uninstalled Capex [(2)]	696	953
Installation/Construction	530	575
Total Facility Cost	**1,226**	**1,528**

[1] Electrolyzer Stamp cost includes the process equipment costs provided by the electrolyzer vendor. In this design, this includes the electrolysis stacks, topping heaters, component housing, and supporting equipment such as a short-term UPS and heat trace. Rectifiers are not included in the electrolyzer cost. These equipment costs are included in the uninstalled capital cost.

[2] Uninstalled Capex includes the Material, Process Equipment, and associated contingency costs. There is no contingency for the electrolyzer stamps; all other materials and process equipment have a 20% contingency applied.

Similar investigations have been performed to assess capital cost for FOAK and NOAK large scale hydrogen production facilities at the 1,000 MW$_{dc}$ scale. Adjusted for inflation based on Handy Whitman Index Production Plant and Chemical Engineering Plant Cost Index escalation data (approximately 30% project escalation from 2021 to 2024), similar estimates have yielded 2024 USD costs in the range of \$750-1,250/kW$_{dc}$ (~\$580-960/kW$_{dc}$ in 2021 USD).

The \$1,200-1,500/kW$_{dc}$ hydrogen facility costs developed in this study are slightly greater than those from previous studies. The primary elevated cost delta is attributed to more conservative indirect and contingency costs. Based on past project experience and industry guidance, the assumptions used in this study are deemed appropriate for these Class 5 (-30%/+50%) estimates. In addition to the installation/construction cost differences, secondary factors contributing to the cost difference include different reference facility sizes, different electrolyzer block sizes, and modular construction versus stick-built. Accounting for these factors, the estimates within this report align with similar investigations. Enhancements in electrolyzer design and construction philosophy should be further investigated in future detailed design efforts.

It should be noted that this pre-conceptual hydrogen facility design herein is not fully optimized. There is strong potential for actual projects to further refine the hydrogen facility design using cost engineering and lean design methods to reduce overall facility cost. In addition, further project savings are envisioned to be accessible by utilizing strategies to reduce the operational and maintenance requirements of the design.

It would be expected that upon incorporating the previously described adjustments, savings in excess of $50 million may be achievable to reduce 2024 USD hydrogen facility costs to approximately $1,100/kW$_{dc}$ (~$850/kW$_{dc}$ in 2021 USD).

Examples of potential design optimizations include the removal of 34.5kV to 13.8kV step-down transformers and supporting electrical equipment for rectifier loads, the removal and/or resizing of specific redundant equipment, and the development of an integrated controls system to reduce operating personnel. Cost-benefit analysis and risk assessment should be performed for these alterations to ensure cost savings outweigh any potential impacts to facility operations and maintenance.

6.3. Total Project Cost

Based on the estimates developed in the previous sections, the total project cost is approximated to be $837 million ($1,674/kW$_{dc}$) for the early adopter project (3-5 years away) and $686 million ($1,373/kW$_{dc}$) for the large module project (8-10 years away). The level of cost estimate accuracy is -30%/+50%.

A breakdown of total project costs is provided in Table 6-5.

Table 6-5. Total Project Cost Summary

Description	Cost (2024 USD)	
	Large Module ($250/kW Electrolyzer)	Early Adopter ($500/kW Electrolyzer)
Nuclear Power Plant Integration	$39,600,000	
High-Voltage Switchyard	$33,640,000	
Hydrogen Production Facility	$613,180,000	$763,840,000
Total Cost	**$686,420,000**	**$837,080,000**
Standardized Cost	**$1,373/kW$_{dc}$**	**$1,674/kW$_{dc}$**

Project costs are primarily driven by the hydrogen production facility cost, which is approximately 90% of the total project cost. Uninstalled capital costs for the hydrogen facility are shown to reduce to approximately $700/kW$_{dc}$ in the large module design when electrolyzer cost falls to $250/kW$_{dc}$. As described in the previous section, cost optimization enhancements may include larger blocks, modularized construction, and modified equipment selection.

7. CONCLUSIONS

This report develops a pre-conceptual design for the development and integration of a 500MW$_{dc}$ high-temperature electrolysis (HTE) hydrogen production facility with an existing Westinghouse 4-loop pressurized water reactor (PWR) nuclear power plant.

Hydrogen is produced using 416 Bloom Energy solid oxide electrolysis cell (SOEC) stamps each rated at 1.2 MW$_{dc}$; each stamp contains a set of hydrogen generation modules. The stamps are configured in groups of eight (8) to create a block; the facility has fifty-two (52) blocks, each with a single rectifier for supplying the required dc power for electrolysis. The electrolyzers produce wet hydrogen at low pressure, which then requires cooling, compression, drying, and purification to reach the desired conditions for offtake. Balance of plant (BOP) systems include condensate recovery, water treatment, cooling, and utility gases. The hydrogen production facility is also equipped with safety systems, plumbing, HVAC, and other industry standard provisions. Also developed within the facility design are the electrical systems, including rectification for direct-current electrolyzers and distribution for auxiliary loads. In support of the large facility electrical load, a new high-voltage switchyard is developed to step down transmission voltages to the levels required for rectification and distribution. Monitoring and control of the facility will be performed by a supervisory control and data acquisition (SCADA) system with human-machine interface (HMI) in the new facility control center.

The nuclear plant interfaces are developed based on the thermal and electrical power requirements of the hydrogen facility. Electrical power is dispatched through a new connection on the high-voltage side of the generator step-up (GSU) transformers before being routed to the high-voltage switchyard via transmission line. Thermal power is extracted from the nuclear plant Main Steam system (High-Pressure [HP] Turbine exhaust location) to boil demineralized water for electrolysis. After passing through a set of heat exchangers in the nuclear plant protected area, the nuclear plant steam is condensed, subcooled, and returned to the main condenser, while the hydrogen process feed steam is sent to the electrolyzers at the hydrogen facility. Additional interfaces are established between the nuclear plant and hydrogen facility to support BOP systems. A dedicated set of operator controls with remote HMI will be established in the nuclear plant Main Control Room to allow for control, indication, and alarm of the integration systems.

Following the development of these designs, Class 5 cost estimates (-30%/+50% accuracy) were developed for the nuclear plant integration, high-voltage switchyard, and hydrogen production facility. All estimates were in 2024 United States dollars (USD). Nuclear plant modification, including the thermal, electrical, and BOP integration, was anticipated to cost approximately $40 million, and closely aligns with previous estimates. The high voltage switchyard cost was slightly lower, at approximately $34 million. Both of these items are approximately 5% of the project cost, with the hydrogen production facility making up the remaining ~90% of the cost.

Two hydrogen production facility cost estimates were developed. The first estimate was representative of an early adopter design with a project timeframe 3-5 years away. At an assumed electrolyzer stamp cost of $500/kW$_{dc}$ for the electrolysis stacks, topping heaters, component housing, and supporting electrical equipment, the hydrogen production facility was estimated to cost approximately \$750 million, or \$1,500/kW_{dc}. The second estimate assumed a refined electrolyzer design implementing large electrolysis modules within the vendor-provided stamps. At an assumed electrolyzer stamp cost of \$250/kW_{dc} and a target project timeframe 8-10 years away, the hydrogen facility was estimated to cost approximately \$600 million, or \$1,200/kW_{dc}.

Enhancement and optimization of this pre-conceptual HTE facility design can support savings in excess of \$50 million, resulting in hydrogen facility costs of approximately \$1,100/kW_{dc} (~\$850/kW_{dc} in 2021 USD). This strongly aligns with other similar estimates in the 2024 USD cost range of \$750-1,250/kW_{dc} (~\$580-960/kW_{dc} in 2021 USD). Cost-benefit and risk analyses should be performed for specific projects to ensure the facility design meets applicable requirements for operational flexibility and facility reliability.

This study illustrates the technical and economic feasibility of a large-scale nuclear-integrated HTE hydrogen production facility. Given the value nuclear-integrated HTE can provide to a clean hydrogen economy, future work is recommended to investigate the proposed hydrogen production facility cost optimization strategies alongside site-specific front-end engineering design studies to support refined project costs.

8. REFERENCES

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2. "Bloom Electrolyzer™ – Data Sheet", Bloom Energy, December 2023.
3. INL/EXT-20-60104, Rev. 1, "Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant," Vedros/Christian/Rabiti, November 2022.
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5. INL/EXT-10-20208, "Cooling Water Issues and Opportunities at U.S. Nuclear Power Plants", 2010.
6. ASHRAE Climactic Design Conditions 2021, http://ashrae-meteo.info/v2.0/index.php.
7. 18R-97, "Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries", Association for the Advancement of Cost Engineering, August 2020.
8. SL-017513, Rev. 1, "Nuclear Power Plant Pre-Conceptual Licensing Support for Large-Scale 500-MWnom Hydrogen Production Facility", May 2023.

9. ATTACHMENTS

Nuclear Power Plant

A. PEPSE Modeling
B. Thermal Extraction Piping and Instrumentation Diagram
C. Pipe Sizing Evaluations
D. Steam Reboiler Arrangement Drawing

Hydrogen Production Facility

E. Process Flow Diagrams
F. Mechanical Equipment List
G. Utility List
H. Electrical Single-Line Diagram
I. Relay and Protection Diagram
J. H_2 Facility General Arrangement Drawing
K. Switchyard Layout Drawing

General

L. Site General Arrangement Drawing
M. Project Cost Estimates

Attachment A. PEPSE Modeling

(6 Pages)

ATTACHMENT A
PEPSE Modeling – Thermal Extraction

A1.0 Purpose

The purpose of this attachment 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. The main purpose of this attachment is to evaluate extraction of thermal energy from the main power cycle. Parameters are summarized to provide input for sizing the reboiler considering thermal energy extraction.

A2.0 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 ~1250 MWe. PEPSE case results and diagrams for the preferred extraction (cold reheat) and two preferred return locations (main condenser and heater drain tank) 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 return to the main condenser / heater drain tank. Pressure and temperature losses to the environment (determined from Arrow models in Attachments C.i & C.ii) are included in the associated stream components. The PEPSE and Arrow models are iterated to achieve a steam quality of 1.0 out of the boiler (in PEPSE, Splitter 910's fraction of flow diverted and the boiler's specific volume are adjusted). Note that the pressure and temperature losses are developed in Arrow to size the associated piping and components for thermal extraction to the hydrogen production facility with extraction from cold reheat.

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 (which is then supplied to the hydrogen production facility). The amount of thermal energy extracted is calculated within PEPSE using operational variables and is controlled by changing the flow fraction out of the splitter supplying the reboiler.

A3.0 Inputs

A3.1 Steam piping pressure and temperature losses are taken from the Arrow modeling of these piping systems (See Attachments C.i and C.ii). The Arrow models take into account best estimate 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 temperature for worst case thermal losses through the piping network from the nuclear power station to the hydrogen production facility. The following lists the parameters taken from the Arrow modeling.

The plant steam supply piping from cold reheat is expected to have a pressure drop of 28.5 psid and estimated heat loss of 50,000 Btu/hr (Attachment C.i).

The pressure in the steam supply piping to the hydrogen production facility at the reboiler outlet is 125 psia at 350°F.

The steam supply piping to the hydrogen production facility is expected to have a pressure drop of 27.0 psid and estimated heat loss of 455,000 Btu/hr (Attachment C.ii).

A4.0 Assumptions

A4.1 Temperature of the condensed and subcooled extraction steam is assumed to be 200°F before it is returned to condenser / heater drain tank.

A5.0 References

A5.1 PEPSE V87 computer software, (S&L Program No. 03.7.551-87.0)

A6.0 Results

The preferred extraction location is at cold reheat (i.e., between the HP turbine outlet and the moisture separator reheaters). 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 to the nuclear power station making the main condenser the preferred return location. Return to the heater drain tank is also considered.

The base PEPSE model is modified as discussed in Section A2.0 to allow a thermal extraction level of ~107 MWt to be achieved. The attached PEPSE diagrams show the results considering thermal extraction of ~107 MWt from cold reheat and draining to the condenser or heater drain tank. Additionally, Table A1 compares important operating parameters within the nuclear power cycle to determine possible significant impact to station equipment. Note: worst-case values between cases draining to the condenser and heater drain tank are used in the table below.

Table A1: Summary of Important System Parameters for 107 MWt extraction

		Extraction Level		
Parameter	Units	0MWt	107MWt	Δ
Extraction Location	-	-	Cold Reheat	Cold Reheat
HP Exhaust Pressure	psia	190.1	182.5	-7.6 psi
Cold Reheat Flow	Mlb/hr	12.73	12.64	-0.7%
Remaining Steam to MSRs (Cold Reheat Flow – Steam Supply from Cold Reheat, Table A2)	Mlb/hr	12.73	12.25	-3.8%
Heater Drain Tank Pressure	psia	185.5	176.4	-9.1 psi

Based on the above comparison, the turbine vendor should be consulted to ensure the reduced HP turbine exhaust pressure is acceptable.

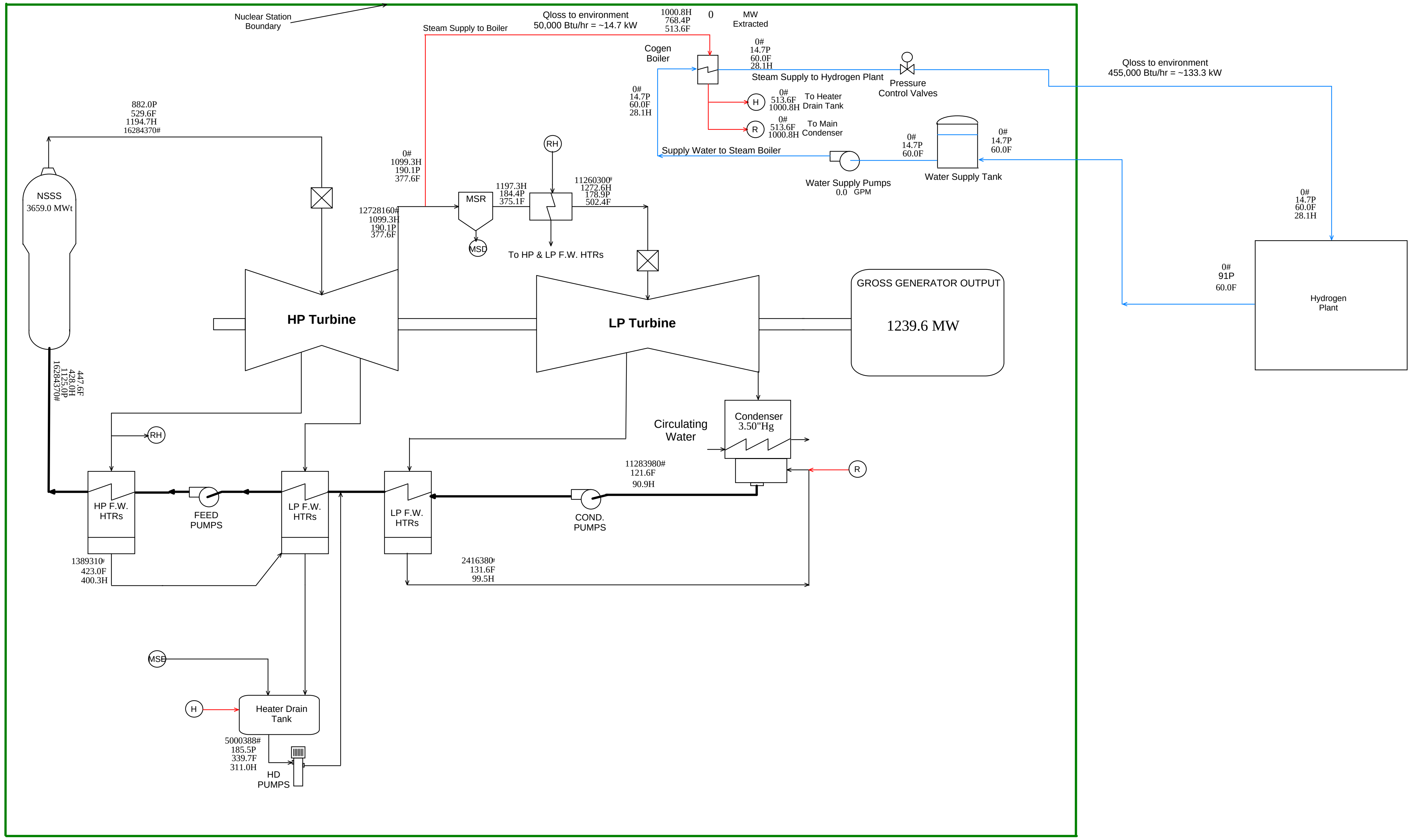
The Cold Reheat flow, Steam to MSRs, and heater drain tank pressure may be decreased which could slightly reduce the NPSH margin on the heater drain pumps. Therefore, if existing NPSH margin is low on station heater drain pumps, margins will be further reduced and will require further investigation.

ATTACHMENT A
PEPSE Modeling – Thermal Extraction

Table A2 summarizes the important system parameters for sizing the reboiler for a duty of 107 MWt thermal power extraction (from cold reheat) for use at the hydrogen production facility. Note: Results are rounded and vary slightly between the cases with draining to the condenser vs. heater drain tank.

Table A2: Summary of Parameters for 107 MWt Thermal Power Extraction (Cold Reheat Case)

	Mass Flow Rate (lbm/hr)	Temperature (°F)	Pressure (psia)
Steam Supply from Cold Reheat	395,000	~374	~183
Steam Supply from Cold Reheat (at boiler)	395,000	~361	~154
Drain to Main Condenser / Heater Drain Tank	395,000	200	by Vendor
Demineralized Water Supply	350,000	178	145
Steam Supply to H2 Production Facility	350,000	344	125



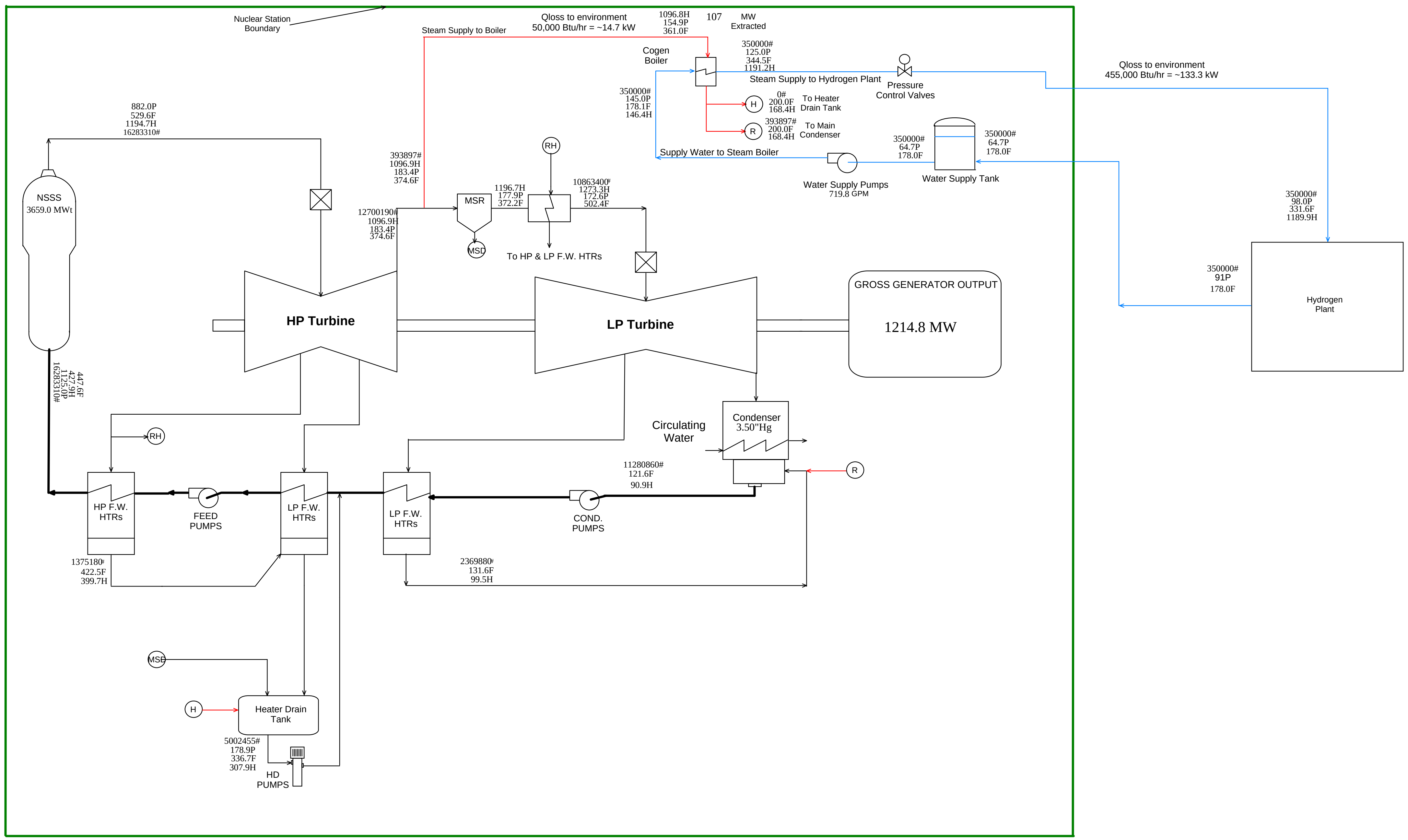
Turbine Cycle Heat Balance

CLTP

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

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

Prepared by:	Date:
Reviewed by:	Date:



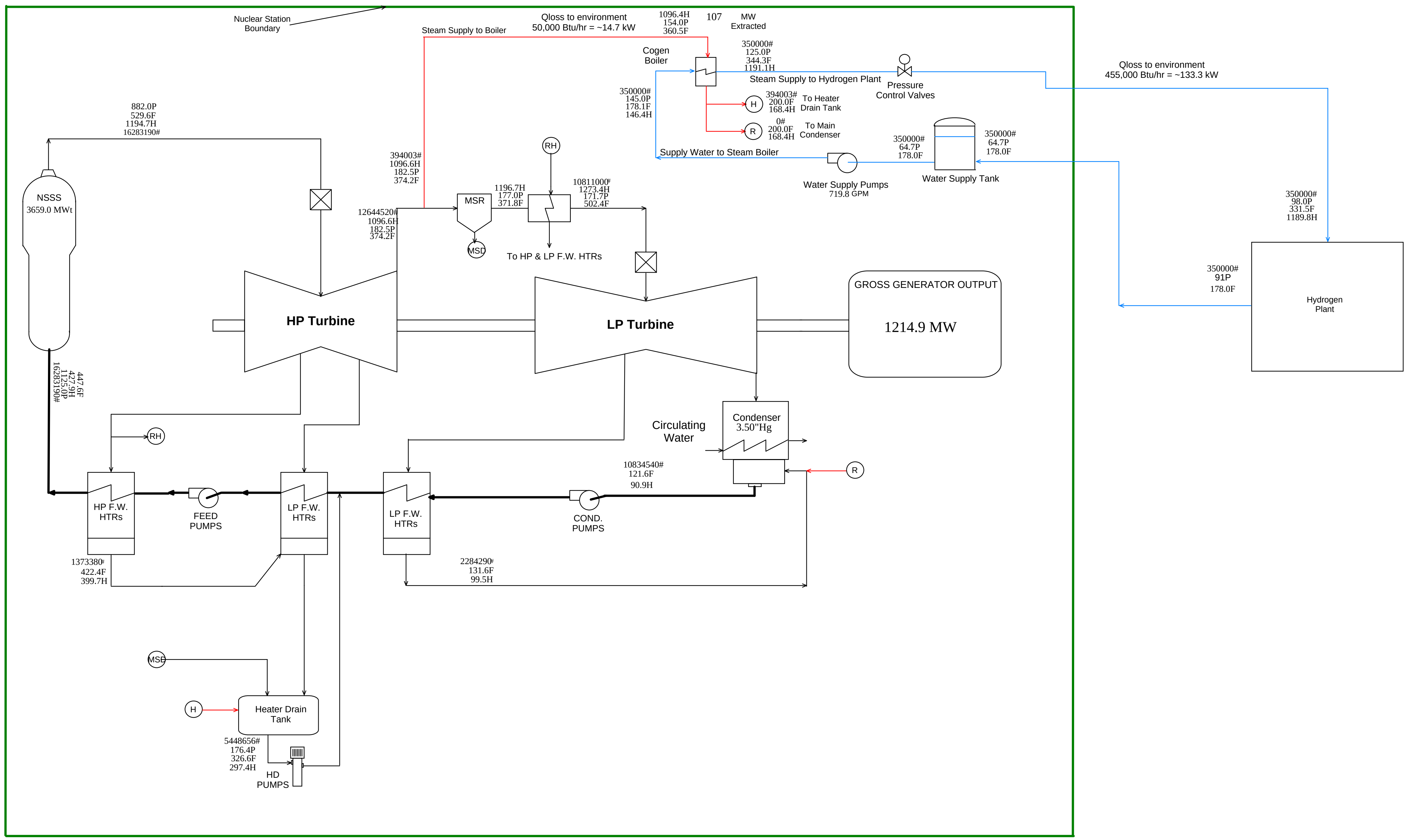
Turbine Cycle Heat Balance

Cogen Thermal Extraction - Cold Reheat to Condenser

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

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

Prepared by:	Date:
Reviewed by:	Date:



Turbine Cycle Heat Balance

Cogen Thermal Extraction - Cold Reheat to HDT

P - Pressure, psia	MW - Megawatts
F - Temperature, F	MWs - Megawatts Shaft Power
H - Enthalpy, Btu/lbm	MWt - Megawatts Thermal
# - Flow Rate, lbm/hr	
× - Quality	

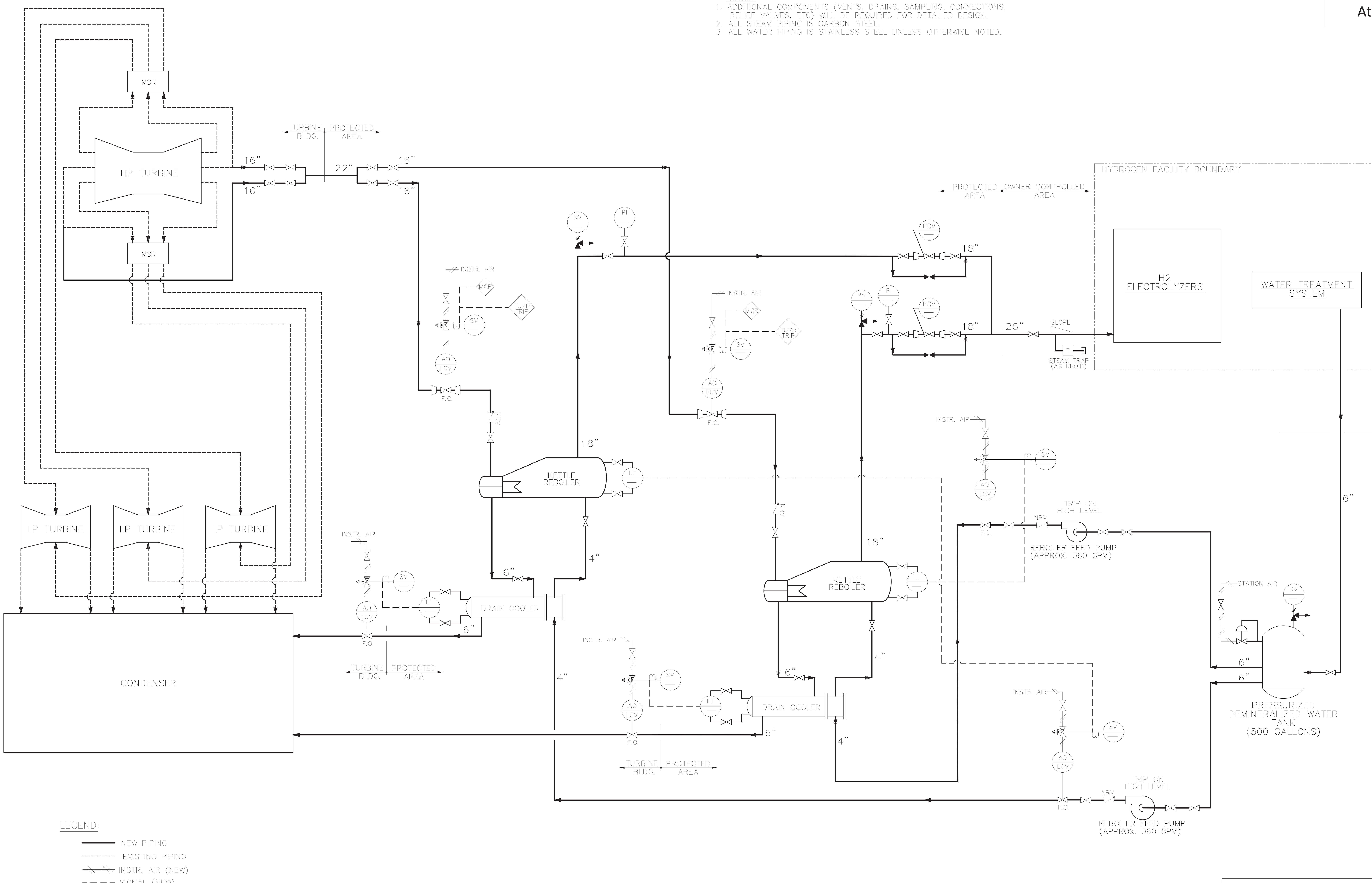
Prepared by:	Date:
Reviewed by:	Date:

Attachment B. Thermal Extraction Piping and Instrumentation Diagram

(1 Page)

SL-018670, Rev 1
Attachment B

NOTES:
1. ADDITIONAL COMPONENTS (VENTS, DRAINS, SAMPLING, CONNECTIONS, RELIEF VALVES, ETC) WILL BE REQUIRED FOR DETAILED DESIGN.
2. ALL STEAM PIPING IS CARBON STEEL.
3. ALL WATER PIPING IS STAINLESS STEEL UNLESS OTHERWISE NOTED.



THERMAL EXTRACTION P&ID
FOR 500 MW
H2 PRODUCTION FACILITY

DRAWING NUMBER	SHEET NUMBER	REV
INL-HTE-PID-001	N/A	0

Attachment C. Pipe Sizing Evaluations

Appendices (13 Pages Total):

C.i.1.0 Purpose

The purpose of this attachment is to size the thermal extraction steam piping to the H2 plant steam generator. This extraction steam is to be taken from the HP Turbine exhaust and routed to the new heat exchanger (H2 plant steam generator/boiler). The pipe is sized to deliver the required steam flow based on the PEPSE Heat balance [Ref. C.i.5.1] with a maximum steam velocity of 150 ft/sec [Ref. C.i.5.3].

C.i.2.0 Methodology

The simplified model is developed in the Arrow computer software [Ref. C.i.5.2] to size the extraction steam piping with the maximum steam velocities of 150 ft/sec [Ref. C.i.5.3]. Steam inlet conditions are based on the PEPSE heat balance [Ref. C.i.5.1]. The extraction steam pipe length, valves, and fittings are based on Assumption C.i.4.1. The piping is assumed to be insulated by 4.5 inches of Calcium Silicate based on Assumption C.i.4.2. The turbine building temperature and air velocity are based on Assumption C.i.4.3.

Note that two extraction points are considered, each with 50% of the steam flow. The piping then headers together for the majority of the pipe run. The pipe then splits to provide connections to each of the reboilers. An Arrow model diagram is attached.

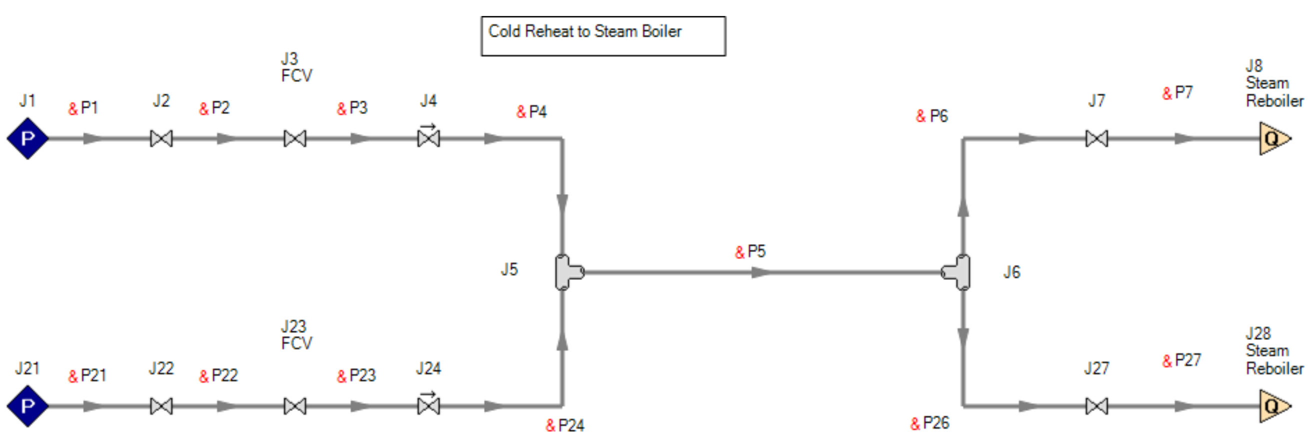
C.i.3.0 Inputs

C.i.3.1 Steam inlet conditions are based on Stream 810 of the PEPSE heat balance [Ref. C.i.5.1]. Steam conditions are rounded slightly and apply to both the “Cold Reheat to Condenser” and “Cold Reheat to Heater Drain Tank” PEPSE cases.

- Flow: 395,000 lbm/hr (197,500 lbm/hr per train)
- Pressure: 182.5 psia
- Temperature: 374.5°F

C.i.4.0 Assumptions

C.i.4.1 Extraction piping length, valves, and fittings are assumed based on the diagram shown below. Fitting losses are taken from Reference C.i.5.4 unless otherwise noted:



Input data for pipes is listed below.

Pipe	Length (ft)	Losses	Fittings and Losses Total K per Pipe
P1, P2, P3, P4, P6, P21, P22, P23, P24, P26	10	2x 90° Elbows (r/D=1.5)	0.36
P7, P27	10	2x 90° Elbows (r/D=1.5), Exit Loss	1.36
P5	200	10x 90° Elbows (r/D=1.5)	1.68

Valves: J2, J7, J22, and J27 are gate valves (K: 0.104 per valve).

Flow Control Valves: J3 and J23 are assumed to have a constant pressure drop of 20 psid.

Check Valves: J4 and J24 are stop check globe valves ($K = 400*f_T = 5.1$ per valve).

C.i.4.2 Pipe insulation is assumed to be Calcium Silicate, 4.5 inches in thickness. Insulation properties are based on the Arrow built-in properties [Ref. C.i.5.2].

C.i.4.3 The turbine building temperature is assumed to be 70°F and the air velocity is assumed to be 1 ft/sec (0.7 mph). These conditions are reasonable for the typical Turbine Building during winter operation.

C.i.4.4 All piping elevations are assumed to be at same elevation of 0 ft, which is reasonable since piping elevations have negligible impact on the system design of steam systems.

C.i.5.0 <u>References</u>

C.i.5.1 PEPSE Heat Balances as shown in Attachment A

C.i.5.2 Arrow computer software version 7, (S&L Program No. 03.7.722-7.0-08/06/2018)

C.i.5.3 S&L Standard MES 2.11, "Recommended Allowable Velocities in Piping Systems"

C.i.5.4 Crane Technical Paper 410, 2012 Edition

C.i.6.0 <u>Results</u>

The Arrow model for the extraction steam to the H2 plant steam generator was developed and iterated until the final pipe sizes are determined.

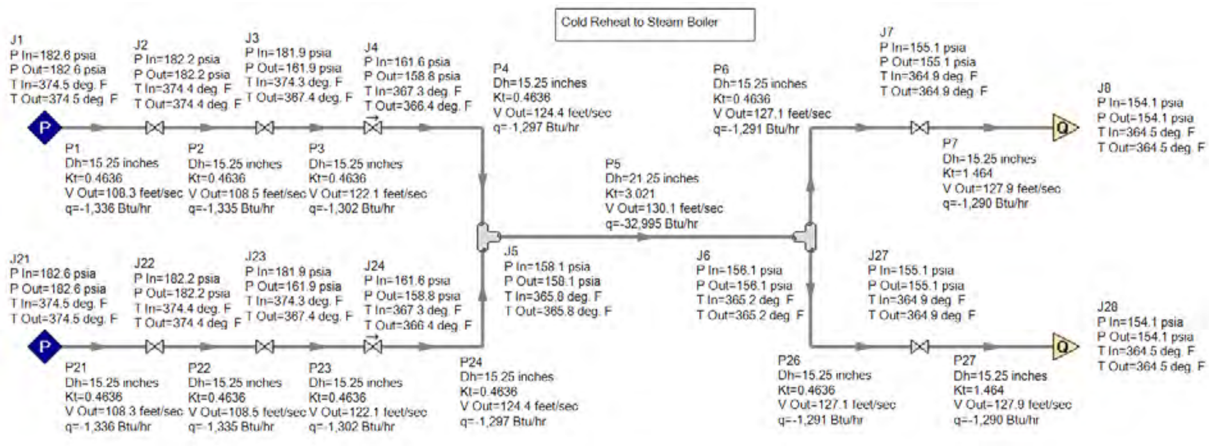
A final common pipe size of 22-inch (common 200 ft length pipe) and 16-inch branches (60 ft for each train), STD schedule, were modeled and resulted in a maximum steam velocity of ~130 ft/sec. The estimated heat loss from the pipe walls is ~50,000 Btu/hr. The total pressure drop is 28.5 psi (182.6 psia – 154.1 psia). These values are input into the PEPSE model [Ref. C.i.5.1].

A design pressure of 200 psig and design temperature of 400°F would envelop the conditions shown.

ATTACHMENT C.i

THERMAL EXTRACTION - EXTRACTION STEAM PIPE SIZING – COLD REHEAT

Detailed results are shown on the diagram below:



ATTACHMENT C.ii
THERMAL EXTRACTION PROCESS STEAM PIPE SIZING

C.ii.1.0 Purpose

The purpose of this attachment is to size the process steam piping to the H2 plant. This process steam is to be taken from the Process Steam Generator/Boiler and routed to the H2 plant (~500 meters away). The pipe is sized to deliver the required steam flow based on the Process Model Inputs [Ref. C.ii.5.5] with a maximum steam velocity of 150 ft/sec [Ref. C.ii.5.3].

C.ii.2.0 Methodology

A simplified model is developed in the Arrow computer software [Ref. C.ii.5.2] to size the process steam piping with maximum steam velocities of 150 ft/sec [Ref. C.ii.5.3]. Steam inlet conditions are iterated in order to achieve the required steam conditions at the H2 plant provided in the Process Model Inputs [Ref. C.ii.5.5]. The process steam pipe length, valves, and fittings are based on Assumption C.ii.4.1. The piping is assumed to be insulated by 4.5 inches of Calcium Silicate based on Assumption C.ii.4.2. The outside air temperature and air velocity are based on Assumption C.ii.4.3. Heat loss and pressure drop through the piping is input in the PEPSE model [Ref. C.ii.5.1].

Note that two flow paths from the boiler combine into one pipe before flowing to the H2 plant.

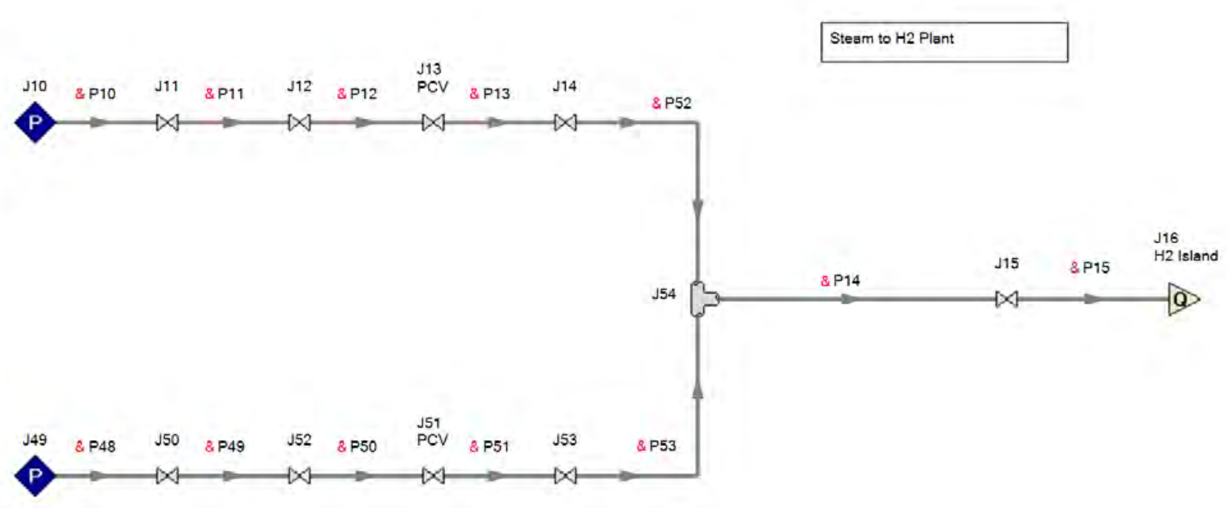
C.ii.3.0 Inputs

C.ii.3.1 The required steam flow rate to the H2 plant is 350,000 lbm/hr, based on the value from the Process Model Inputs [Ref. C.ii.5.5] with margin added.

C.ii.3.2 The required steam conditions at the H2 plant are 324°F and 80 psig (94.7 psia) [Ref. C.ii.5.5].

C.ii.4.0 Assumptions

C.ii.4.1 Extraction piping length, valves, and fittings are assumed based on the diagram shown below. Fitting losses are taken from Reference C.ii.5.4 unless otherwise noted.



Input data for pipes is listed below.

Pipe	Length (ft)	Losses	Fittings and Losses Total K per Pipe
P10, P11, P12, P13, P48, P49, P50, P51, P52, P53	10	2x 90° Elbows (r/D=1.5)	0.35
P15	10	2x 90° Elbows (r/D=1.5), Exit Loss	1.34
P14	1700	20x 90° Elbows (r/D=1.5)	3.36

Valves: J11, J12, J14, J50, J52, J53, and J15 are gate valves (each K: 0.10)

Pressure Control Valves: J13 and J51 are assumed to have a constant pressure drop of 20 psid.

C.ii.4.2 Pipe insulation is assumed to be Calcium Silicate, 4.5 inches in thickness. Insulation properties are based on the Arrow built-in properties [Ref. C.ii.5.2].

C.ii.4.3 Outside air temperature is assumed to be -10°F and air velocity is assumed to be 50 ft/sec (34 mph). These conditions are reasonable for the typical winter in a cold climate.

C.ii.4.4 All piping elevations are assumed to be at same elevation of 0 ft, which is reasonable since the piping elevations for steam systems have negligible impact on the system design.

C.ii.5.0 References

C.ii.5.1 PEPSE Heat Balances as shown in Attachment A

C.ii.5.2 Arrow computer software version 7 (S&L Program No. 03.7.722-7.0-08/06/2018)

C.ii.5.3 S&L Standard MES 2.11, "Recommended Allowable Velocities in Piping Systems"

C.ii.5.4 Crane Technical Paper 410, 2012 Edition

C.ii.5.5 Process Model Inputs (Process Model Inputs_Calcs_20240301.xlsx)

C.ii.6.0 Results

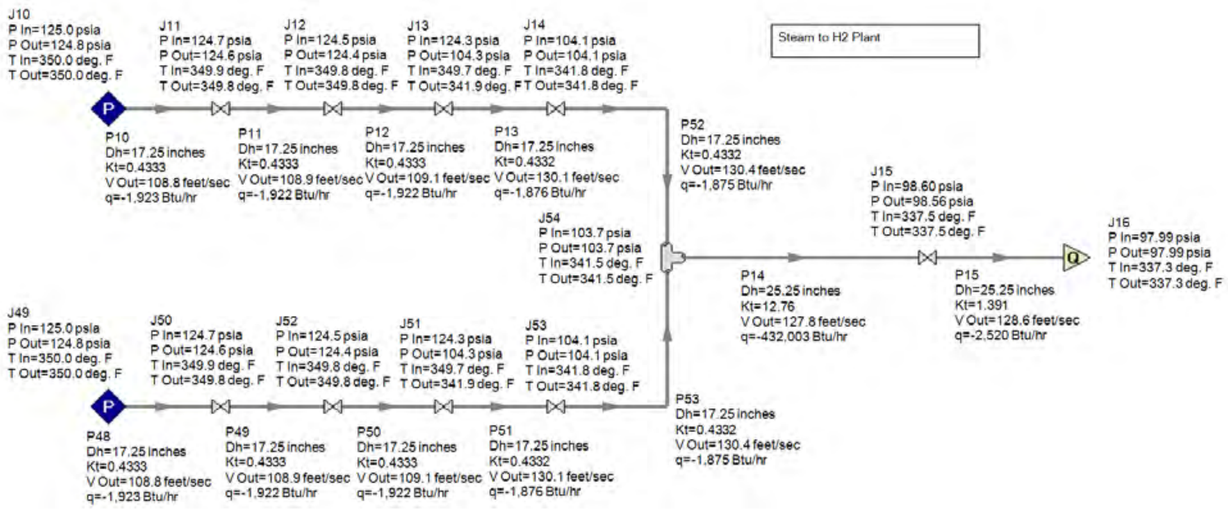
The Arrow model for the process steam to the H2 plant was developed and iteratively changed until the final pipe sizes are determined. The steam inlet conditions which ensure margin to the required steam conditions at the H2 plant (324°F and 80 psig per Input C.ii.3.2) are 125.0 psia (110.3 psig) and 350°F.

Boiler to H2 plant:

Pipes carrying half of the steam flow are chosen to be STD schedule 18-inch pipe (100 ft total length), resulting in a maximum steam velocity of ~131 ft/sec. The pipe carrying the full steam flow to the H2 plant is chosen to be STD schedule 26-inch pipe (1710 ft total length), resulting in a maximum steam velocity of ~129 ft/sec. The estimated total heat loss from the pipe is ~455,000 Btu/hr. The total pressure loss is 27 psi (125.0 psia – 98.0 psia).

A design pressure of 150 psig and design temperature of 400°F would envelop the conditions shown.

Detailed results are shown on the diagram below:



C.iii.1.0 Purpose

The purpose of this attachment is to size the reboiler feed water pump and piping to the H2 plant steam generator (reboiler), the water return line from the H2 plant to the pressurized storage tank, and the tank volume. Water returns to the pressurized storage tank from the H2 plant and is then routed to the two new pumps which deliver the water to the two new heat exchangers (H2 plant steam generators / boilers). Each reboiler feed water pipe is sized to deliver the required water flow based on the Process Model Inputs [Ref. C.iii.5.5] with the water velocity below 10 ft/sec based on general service piping recommendation [Ref. C.iii.5.3].

C.iii.2.0 Methodology

The simplified model is developed in the Fathom computer software [Ref. C.iii.5.2] to keep water velocities in piping below 10 ft/sec and as low as ~4 ft/sec for pump suction lines [Ref. C.iii.5.3]. The required water flow rate is taken from the Process Model Inputs [Ref. C.iii.5.5]. Water storage tank conditions are taken from the Process Model Inputs Heat Recovery Cases [Ref. C.iii.5.5]. The pipe length, valves, and fittings are based on Assumption C.iii.4.1. Heat transfer from the piping is included in the model. Results from this attachment are input into the PEPSE model [Ref. C.iii.5.1].

The volume of the pressurized storage tank is calculated to contain an increase in water volume due to thermal expansion. The increase in the volume of water from 32°F (minimum water temperature) to 267°F (maximum water temperature per Input C.iii.3.2) is applied to the total fluid volume in the system piping.

Note that two identical reboiler feed water pump trains are proposed, and each train representing 50% of duty is modeled in AFT Fathom.

C.iii.3.0 Inputs

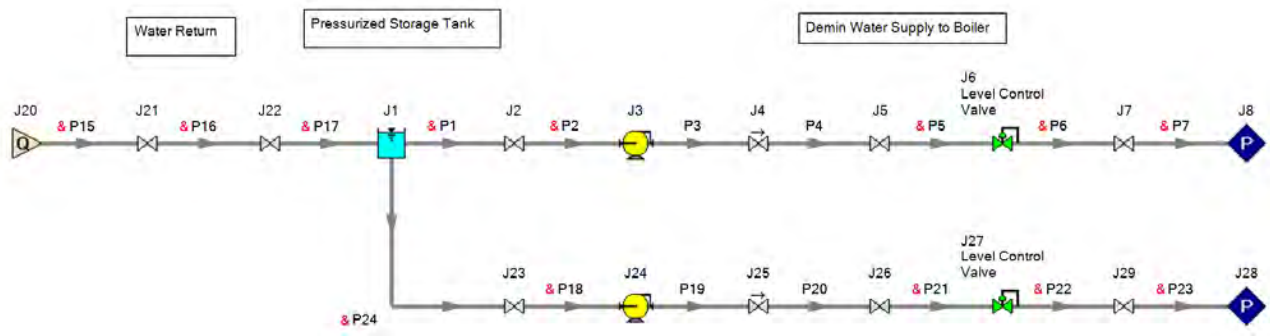
C.iii.3.1 The required water flow rate (J20) is 350,000 lbm/hr. This value is based on the input from the Process Model Inputs [Ref. C.iii.5.5] with margin added.

C.iii.3.2 The system water temperature of 179°F is based on the heat recovery cases from the Process Model Inputs [Ref. C.iii.5.5] at the maximum H2 flow. The maximum water return temperature is 267°F at 10,000 lbm/hr [Ref C.iii.5.5].

C.iii.3.3 The specific volume of water is 0.016022 ft^3/lb at 32°F and ~0.01715 ft^3/lb at 267°F (interpolated between 0.017084 ft^3/lb and 0.017170 ft^3/lb at 260°F and 270°F) [Ref. C.iii.5.4].

C.iii.4.0 Assumptions

C.iii.4.1 The reboiler feed water piping length, valves, and fittings are assumed based on the diagram shown below. Fitting losses are taken from Reference C.iii.5.4 unless otherwise noted.



Input data for pipes is listed below.

Pipe	Length (ft)	Losses	Fittings and Losses Total K per Pipe
P1, P24	20	2x 90° Elbows (r/D=1.5), Entrance Loss	0.92
P2, P18	20	2x 90° Elbows (r/D=1.5)	0.42
P3, P4, P19, P20	10	-	-
P5, P21	200	10x 90° Elbows (r/D=1.5)	2.38
P6, P22	10	2x 90° Elbows (r/D=1.5)	0.48
P7, P23	10	2x 90° Elbows (r/D=1.5), Exit Loss	1.48
P15	10	2x 90° Elbows (r/D=1.5)	0.42
P16	1700	20x 90° Elbows (r/D=1.5)	4.19
P17	10	2x 90° Elbows (r/D=1.5), Exit Loss	1.42

Valves J2, J5, J7, J23, J26, and J29 are gate valves (K: ~0.1 each). Level Control Valves J6 and J27 are assumed to have a constant pressure drop of 20 psid, which should enable reasonable control of the valves. Check Valves J4 and J25 are swing check valves with 90 deg. seats (K: 0.9 each).

C.iii.4.2 The reboiler (J8, J28) pressure is set at 145 psia to allow for an assumed dP of 20 psid across the boiler. This is consistent with the PEPSE heat balance [Ref. C.iii.5.1].

C.iii.4.3 All piping elevations are assumed to be at same elevation of 0 ft, which is reasonable since the new equipment is expected to be at similar elevations. During the detailed design phase, actual pipe routing and elevations need to be utilized.

C.iii.4.4 The pump efficiency is assumed to be 80%.

C.iii.4.5 The following pressurized storage tank (J1) conditions are assumed:

- Tank Water Level: 5 ft
- Tank Surface Pressure: 50 psig, chosen to prevent flashing of hot water in the tank

C.iii.4.6 Pipe insulation is assumed to be Calcium Silicate, 2 inches in thickness. Insulation properties are based on the Fathom built-in properties [Ref. C.iii.5.2].

C.iii.4.7 The air temperature is assumed to be -10°F and air velocity is assumed to be 50 ft/sec (34 mph). These conditions are reasonable for the typical winter in a cold climate.

C.iii.4.8 Pump shutoff head is assumed to be 50% higher than pump head at its design flow rate.

C.iii.5.0 **References**

C.iii.5.1 PEPSE Heat Balances as shown in Attachment A

C.iii.5.2 AFT Fathom computer software version 11, (S&L Program No. 03.7.721-11-06/18/2020)

C.iii.5.3 S&L Standard MES 2.11, “Recommended Allowable Velocities in Piping Systems”

C.iii.5.4 Crane Technical Paper 410, 2012 Edition

C.iii.5.5 Process Model Inputs (Process Model Inputs_Calcs_20240301.xlsx)

C.iii.6.0 **Results**

The Fathom model was iterated to determine the final pipe sizes.

C.iii.6.1 Pipe Size:

For the water return line, a 6-inch diameter carbon steel pipe (STD schedule) was modeled, resulting in a maximum water velocity of ~8 ft/sec. A pressure of 91 psia at the H2 plant exit is required to return water to the Pressurized Storage Tank. Assuming a 50% shutoff head margin for the H2 plant pump, the maximum pressure is 137 psia. Given the maximum pressure of 137 psia and maximum temperature of 267°F (Input C.iii.3.2), a design pressure of 150 psig and design temperature of 275°F would envelop the above conditions.

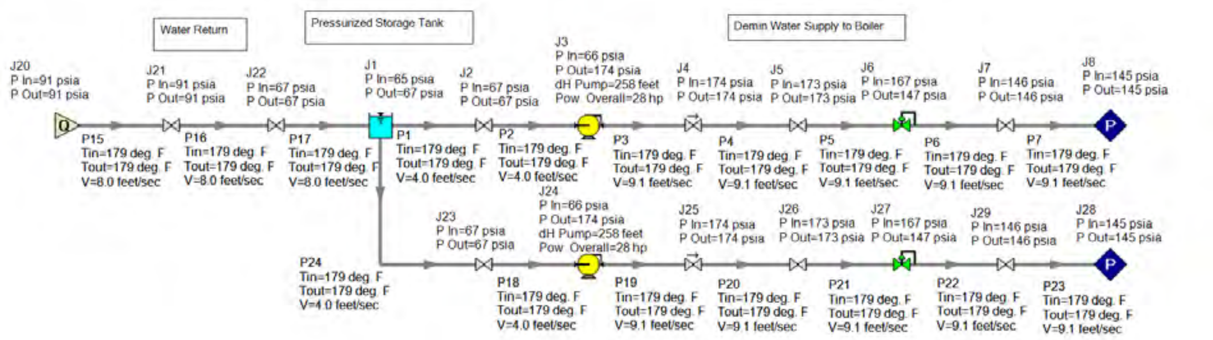
For the water supply to the boiler, the pump suction lines are 6-inch diameter carbon steel pipe (STD schedule) and have a maximum velocity of ~4 ft/sec. The pump discharge lines are 4-inch diameter carbon steel pipe (STD schedule) and have a maximum velocity of ~9 ft/sec. Note that check valve minimum flow velocity should be considered during equipment selection. Given a maximum pressure of 67 psia upstream of the pump and 230 psia downstream of the pump (upstream pressure plus 50% margin for shutoff head allowance applied to pump pressure rise of 109 psid), design pressures of 75 psig for the pump suction and 250 psig for the pump discharge would envelop the above conditions. With a maximum temperature of 267°F, a design temperature of 275°F is chosen.

The total length of 6-inch diameter carbon steel pipe (STD schedule) is 1800 ft, and the total length of 4-inch diameter carbon steel pipe (STD schedule) is 480 ft.

C.iii.6.2 Pump Size:

The initial pump sizing is based on the nominal flowrate of 360 gpm (at 179°F) along with the nominal carbon steel pipe characteristics and resulted in a required pump total developed head of ~260 ft with a horsepower requirement of ~29 hp. Note that the final pump sizing needs to consider appropriate design margin, NPSH requirements, and maximum temperatures.

Detailed results are shown on the diagram below:



C.iii.6.3 Temperature:

The final temperature of 178°F is input into the PEPSE model [Ref. C.iii.5.1].

C.iii.6.4 Pressurized Storage Tank Size:

Given that the specific volume of water is 0.016022 ft^3/lb at 32°F (minimum water temperature) and ~0.01715 ft^3/lb at 267°F (maximum water temperature), thermal expansion could increase the volume of water in the system by a maximum of 7.04%. Fathom results indicate that the total volume of fluid in the system is 403.6 ft^3, which would become 432.0 ft^3 when increased by 7.04%. With 100% margin on the total volume increase of 28.4 ft^3, the calculated volume of the pressurized storage tank is 57 ft^3 (426 gallons).

C.iv.1.0 Purpose

The purpose of this attachment is to size the reboiler drain piping from the H2 plant steam generator (reboiler) to the main condenser and heater drain tank. Additionally, the required differential pressure across the level control valve is determined. The pipes are sized to deliver the required water flow based on PEPSE Heat balance [Ref. C.iv.5.1] with the water velocity below 7 ft/sec based on heater drain piping recommendation [Ref. C.iv.5.3].

C.iv.2.0 Methodology

The simplified model is developed in the Fathom computer software [Ref. C.iv.5.2] to size the reboiler drain water piping with water velocities below 7 ft/sec [Ref. C.iv.5.3]. The required water flow rate, along with drain inlet and condenser / heater drain tank conditions, are taken from the PEPSE Heat Balance [Ref. C.iv.5.1]. The pipe length, valves, and fittings are based on Assumption C.iv.4.1. For the purpose of this analysis no heat transfer is modeled from the water piping. A pump is required in the case with flow to the heater drain tank to overcome the pressure differential.

Note that two identical trains are proposed, each with 50% of the water flow. Therefore, only one train representing 50% of duty is modeled in AFT Fathom.

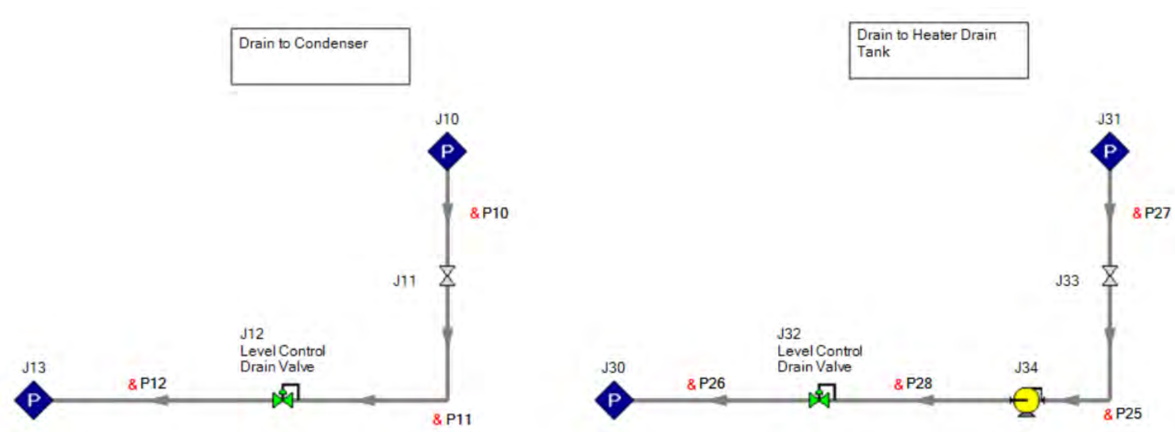
C.iv.3.0 Inputs

C.iv.3.1 The required water flow rate and boundary conditions are based on the PEPSE heat balance [Ref. C.iv.5.1] and rounded as necessary.

- Drain Flow: 395,000 lbm/hr total, 197,500 lbm/hr per train
- Drain Inlet Pressure: 155.9 psia
- Drain Inlet Temperature: 200°F
- Condenser Pressure: 1.7 psia (3.5 in HgA)
- Heater Drain Tank Pressure: 178.9 psia

C.iv.4.0 Assumptions

C.iv.4.1 The reboiler drain piping length, valves, and fittings are assumed based on the diagram shown below. Fitting losses are taken from Reference C.iv.5.4 unless otherwise noted:



Input data for pipes is listed below.

Pipe	Length (ft)	Losses	Fittings and Losses Total K per Pipe
P10, P27	10	2x 90° Elbows (r/D=1.5), Entrance Loss	0.92
P12, P26	10	2x 90° Elbows (r/D=1.5), Exit Loss	1.42
P28	10	2x 90° Elbows (r/D=1.5)	0.42
P11, P25	200	10x 90° Elbows (r/D=1.5)	2.1

Valve: J11 and J33 are gate valves (K: 0.12)

Drain Control Valve: J12 modeled to control the required drain flow.

Drain Control Valve: J32 modeled with an assumed constant pressure drop of 10 psid, which should enable reasonable control of the valve.

Pump: J34 modeled with fixed flow (see Input C.iv.3.1).

C.iv.4.2 All piping elevations are assumed to be at same elevation of 0 ft since it is expected that new equipment will be at a similar elevation. During the detailed design phase, actual pipe routing and elevations need to be utilized.

C.iv.4.3 The pump efficiency is assumed to be 80%.

C.iv.5.0 References

C.iv.5.1 PEPSE Heat Balances as shown in Attachment A

C.iv.5.2 AFT Fathom computer software version 11, (S&L Program No. 03.7.721-11-06/18/2020)

C.iv.5.3 S&L Standard MES 2.11, "Recommended Allowable Velocities in Piping Systems"

C.iv.5.4 Crane Technical Paper 410, 2012 Edition

C.iv.6.0 Results

The Fathom model for the condensate return from the reboiler to the main condenser and heater drain tank was developed and iterated until the final pipe sizes were determined. Note that two identical trains are proposed, each with 50% of the water flow. Results presented below are for a single train.

C.iv.6.1 Pipe Size:

The final drain pipe sizes of 6 inch, STD schedule, Carbon Steel were modeled and resulted in a maximum water velocity of ~4.5 ft/sec. The assumed piping length is 220 ft when draining to the condenser and 230 ft when draining to the heater drain tank. For the Drain to Condenser case, the maximum pressure is 156 psia, which would be covered by a design pressure of 200 psig. For the Drain to Heater Drain Tank case, the maximum pressure is 189 psia. Accounting for a 50% allowance for shutoff head on the pump dP of 35 psid, the maximum pressure would be 207 psia, which would be covered by a design pressure of 215 psig. A design temperature of 250°F would envelop the conditions shown.

C.iv.6.2 Drain Control Valve Size:

The drain control valve to the condenser (J12) sizing results in the following requirements:

- Drain Flow: 197,500 lbm/hr (409.6 gpm)
- Valve Pressure Drop: ~152.7 psid
- Valve Inlet Pressure: ~154.6 psia

Note that due to a very high valve dP, there is a high potential for valve cavitation, which should be considered when specifying the drain control valve. Also, the water is at an elevated temperature and low pressure and may flash unless precautions are taken.

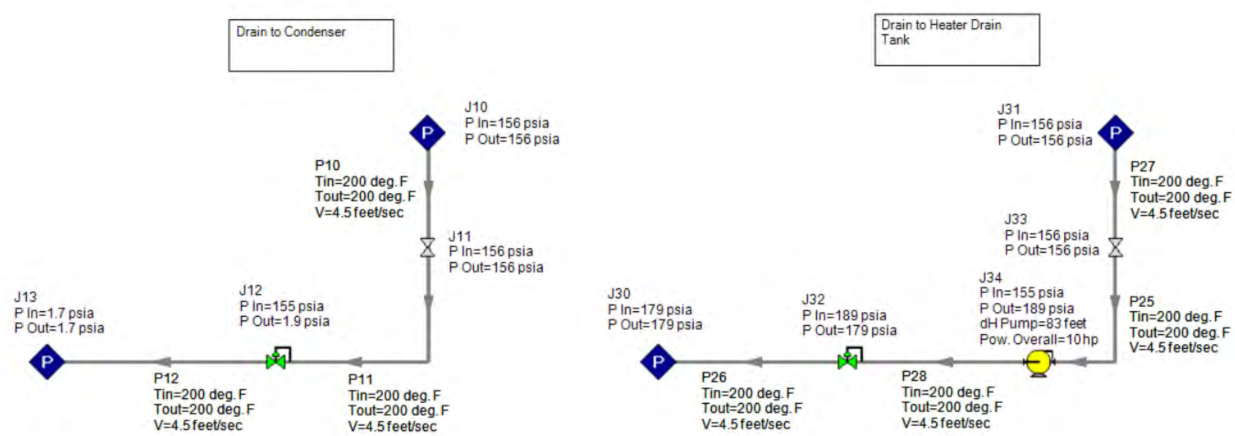
The drain control valve to the heater drain tank (J32) sizing results in the following requirements:

- Drain Flow: 197,500 lbm/hr (409.6 gpm)
- Valve Pressure Drop: 10.0 psid (assumed)
- Valve Inlet Pressure: ~189.1 psia

C.iv.6.3 Drain Pump Size:

The initial drain pump sizing is based on the nominal flowrate of 410 gpm (at 200°F) along with the nominal carbon steel pipe characteristics and resulted in a required pump total developed head of ~83 ft with a horsepower requirement of ~10.5 hp. Note that the final pump sizing needs to consider appropriate design margin, NPSH requirements, and maximum temperatures.

Detailed results are shown on the diagram below:



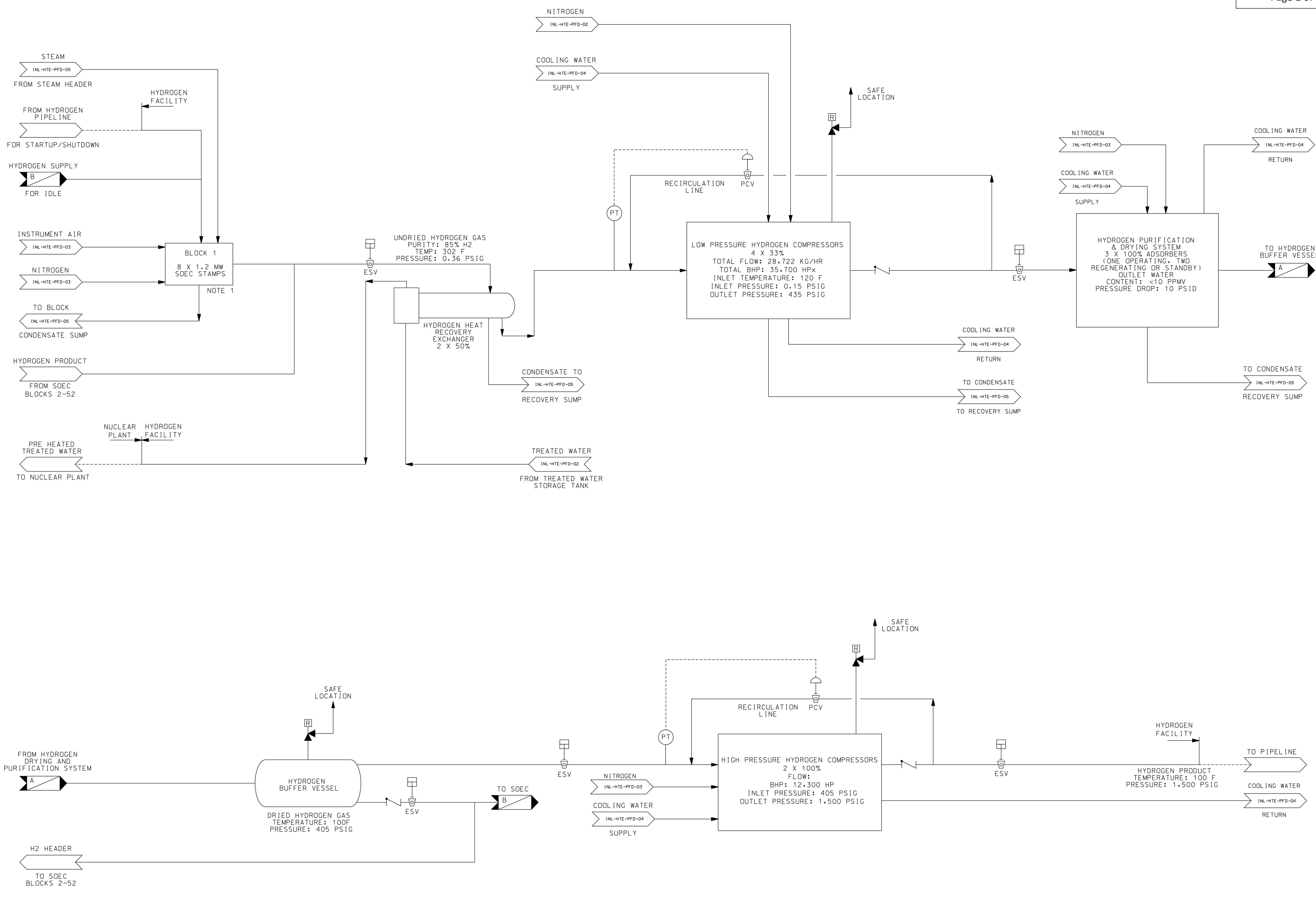
Attachment D. Steam Reboiler Arrangement Drawing

(1 Page)

SL-018670, Rev 1
Attachment D

Attachment E. Process Flow Diagrams

(5 Pages)



NOTES:
1. EACH BLOCK IS COMPRISED OF 8 X 1.2 MW NOMINAL SOEC UNITS. BLOCK 1 IS 1 OF 52.

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REVIEWED BY: MGP
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PROCESS FLOW DIAGRAM
HYDROGEN SYSTEM

DRAWING NUMBER	REVISION
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SHEET 1 OF 1

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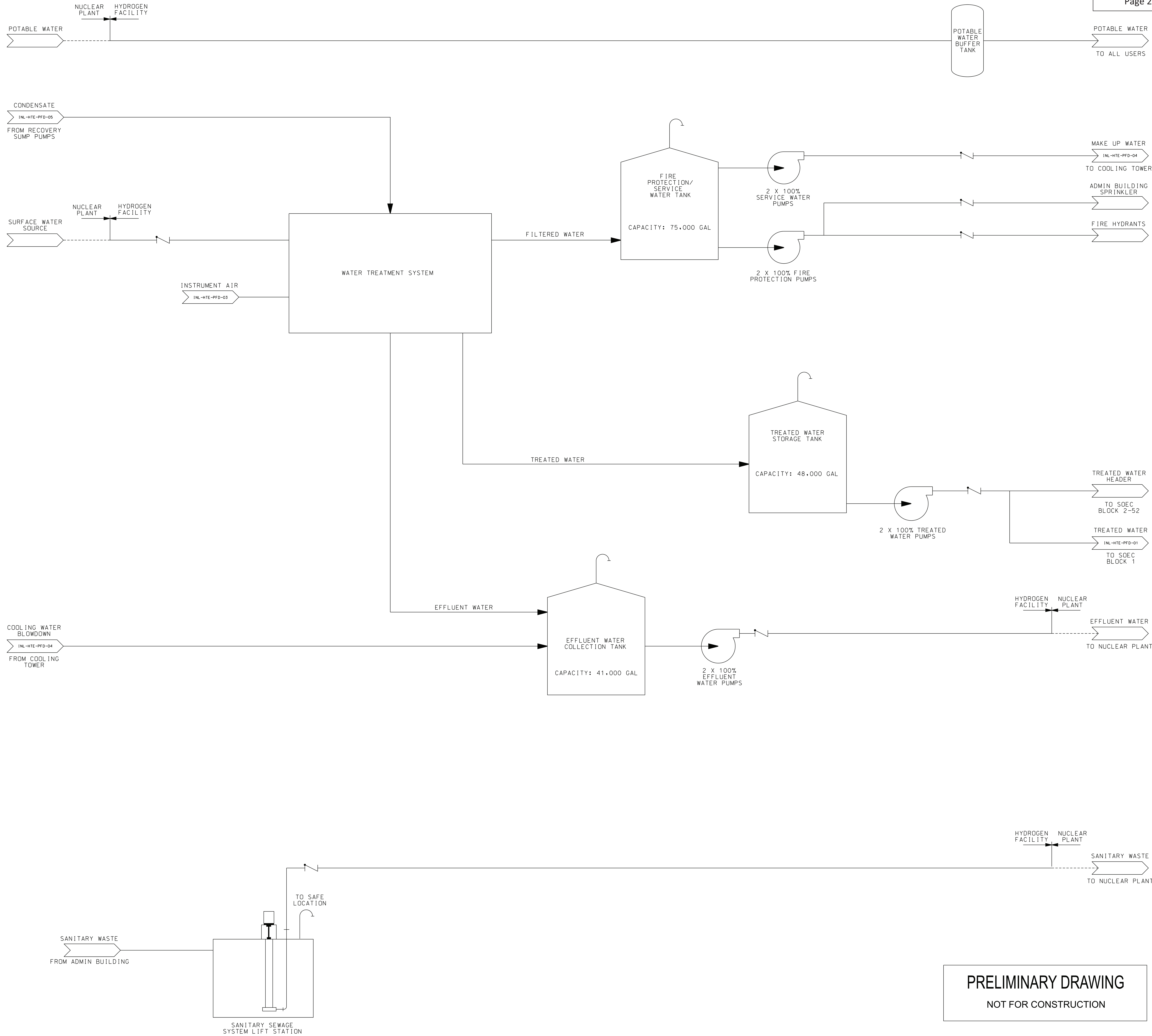
Form SDG-0401-01-08, ANSI (Imperial) MicroStation Border - Size E - 34 x 44
Revision 11A, Revision Date: 04-30-2010



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PROCESS FLOW DIAGRAM
WATER TREATMENT SYSTEM

DRAWING NUMBER	REVISION
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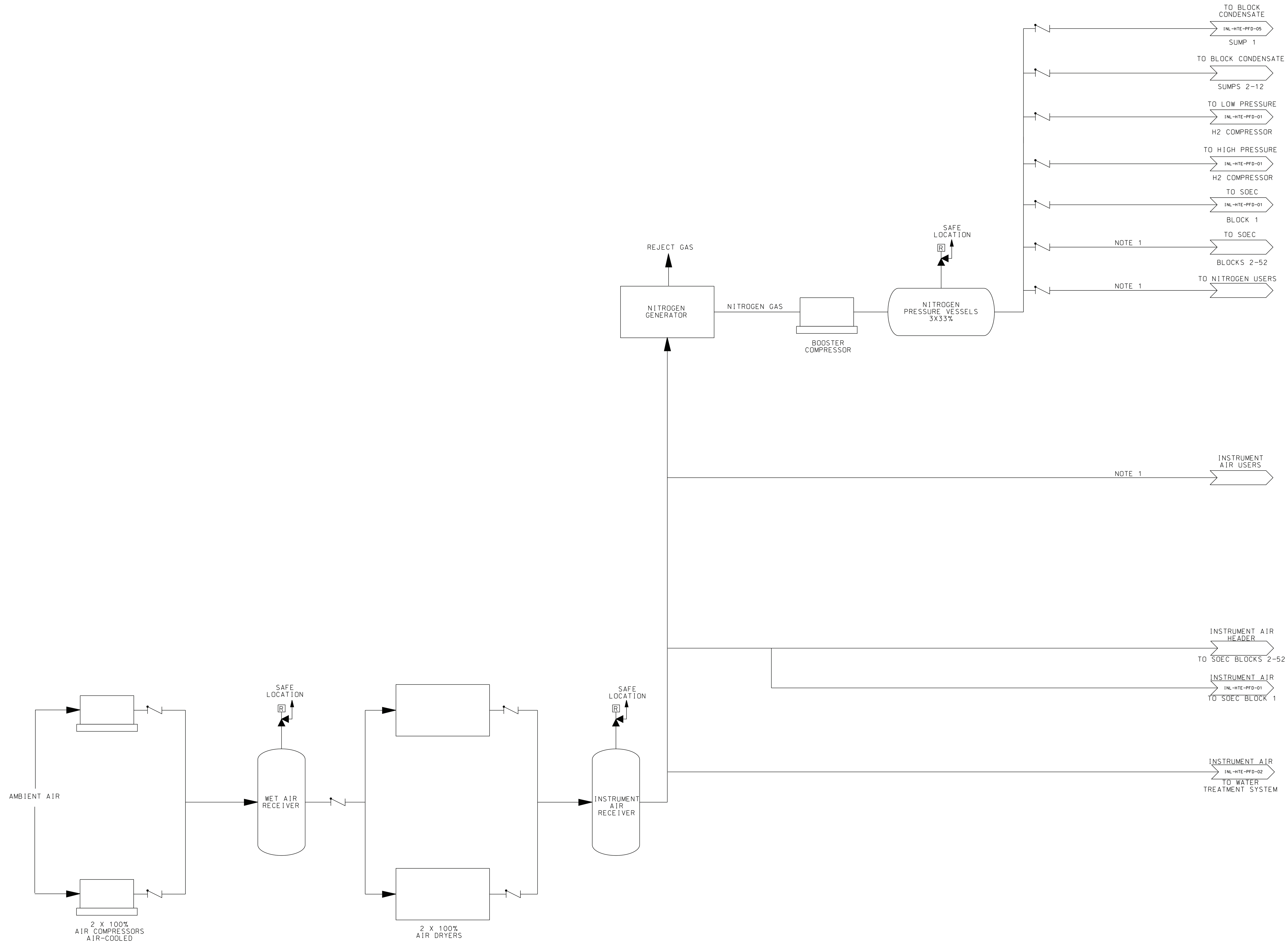
SHEET 1 OF 1



NOTES:
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PROCESS FLOW DIAGRAM
UTILITY GAS SYSTEMS

DRAWING NUMBER	REVISION
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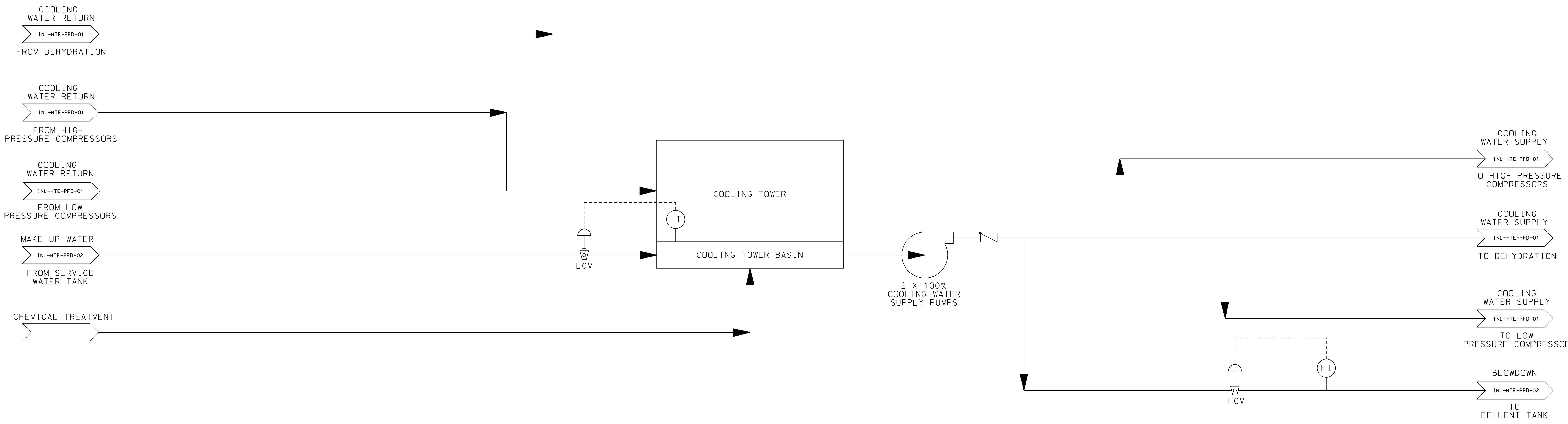

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PROCESS FLOW DIAGRAM
COOLING WATER SYSTEM

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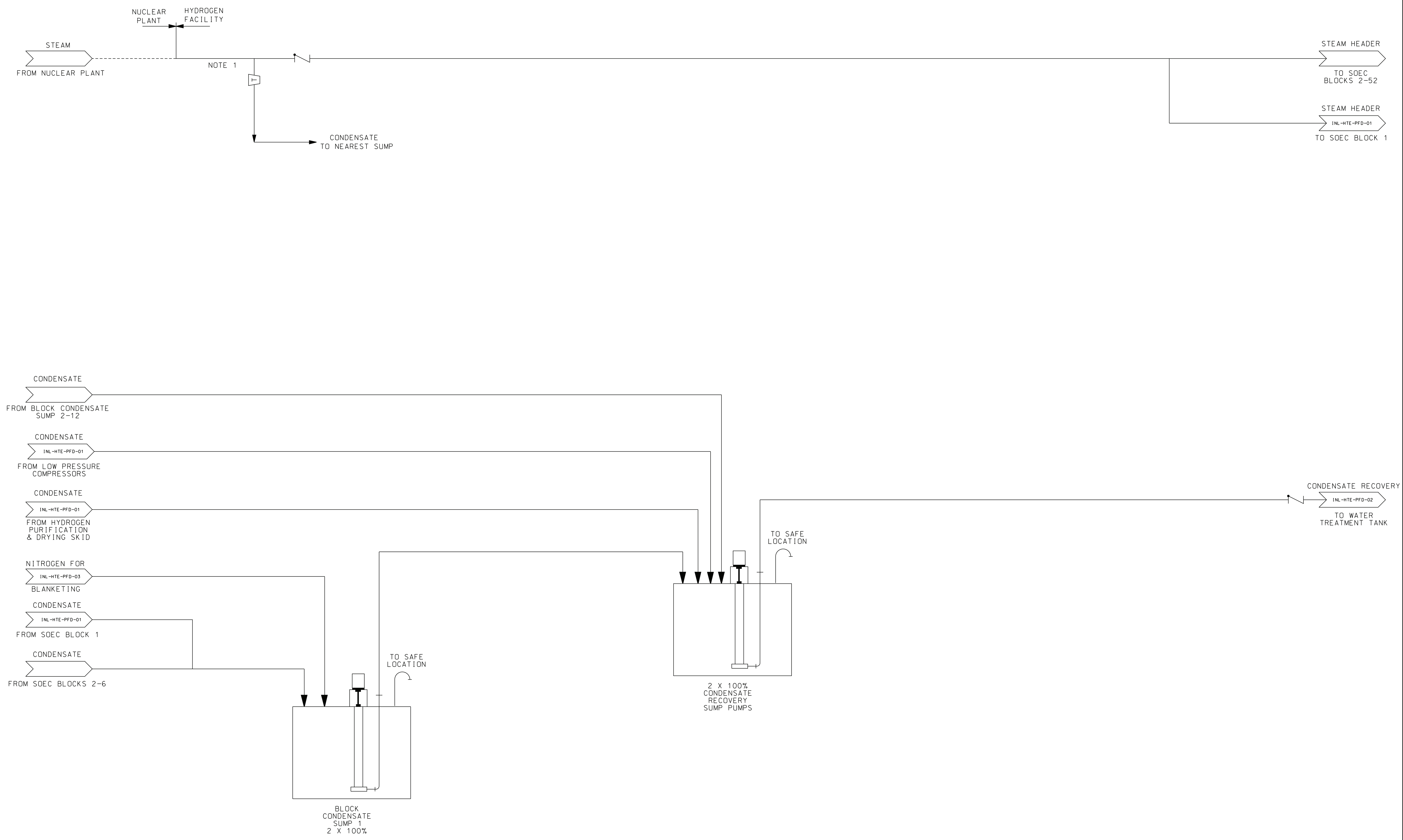

NOTES:
1. STEAM LINE WILL BE INSULATED AND SLOPED WITH STEAM TRAPS AS REQUIRED BETWEEN NPP AN HYDROGEN FACILITY.TRAPS WILL BE ROUTED TO ONE VESSEL TO THE NEAREST SUMP. QUANTITY OF STEAM TRAPS IS TBD.

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PROCESS FLOW DIAGRAM
STEAM AND CONDENSATE SYSTEMS

DRAWING NUMBER	REVISION
INL-HTE-PFD-05	1

SHEET 1 OF 1

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Attachment F. Mechanical Equipment List

(2 Pages)

Item #	Equipment Tag #	Description	Drawing No.	System	Quantity	Redundancy	Operating Conditions	Operating Voltage	Estimated Load (Each)	Estimated Load (Total)	Remarks
1	INL-E-001	SOEC Electrolyzer Block (8 x 1.2 MW SOEC Stamps)	INL-HTE-PFD-01	HYDROGEN	52	1 x 100%	Flowrate: 34789.1 kg/hr (total) Discharge Pressure: 0.36 psig Discharge Temperature: 302°F	34.5 kV	9.6 MW	499.2 MW	Load based on beginning of life.
2	INL-HE-001	Hydrogen Heat Recovery Exchanger	INL-HTE-PFD-01	HYDROGEN	2	2 x 50%	Water Flowrate: 342,918 lb/hr Water Temp. In / Out: 78°F / 186.5°F Product Gas Flowrate: 76,697 lb/hr Product Gas Temp. In / Out: 302°F / 120°F	-	-	-	
3	INL-C-001	LP Hydrogen Compressor	INL-HTE-PFD-01	HYDROGEN	4	4 x 33%	Flowrate In: 28,721.9 kg/hr Inlet Pressure: 0.15 psig Inlet Temp: 120 F Outlet Pressure: 435 psig	13.8 kV	11,900 HP	35,700 HP	
4	INL-A-001A/B/C	Adsorbers (Hydrogen Purification and Drying System)	INL-HTE-PFD-01	HYDROGEN	4	4 x 33%	By Vendor	4.16 kV	350 KW	1050 KW	
5	INL-HBV-001	Hydrogen Buffer Vessel	INL-HTE-PFD-01	HYDROGEN	1	1 x 100%	Capacity: 800 gallons 4.6' dia x 11.2' long	-	-	-	
6	INL-C-002A/B/C	HP Hydrogen Compressors	INL-HTE-PFD-01	HYDROGEN	2	2 x 100%	Flowrate In: 13,312 kg/hr Inlet Pressure: 405 psig Inlet Temp: 100 F Outlet Pressure: 1,500 psig	13.8 kV	12,300 HP	12,300 HP	
7	INL-WT-001	Water Treatment System	INL-HTE-PFD-02	WATER TREATMENT	1	1 x 100%	Capacity: 1,400 gpm	4.1 kV	1309 HP	1309 HP	
8	INL-T-001	Treated Water Storage Tank	INL-HTE-PFD-02	WATER TREATMENT	1	1 x 100%	Capacity: 48,000 gallons 18.5' dia x 24' ht	480 V	30 KW	30 KW	1 Hour Capacity
9	INL-P-001A/B	Treated Water Pumps	INL-HTE-PFD-02	WATER TREATMENT	2	2 x 100%	Flowrate: 684.81 gpm Required Head: 180 ft Efficiency: 75%	480 V	50 HP	50 HP	500 ft length 10 ft elevation 90 psig BL pressure
10	INL-T-003	Effluent Water Collection Tank	INL-HTE-PFD-02	WATER TREATMENT	1	1 x 100%	Capacity: 41,000 gallons 21' dia x 16' ht	480 V	10 KW	20 KW	1.5 Hour Capacity
11	INL-P-007A/B	Effluent Water Pumps	INL-HTE-PFD-02	WATER TREATMENT	2	2 x 100%	Flowrate: 380 gpm Required Head: 55 ft Efficiency: 75%	480 V	5 HP	7.5 HP	500 ft length 10 ft elevation
12	INL-P-008	Block Condensate Sump Pumps		WATER TREATMENT	24	2 x 100%	Flowrate: 50 gpm Required Head: 52 ft Efficiency: 75%	480 V	2 HP	24 HP	675 ft length 20 ft elevation
13	INL-T-002	Fire Protection/Service Water Tank	INL-HTE-PFD-02	WATER TREATMENT	1	None	Capacity: 75,000 gallons 23.5' dia x 24' ht	480 V	40 KW	40 KW	
14	INL-P-002A/B	Service Water Pumps	INL-HTE-PFD-02	WATER TREATMENT	2	2 x 100%	Flowrate: 350 gpm Required Head: 135 ft Efficiency: 75%	480 V	20 HP	20 HP	500 ft length 5 ft elevation
15	INL-P-003A/B	Fire Protection Pumps	INL-HTE-PFD-02	WATER TREATMENT	2	2 x 100%	Flowrate: 500 gpm Required Head: 295 ft Efficiency: 75%	480 V	50 HP	50 HP	500 ft length 5 ft elevation
16	INL-LS-001	Sanitary Sewage System Lift Station	INL-HTE-PFD-02	WATER TREATMENT	1	1 x 100%	Flowrate: 150 gpm Required Head: 55 ft Efficiency: 75%	480V	5 HP	5 HP	3000 ft length 10 ft elevation 300 gallon holding capacity
17	INL-T-008	Potable Water Buffer Tank		WATER TREATMENT	1	1 x 100%	Capacity: 86 gallons 2.2' dia x 3.9' ht	-	-	-	
18	INL-C-003A/B	Air Compressors	INL-HTE-PFD-03	UTILITY GAS	2	2 x 100%	Flowrate: 4,233 scfm Outlet Pressure: 116 psig	4.16 kV	900 HP	900 HP	3670 scfm for stamps 215 scfm for WT equipment 348 scfm for N2
19	INL-R-001	Wet Air Receiver	INL-HTE-PFD-03	UTILITY GAS	1	1 x 100%	By Vendor	-	-	-	
20	INL-D-003A/B	Air Compressor Dryers	INL-HTE-PFD-03	UTILITY GAS	2	2 x 100%	By Vendor	-	-	-	
21	INL-T-007	Instrument Air Receiver	INL-HTE-PFD-03	UTILITY GAS	1	1 x 100%	By Vendor	-	-	-	
22	INL-G-001	Nitrogen Generator	INL-HTE-PFD-03	UTILITY GAS	1	1 x 100%	Flowrate: 295 scfm Outlet Pressure: 45.5-72.5 psig	4.16 kV	165 HP	165 HP	

Item #	Equipment Tag #	Description	Drawing No.	System	Quantity	Redundancy	Operating Conditions	Operating Voltage	Estimated Load (Each)	Estimated Load (Total)	Remarks
23	INL-C-004	Nitrogen Booster	INL-HTE-PFD-03	UTILITY GAS	1	1 x 100%	Flowrate: 19 scfm Inlet Pressure: 45.5 psig Outlet Pressure: 4,250 psig	480 V	20 HP	20HP	
24	INL-T-005	Nitrogen Receiver	INL-HTE-PFD-03	UTILITY GAS	1	1 x 100%	400 gallon	-	-	-	
25	INL-T-006A/B/C	Nitrogen Pressure Vessels	INL-HTE-PFD-03	UTILITY GAS	3	3 x 33%	255 gallon vessels rated to 5,221 psig 1.7' dia. x 23' long	-	-	-	
26	INL-CT-001	Cooling Tower	INL-HTE-PFD-04	Cooling Water	9	1 x 100%	Total Flow Rate: 35,250 gpm CWT: 85°F HWT: 95°F	480 V	75 HP	675 HP	
27	-	Cooling Tower Basin Heaters	INL-HTE-PFD-04	Cooling Water	9	1 x 100%	By Vendor	480 V	30 kW	270 kW	
28	INL-P-004A/B	Cooling Water Supply Pumps	INL-HTE-PFD-04	WATER TREATMENT	2	2 x 100%	Total Flow Rate: 35,250 gpm Required Head: 30 ft Efficiency: 75%	4.16 kV	400 HP	400 HP	1000 ft length 20 ft elevation
29	INL-P-006A/B	Condensate Recovery Sump Pumps	INL-HTE-PFD-05	STEAM AND CONDENSATE	2	2 x 100%	Total Flowrate: 260 gpm Required Head: 30 ft Efficiency: 75%	4.16 kV	125 HP	125 HP	500 ft length 25 ft elevation 167 gpm from stamps 95 gpm from equipment
30	-	Admin Building HVAC	-	HVAC	1	1 x 100%	Cooling: 4 tons Heating: 37.5 MBH	480 V	18 kW	18 kW	Assuming 1,500sqft Building 5 Occupants

Attachment G. Utility List

(1 Page)

Instrument Air (Note 1)	Temperature (F)	Pressure (psig)	Max. Flowrate (scfm)	Remarks
SOEC Electrolyzer Block (8 x 1.2 MW SOEC Stamps)	14-122	50-90		52 Total
Electrolyzer Outlet ESVs	100	100		2 Total
Low Pressure H2 Compressors	100	100		3 Operating (4 Total)
Low Pressure H2 Compressors Outlet ESV	100	100		1 Total
Low Pressure H2 Compressor Recirculation PCV	100	100		1 Total
Hydrogen Drying and Purification System	100	90		1 Total
Hydrogen Buffer Vessel ESV	100	100		1 Total
High Pressure H2 Compressors	100	100		1 Operating (2 Total)
High Pressure H2 Compressors Inlet ESV	100	100		1 Total
High Pressure H2 Compressor Recirculation PCV	100	100		1 Total
High Pressure H2 Compressors Outlet ESV	100	100		1 Total
Miscellaneous Pneumatic / Modulating Control Valves	100	100		Assumed 200 based on S&L experience with hydrogen plants of this size. Includes water treatment instrument air requirements.
Nitrogen Generator	100	100		1 Total
Nitrogen Booster Compressor	100	100		1 Total
Total			4,526	

Nitrogen	Temperature (F)	Pressure (psig)	Max. Flowrate (scfm)	Remarks
SOEC Electrolyzer Block (8 x 1.2 MW SOEC Stamps)	80	120		Per Block - Note 2
Low Pressure H2 Compressors	80	120		3 Operating (4 Total) - Note 3
Hydrogen Drying and Purification System	80	120		Note 3, 5
High Pressure H2 Compressors	80	120		1 Operating (2 Total) - Note 3
Condensate Recovery Sump	80	120		Note 4
Total			25,576	

Cooling Water	Temperature (F)	Pressure (psig)	Max. Flowrate (gpm)	Remarks
Low Pressure H2 Compressors	100	70	24,701	Calculated Heat Duty: 41.2 MMBtu/hr per compressor
Hydrogen Drying and Purification System	100	70	220	Calculated Heat Duty: 0.3 MMBtu/hr per train - Note 5
High Pressure H2 Compressors	100	70	5,944	Calculated Heat Duty: 29.7 MMBtu/hr per compressor
Total			30,865	

Potable Water	Temperature (F)	Pressure (psig)	Max. Flowrate (gpm)	Remarks
Admin Building	77	90	10	
Total			10	

Raw Water	Temperature (F)	Pressure (psig)	Max. Flowrate (gpm)	Remarks
Water Treatment System	77	25	1,400	Water Treatment provides Treated and Service Water to the plant.
Total			1,400	

Treated Water	Temperature (F)	Pressure (psig)	Max. Flowrate (gpm)	Remarks
Heat Recovery Exchangers	50-77	90	685	Note 6
Total			685	

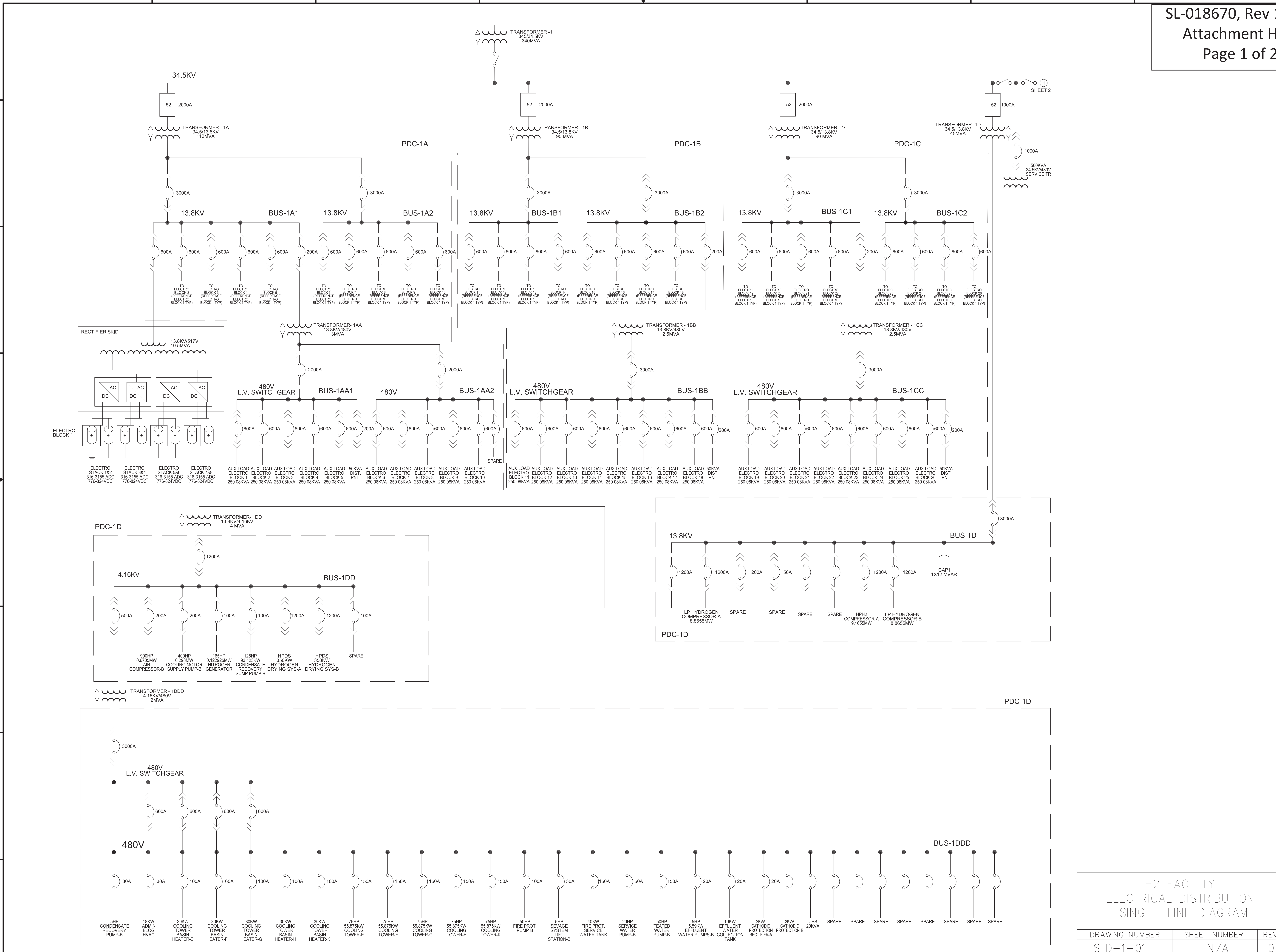
Service / Fire Protection Water	Temperature (F)	Pressure (psig)	Max. Flowrate (gpm)	Remarks
Cooling Tower Makeup	77		355	
Fire Protection Users	77	70	1,000	Note 7
Total			1,355	

Notes:

1. Per Standards, a maximum air requirement of 1.06 scfm was assumed for pneumatic/modulating control valves or ESVs.
2. N2 is typically used to purge out the H2 for safety.
3. A connection for nitrogen will be provided to the compressors and drying and purification system to allow for purging prior to servicing.
4. A connection for nitrogen will be provided to the condensate recovery sump to allow for purging in the event that hydrogen drains through one of the condensate drains of the hydrogen equipment. Value is assumed based S&L experience.
5. Estimated based on similar projects.
6. Treated water will be preheated using H2 process gas in the Heat Recovery Exchangers from the SOEC before going to the auxiliary boiler. This treated water will return the H2 facility as LP steam.
7. Max flowrate is typical fire protection pump size for a fire protection loop of the size of the new hydrogen facility with hydrants surrounding the loop.

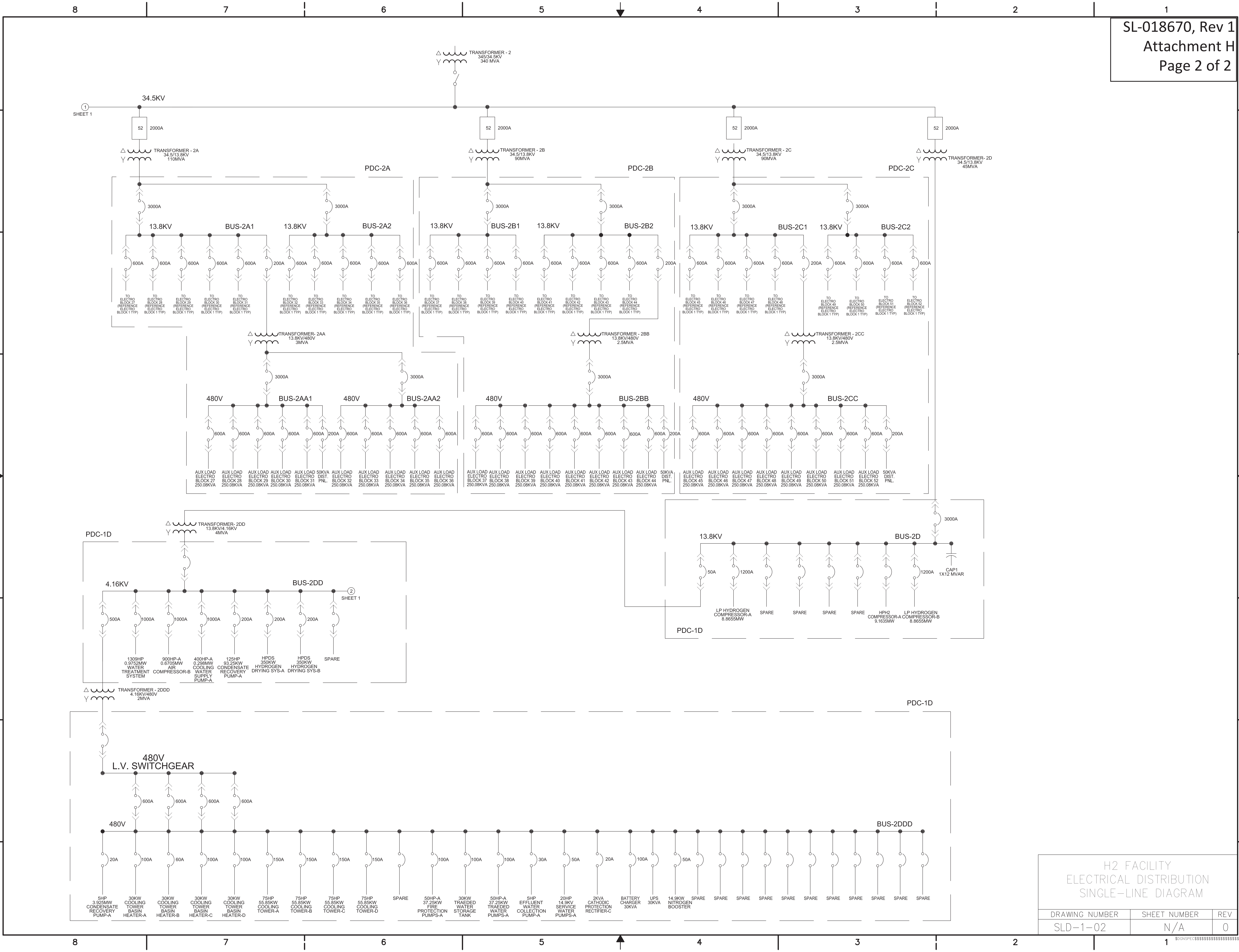
Attachment H. Electrical Single-Line Diagram

(2 Pages)



H2 FACILITY
ELECTRICAL DISTRIBUTION
SINGLE-LINE DIAGRAM

DRAWING NUMBER	SHEET NUMBER	REV
SLD-1-01	N/A	0



H2 FACILITY
ELECTRICAL DISTRIBUTION
SINGLE-LINE DIAGRAM

DRAWING NUMBER	SHEET NUMBER	REV
SLD-1-02	N/A	0

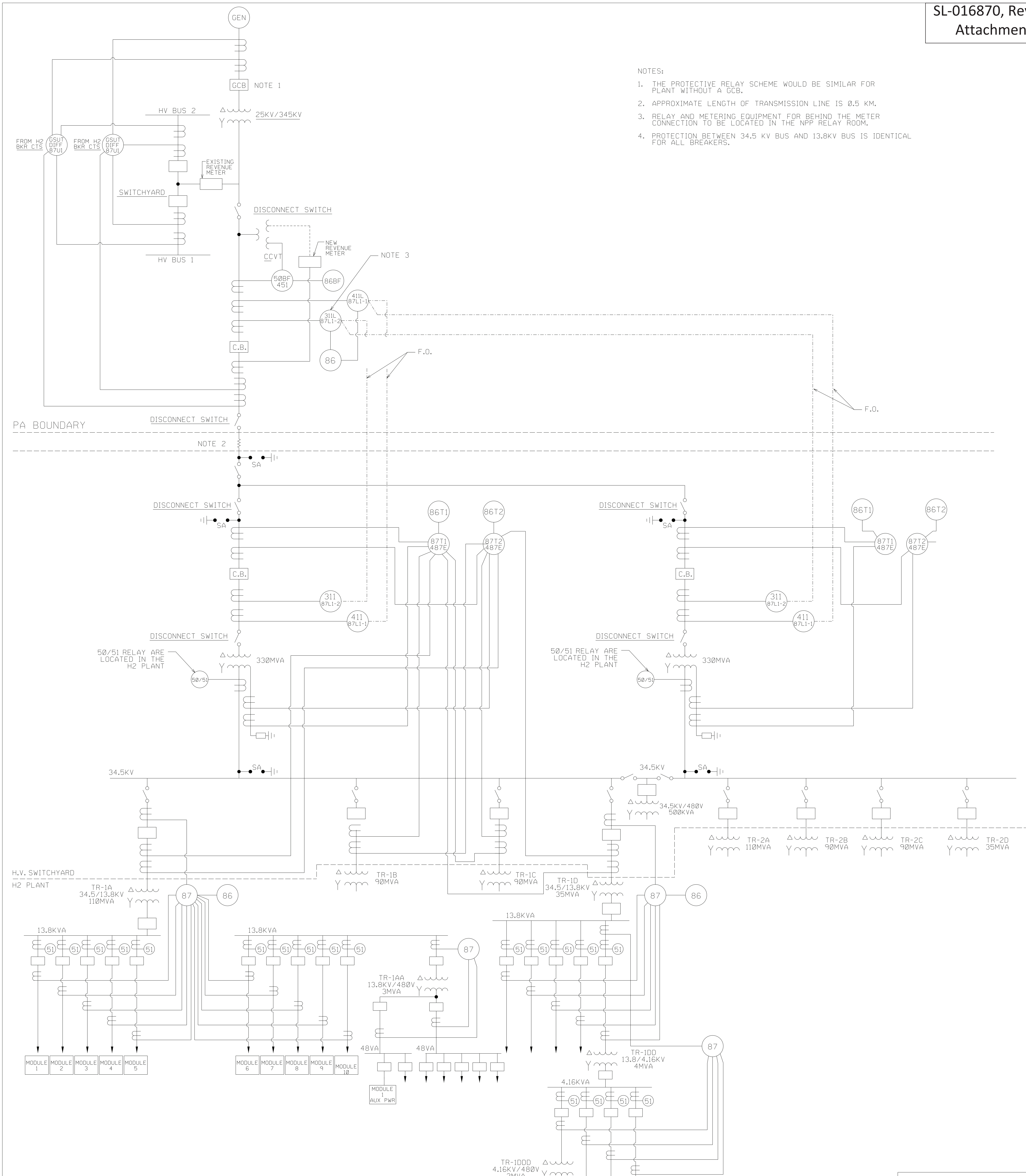
Attachment I. Relay and Protection Diagram

(1 Page)

SL-016870, Rev 1
Attachment I

NOTES:

1. THE PROTECTIVE RELAY SCHEME WOULD BE SIMILAR FOR PLANT WITHOUT A GCB.
2. APPROXIMATE LENGTH OF TRANSMISSION LINE IS 0.5 KM.
3. RELAY AND METERING EQUIPMENT FOR BEHIND THE METER CONNECTION TO BE LOCATED IN THE NPP RELAY ROOM.
4. PROTECTION BETWEEN 34.5 KV BUS AND 13.8KV BUS IS IDENTICAL FOR ALL BREAKERS.

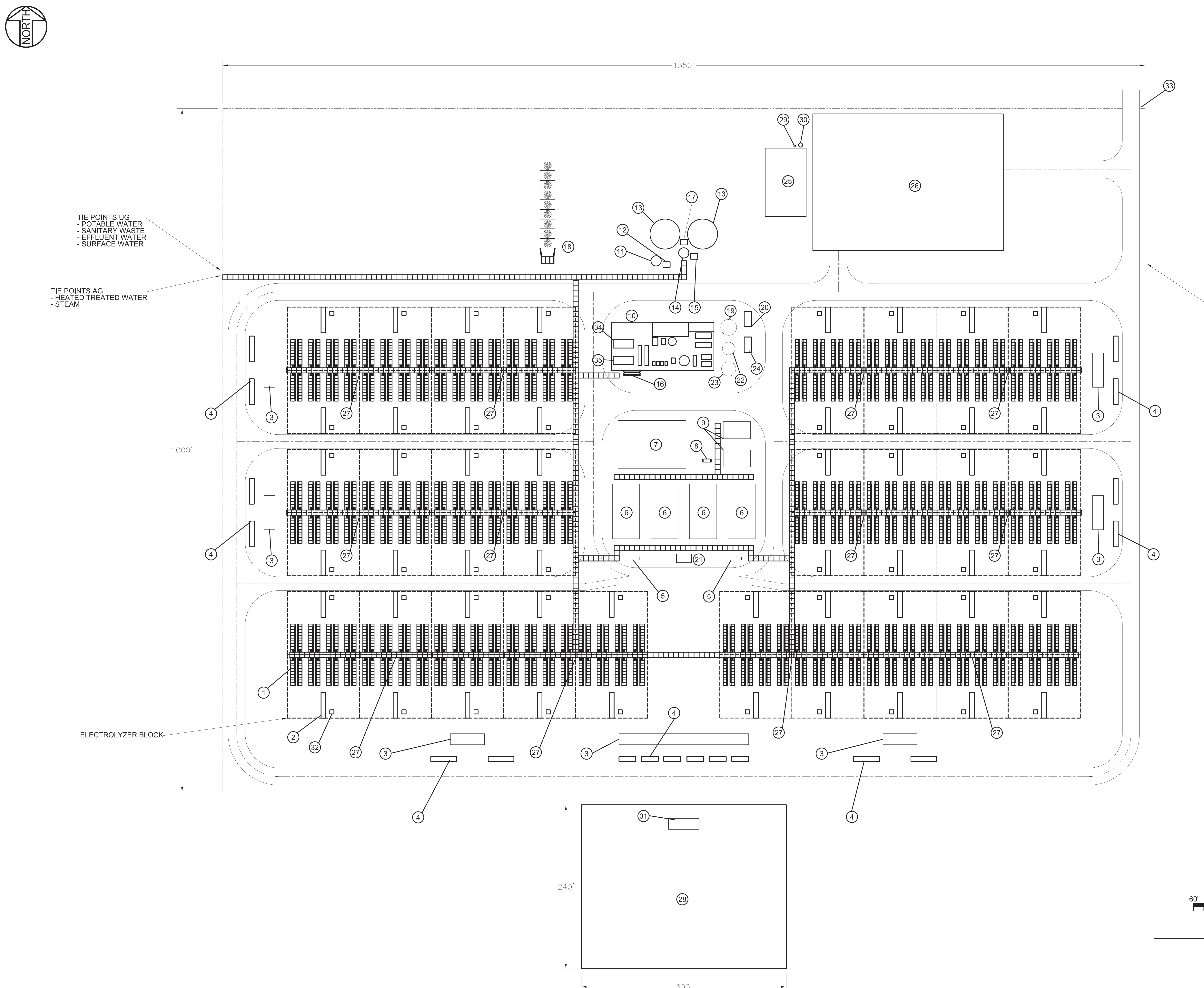


500 MW Relay Protection Diagram

Attachment J. H_2 Facility General Arrangement Drawing

(1 Page)

SL-018670, Rev 1
Attachment J



LEGEND	
01	1.2MW ELECTROLYZER STAMP (QTY 416)
02	RECTIFIER/TRANSFORMER (QTY 52)
03	PDC
04	TRANSFORMER
05	HYDROGEN HEAT RECOVERY EXCHANGER
06	LOW PRESSURE COMPRESSION
07	PURIFICATION AND DRYING
08	HYDROGEN BUFFER VESSEL
09	HIGH PRESSURE COMPRESSION
10	UTILITY AIR AND WATER TREATMENT BLDG
11	SLUDGE HOLDING TANK
12	FILTER PRESS FEED PUMPS
13	CLARIFIER
14	CLEARWELL
15	CLARIFIED WATER PUMPS
16	NITROGEN PRESSURE VESSELS
17	CLARIFIED SLUDGE PUMPS
18	COOLING TOWER
19	SERVICE/FIRE PROTECTION TANK
20	FIRE PROTECTION PUMPS
21	CONDENSATE RECOVERY SUMP
22	TREATED WATER TANK
23	EFFLUENT TANK
24	WATER PUMP HOUSE
25	ADMINISTRATION/CONTROL BUILDING
26	PARKING AND STAGING AREA
27	MODULE CONDENSATE SUMP
28	SWITCHYARD
29	POTABLE WATER BLADDER TANK
30	SANITARY LIFT STATION
31	HIGH VOLTAGE PDC
32	TELEMETRY CABINET (QTY 52)
33	ENTRY GATE
34	INSTRUMENT AIR SKID
35	NITROGEN SKID

60' 0 60' 120' 180'
GRAPHIC SCALE

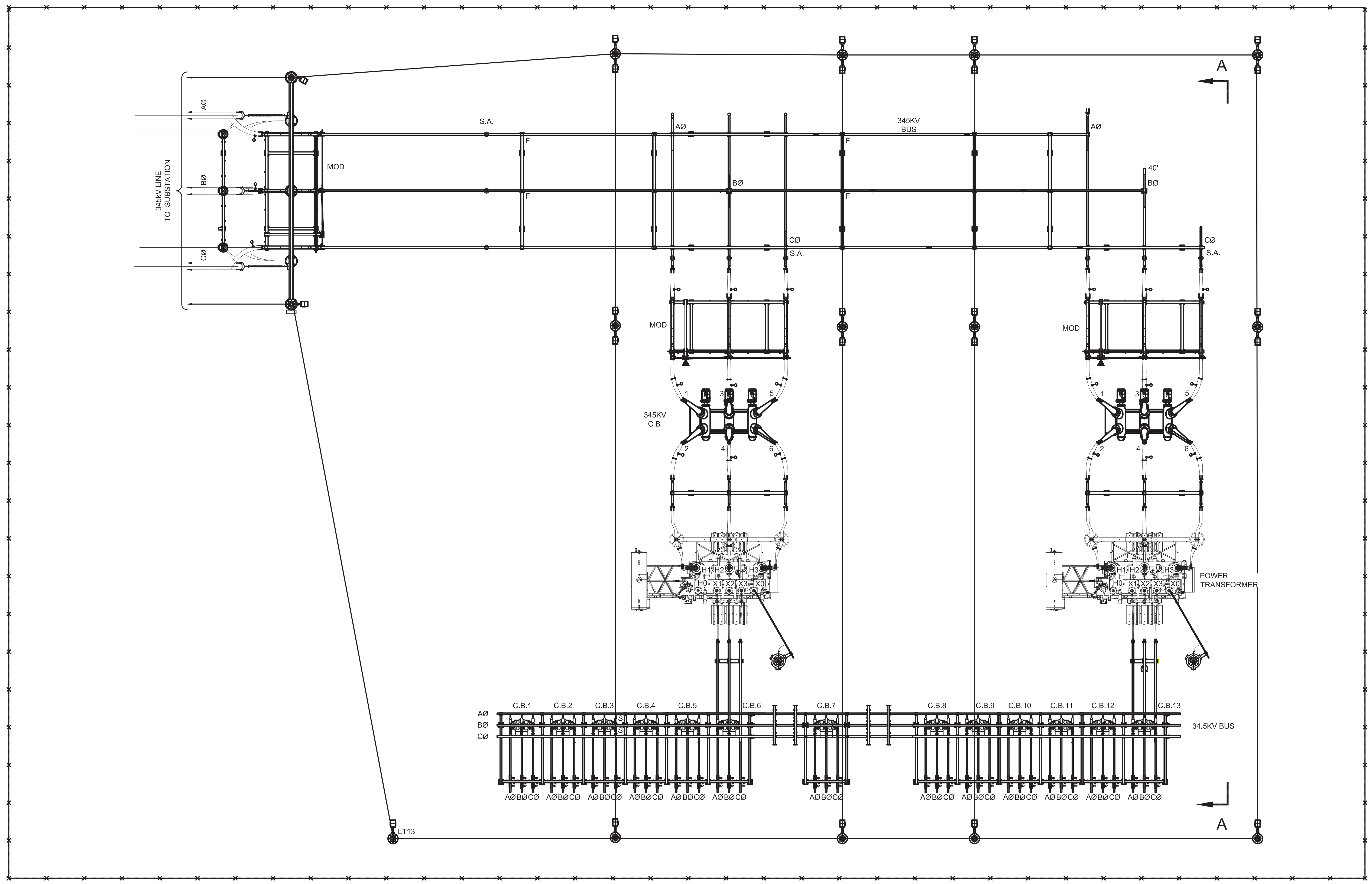
H2 FACILITY
GENERAL
ARRANGEMENT

DRAWING NUMBER	SHEET NUMBER	REV
INL-MSK-GA-001	N/A	0

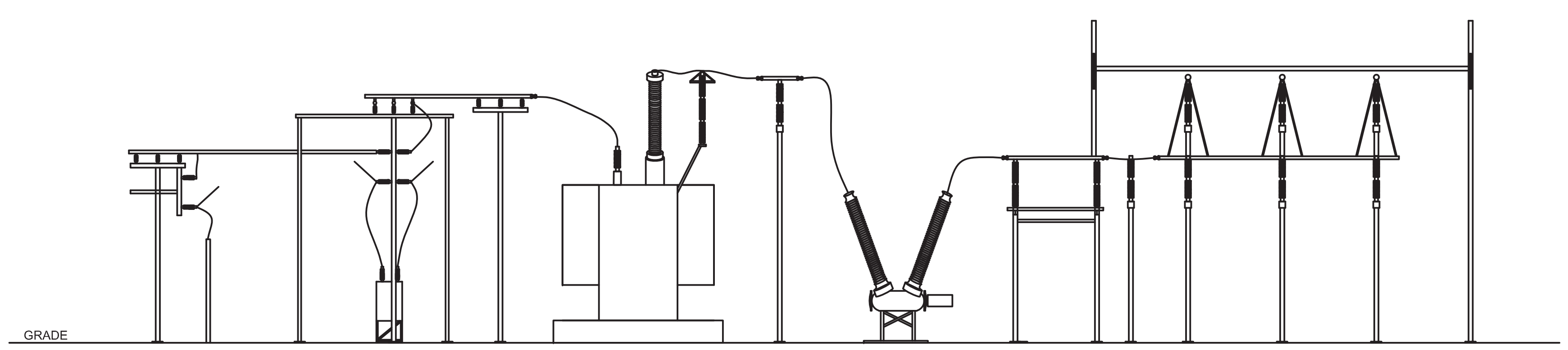
Attachment K. Switchyard Layout Drawing

(1 Page)

SL-018670, Rev 1
Attachment K



PLAN VIEW

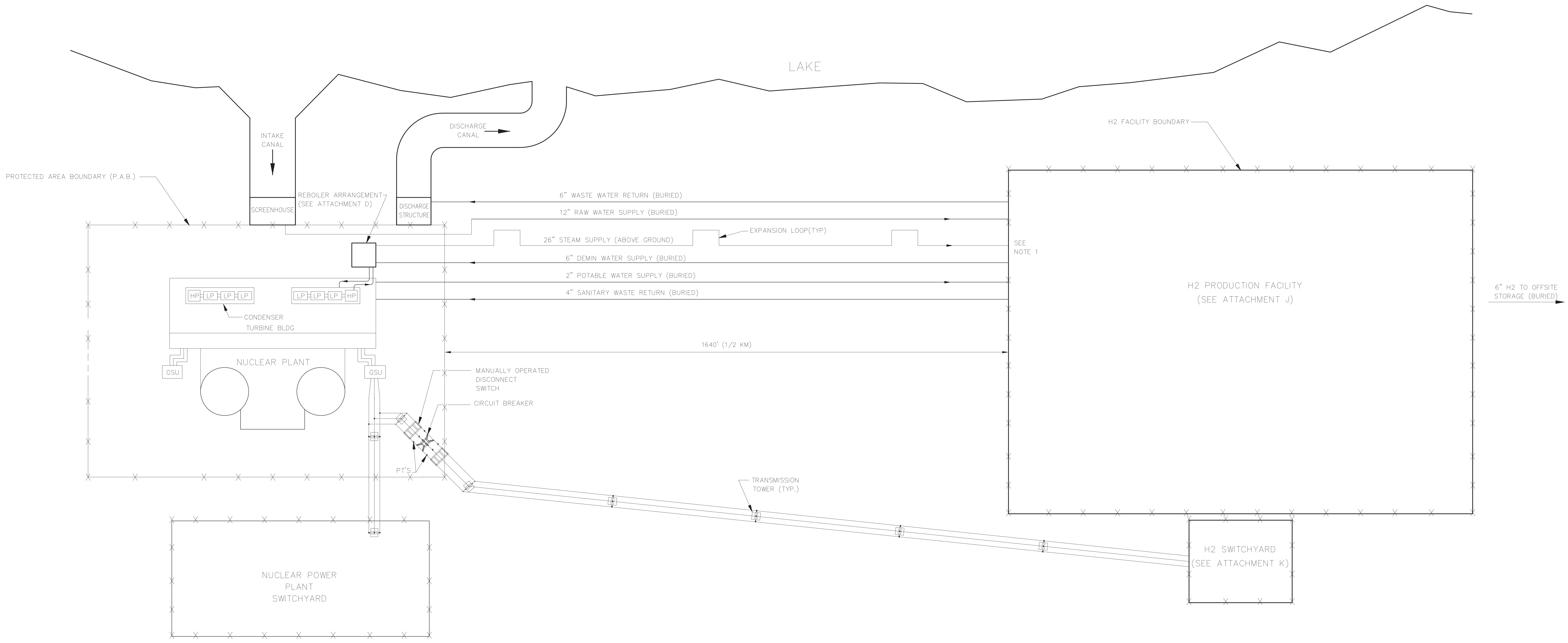


SECTION A-A

SWITCHYARD GENERAL ARRANGEMENT		
DRAWING NUMBER	SHEET NUMBER	REV
INL-HV-GA-001	N/A	0

Attachment L. Site General Arrangement Drawing

(1 Page)



NOTES:
1. WATER AND STEAM INTERFACES BETWEEN THE NUCLEAR PLANT AND H2 FACILITY ARE NOT SHOWN TO SCALE. SEE ATTACHMENT J FOR TIE POINT LOCATIONS AT H2 FACILITY.

500 MW
H2 SITE LAYOUT

DRAWING NUMBER	SHEET NUMBER	REV
INL-GEN-GA-001	N/A	0

Attachment M. Project Cost Estimates

(33 Pages)

Basis of Estimate

Project Title:	Pre-Conceptual Design for Large-Scale Nuclear Integrated Hydrogen Production Facility
Client Name:	Batelle Energy Alliance – Idaho National Laboratory
Station:	500 MW Reference Plant
Project Number:	A14248.015
Date:	06/06/2024

Sargent & Lundy LLC
55 East Monroe Street
Chicago, IL 60603-5780

Basis of Estimate

Client: DOE – Idaho National Laboratory
Station: Reference Plant
Date: 6/6/2024
Project No.: A14248.015

Table of Contents

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, 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.

2. General Information

2.1. Estimate(s)

Estimate No.: 36779B – "Nuclear-Hydrogen Plant Integration"

This estimate has been created to identify costs for the nuclear plant modification to support a 500MW hydrogen production facility. This estimate is an update of Estimate 36104B, developed as part of report SL-016181, Revision 1. The scope of this estimate includes the hydrogen steam supply (HSS) equipment used for extraction of nuclear plant steam to heat process water for electrolysis at the hydrogen facility, as well as the electrical dispatch and transmission lines to the hydrogen production facility high-voltage switchyard. Additionally, other plant systems such as the circulating water, potable water, and sanitary waste systems will be integrated with the hydrogen facility. This estimate includes costs for the nuclear plant modifications, with the primary focus on thermal and electrical systems.

Estimate No.: 36780B – "Hydrogen Production Facility High Voltage Switchyard"

This estimate has been created to identify costs for the high voltage electrical switchyard to support the development of a 500MW hydrogen production facility at an existing nuclear power plant site. This estimate includes the scope of the high voltage switchyard for the hydrogen production facility. Electric power is fed from the nuclear plant generator step-up (GSU) transformer to the switchyard at 345 kV, as detailed in Estimate 36779B above. In the high-voltage switchyard, power is dropped to medium voltage (345 kV/34.5 kV), before being distributed to users in the hydrogen production facility.

Estimate No.: 36834B – "Hydrogen Production Facility – Early Adopter"

36835B – "Hydrogen Production Facility – Large Module"

These estimates have been created to identify costs for the development of a 500MW hydrogen production facility at an existing nuclear power plant site. This project would include approximately 500MW_{dc} of Solid Oxide Electrolysis Cells (SOECs) to produce hydrogen from nuclear plant steam and electricity. Various mechanical systems will be integrated with the nuclear plant as detailed in Estimate 36779B above to source or return water and steam. Electricity will be provided at 34.5 kV from the high voltage switchyard, detailed in Estimate 36780B above, before being further stepped down for distribution throughout the hydrogen facility. Steam and electricity will be supplied to electrolyzers to produce hydrogen, before being cooled, compressed, and dried. The final high-purity hydrogen will then be piped offsite for storage and/or utilization. The hydrogen facility will also consist of cooling systems, firewater systems, instrument air systems, nitrogen generation systems, electrical systems to support all plant loads, instrumentation, a new control room for the facility, and all additional piping, foundations, supports, and other infrastructure needed to support the hydrogen generation process and balance-of-plant. These estimates include costs for the hydrogen facility and commodities up to the hydrogen facility fence line. High-pressure compression costs are provided separately, but are excluded from the total hydrogen facility costs for research comparison purposes.

The purpose of these two separate estimates is to identify the change in capital cost as high-temperature electrolysis technology develops and more facilities are built. The main cost driver of these estimates is the electrolyzer equipment cost. Below are the assumed costs of the SOEC electrolyzers at different levels of adoption, as provided by INL. Additional cost saving considerations associated with technology development are described below in sections 10 and 15.

- 36834B – "Hydrogen Production Facility – Early Adopter" @$500/KW
- 36835B – "Hydrogen Production Facility – Large Module" @$250/KW

2.2. Facility Location: Not Identified

2.3. Facility Type: Nuclear

2.4. New or Existing Facility: Existing Site

2.5. Unit of Measurement: U.S. Imperial

2.6. Currency: U.S. Dollar

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.

3.1. Civil work
3.2. Structural work
3.3. Concrete work
3.4. Mechanical work
3.5. Electrical work
3.6. Instrumentation and controls work

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 estimate

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 -30% to +50%. Accuracy range is calculated on the total cost estimate after the application of appropriate contingency.

The Association for the Advancement of Cost Engineering (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).

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.

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.

7. Structure and Coding of the Estimate

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 is shown below.

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
34.00.00	HVAC
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 AND INSTRUMENTATION
51.00.00	SUBSTATION, SWITCHYARD & TRANSMISSION LINE
61.00.00	CONSTRUCTION INDIRECT
90.00.00	ADDITIONAL LABOR COSTS
91.00.00	SITE OVERHEADS
92.00.00	OTHER CONSTRUCTION INDIRECTS
93.00.00	PROJECT INDIRECT COSTS
94.00.00	CONTINGENCY

8. Direct Costs

Direct field costs represent the permanently installed facilities and include (1) subcontract costs, (2) material costs, (3) process equipment costs, (4) labor costs, and (5) construction equipment costs. Each line item in the estimate may have any combination of these cost categories.

These five (5) direct cost categories are discussed as follows.

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.

The below equipment pricing inputs to this estimate were obtained from vendor quotations unless otherwise noted:

- SOEC Electrolyzers ($500/KW and $250/KW allowances given by INL)
- Rectifier Skids
- Hydrogen Heat Recovery Exchangers
- Hydrogen Compressors
- Cooling Towers
- Distribution Control Center

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.

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.

8.3.1. 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 US 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). Manhours 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.

8.3.2. Labor Productivity

In evaluating productivity, factors such as jobsite location, type of work and site congestion were considered.

A regional labor productivity multiplier of 1.1 is included for estimates 36780B, 36834B, and 36835B. This is the standard labor productivity factor as listed in Compass International Global Construction Yearbook is 1.1 for the Bloomington, IL area. The use of this productivity factor is an approach to compare construction productivity in various locations in the USA to a known basis or benchmark of 1.00 for Texas, Gulf Coast productivity. Productivity multiplier does not include weather related delays.

A labor productivity multiplier of 1.35 is included for estimate 36779B which includes work within the nuclear power plant, within the protected area, and outside the protected area. This factor is applied to account for the additional effort, oversight, and requirements associated with portions of the work performed within a nuclear power plant in a congested area without radiation protection and a portion of the work performed during an outage. This productivity factor is a blended value and has been developed based on historical data which is dependent upon several factors, such as congestion, outage or non-outage activities, and the level of radiation protection.

8.3.3. 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”, 2024 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.

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.

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.

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 S&L experience with similar type and size projects. Listed below are the additional costs included (unless noted as not included).

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, on the basis of a 50 hour work week (5 – 10 hour days)
- Per Diem of $10/hr has been included to attract and retain labor

9.2. Site Overheads

- Construction Management (Includes project manager, superintendents, project controls, site clerical)
- Field Office Expenses (trailer rental, furniture, office equipment, computers, site communication, office supplies)
- Material & Quality Control (inspectors, quality assurance personnel)
- Site Services (Labor cost to receive, unload & 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 required at the job site such as: temporary warehouse, change trailers, or site security
- Temporary Utilities Includes ant temporary utilities required at the job site such as: temporary electric grid, water consumed during construction, trash hauling fees, sanitary facilities)
- Mobilization/Demobilization to the jobsite
- Legal Expenses/Claims

9.3. Other Construction Indirects

- Small Tools and Consumables
- Scaffolding (includes rental, erection & removal)
- General Liability Insurance (covers premiums likely to be incurred)
- Construction Equipment Mobilization/Demobilization
- Freight on Material
- Freight on Process Equipment
- Contractors General & Administration (G&A) Expense (7% on all categories, except 4% on electrolyzer costs)
- Contractors Profit (10% on all categories, except 4% on electrolyzer costs)

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

10. Project Indirect Costs

Listed below are additional project indirect costs 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. The lump sum dollar values below are for a first of a kind (FOAK) facility. Engineering Services, Construction Management Support, and Start-up/Commissioning costs for Early Adopters have been reduced by 12% represented in estimate 36834B, and 18% for Large Module represented in estimate 36835B, based on anticipated learning rates.

- Professional Engineering Services (Lump Sum of $32M)
- Professional Construction Management Services (Lump sum of $24M)
- Professional Start-up and Commissioning support services (Includes the development and implementation of the procedures and testing in order to energize plant systems and turnover a fully operational facility to the owner) (Lump sum of 8M)
- Start-Up Spare Parts

11. Contingency

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

- Material Contingency Cost .... Calculated @ 20% of cost
- Process Equipment Contingency Cost .... Calculated @ 20% of cost
  (Excluding electrolyzer cost at 0% contingency)
- Labor Contingency Cost... Calculated @ 20% of cost
- Construction Equipment Contingency Cost .... Calculated @ 20% of cost
- Subcontract Contingency Costs............................. Calculated @ 20% of cost
- Indirect Contingency Costs .... Calculated @ 20% 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.

12. Escalation

Escalation is not included.

13. Contracting Approach

The estimates(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 construction management 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.

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, Construction Management, and Start-Up & Commissioning (offices/trailers, guard houses, furniture, signage, staff parking, vehicles, access control, computer network/servers, safety equipment, etc.)
- Site Services for Owner's Personnel, Construction Management, and Start-Up & Commissioning (Telephone, electricity, natural gas, potable water, sewage, sanitary, garbage collection, recycled materials/metals collection, snow removal, dust control, janitorial services, internet, cable services, reprographics, etc.)
- Land acquisition / Rights of Way / Access Road 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 cost 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

15. Notes/Assumptions /Clarifications

15.1. Nuclear-Hydrogen Plant Integration (Estimate 36779B)

15.1.1. It is assumed that the hydrogen facility systems will be integrated with the nuclear plant potable water and sanitary sewage systems, which are assumed to be tied into the neighboring city or municipalities water and sewage systems. There is an assumed 2,000 ft of piping for sanitary and potable water up to the boundary of the hydrogen facility.

15.1.2. The fence-to-fence distance from the nuclear plant Protected Area to the hydrogen facility boundary is assumed to be 0.5 km (1,640 ft).

15.1.3. The nuclear plant and hydrogen facility are assumed to be at equal elevations.

15.2. Hydrogen Production Facility High Voltage Switchyard (Estimate 36780B)

15.2.1. None.

15.3. Hydrogen Production Facility (Estimates 36834B & 36835B)

15.3.1. Compressors are all assumed to be reciprocating type with non-lubricated pistons. Compression will be divided into two services, “low-pressure” and “high-pressure”.

15.3.2. High-Pressure compression, offsite H2 pipeline, storage, and utilization facilities have been excluded from the facility estimate scope.

15.3.3. 416 total stamps will be needed to reach the nominal 499.2 MW_{DC} of SOEC capacity. These 416 stamps will be divided into 52 modules of 8 stamps each.

15.3.4. It is assumed that deep foundations (piles) will not be required outside of the hydrogen compressors.

15.3.5. Site conditions used to size the cooling system were the highest and lowest of three nuclear plant locations around the Great Lakes.

15.3.6. Facility max occupancy was assumed to be 5 personnel.

15.3.7. Because site-specific geotechnical reports are not available, frost depth is assumed to be 30” below grade.

15.3.8. Fiber optic design will be based on star topology.

15.3.9. Only a large-scale Distributed Control System (DCS) is considered for the overall plant controls. PLC’s for packaged specialized equipment is included with the equipment costs.

15.3.10. Power Distribution Center (PDC) costs include the cost of the PDC shell and all equipment contained within such as switch gears and panels.

15.3.11. A 15% reduction on the rectifier equipment cost has been applied to the estimates due to vender learning effects and efficiency gains post-FOAK.

General Cost Estimate Summary

	Cost Estimate			
	Nuclear Power Plant Integration	High-Voltage Switchyard	Hydrogen Production Facility (Large Module)	Hydrogen Production Facility (Early Adopter)
Total Direct Cost	14,782,322	19,854,889	359,765,175	484,565,175
General Conditions	13,177,700	5,809,800	118,550,700	135,835,500
Project Indirect Costs	5,042,900	2,364,100	53,468,800	57,735,000
Contingency	6,600,600	5,605,700	81,396,900	85,707,100
Total ($)	**39,603,522**	**33,634,489**	**613,181,575**	**763,842,775**
Total ($/kW)	**79**	**67**	**1,226**	**1,528**
Total Project ($)*	--	--	**686,419,586**	**837,080,786**
Total Project ($/kW)*	--	--	**1,373**	**1,674**

* Includes Hydrogen Production Facility (for associated option), Nuclear Power Plant Integration, and High-Voltage Switchyard.

Uninstalled and Installed Costs

Cost Item ($/kW)	Nuclear Power Plant Integration	High-Voltage Switchyard	Hydrogen Production Facility (Large Module)	Hydrogen Production Facility (Early Adopter)
Electrolyzer Stamps	**--**	**--**	**250**	**500**
Uninstalled Capex*	**19**	**43**	**696**	**953**
Installation/Construction	**60**	**24**	**530**	**575**
Total Cost	**79**	**67**	**1,226**	**1,528**

*

Uninstalled Capex = Material + Process Equipment (including Electrolyzer Stamps) + Material/Process Equipment Contingency (excluding Electrolyzer Stamps)

All values in 2024 US Dollars.

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
NUCLEAR & HYDROGEN PLANT INTEGRATION

Estimator	CK
Labor rate table	24ILBLO
Project No.	A14248.015
Estimate Date	5/28/2024
Reviewed By	JM
Approved By	BA
Estimate No.	36779B
Factor table	_8 Productivity 1.35

INL/BEA

Estimate No.: 36779B
Project No.: A14248.015
Estimate Date: 5/28/2024
Prep/Rev/App.: CK/JM/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
NUCLEAR & HYDROGEN PLANT INTEGRATION

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
1			STEAM SUPPLY							
	21.00.00		CIVIL WORK							
		21.17.00	EXCAVATION				281	24,799	3,911	28,710
		21.19.00	DISPOSAL				71	6,246	985	7,231
		21.20.00	BACKFILL			14,823	387	34,108	5,379	54,310
		21.43.00	FENCEWORK	200,000						200,000
		21.54.00	CAISSON	367,380						367,380
			CIVIL WORK	567,380		14,823	739	65,153	10,275	657,631
	22.00.00		CONCRETE							
		22.13.00	CONCRETE			38,354	446	33,262	4,566	76,182
		22.15.00	EMBEDMENT			7,935	179	13,766	263	21,964
		22.17.00	FORMWORK			2,867	418	33,624	2,709	39,200
		22.25.00	REINFORCING			22,219	482	36,478	4,292	62,988
			CONCRETE			71,374	1,525	117,130	11,830	200,335
	23.00.00		STEEL							
		23.25.00	ROLLED SHAPE			1,392,400	11,016	1,042,004	245,371	2,679,776
			STEEL			1,392,400	11,016	1,042,004	245,371	2,679,776
	27.00.00		PAINTING & COATING							
		27.17.00	PAINTING	10,000		37,592	2,077	226,007	10,356	283,955
			PAINTING & COATING	10,000		37,592	2,077	226,007	10,356	283,955
	31.00.00		MECHANICAL EQUIPMENT							
		31.65.00	HEAT EXCHANGER		2,060,000		378	29,888	3,573	2,093,461
		31.75.00	PUMP		60,000		243	19,214	2,297	81,511
		31.83.00	TANK	8,000			14	1,067	128	9,195
		31.99.00	MECHANICAL EQUIPMENT, MISCELLANEOUS		515,000		243	19,214	2,297	536,511
			MECHANICAL EQUIPMENT	8,000	2,635,000		878	69,384	8,294	2,720,678
	35.00.00		PIPING							
		35.13.01	SS 304, ABOVE GROUND, PROCESS AREA			103,050	2,832	224,570	41,718	369,338
		35.13.10	CARBON STEEL, ABOVE GROUND, PROCESS AREA			189,762	2,286	181,310	33,682	404,754
		35.14.10	CARBON STEEL, STRAIGHT RUN			740,601	8,126	644,467	119,722	1,504,790
		35.15.02	SS 316, BURIED			227,384	2,833	224,673	41,737	493,794
		35.35.00	PIPE SUPPORTS, HANGERS			299,152	3,056	242,360	45,023	586,536
		35.45.00	CARBON STEEL VALVES			617,542	669	53,042	9,853	680,437
		35.46.00	STAINLESS STEEL VALVES			161,805	329	26,103	4,849	192,758
		35.49.00	MISCELLANEOUS VALVES			8,160	119	9,422	1,750	19,332
			PIPING			2,347,455	20,249	1,605,948	298,335	4,251,738
	36.00.00		INSULATION							
		36.17.03	PIPE, MINERAL WOOL W/ALUMINUM JACKETING			337,046	4,351	383,583	28,268	748,898
			INSULATION			337,046	4,351	383,583	28,268	748,898
	41.00.00		ELECTRICAL EQUIPMENT							
		41.33.00	HEAT TRACING	20,000		41,211	1,358	100,320	17,349	178,880
			ELECTRICAL EQUIPMENT	20,000		41,211	1,358	100,320	17,349	178,880
	44.00.00		CONTROL & INSTRUMENTATION							
		44.21.30	LEVEL DEVICES			18,320	108	7,786	431	26,537
		44.21.40	PRESSURE DEVICES			8,710	30	2,141	119	10,970
			CONTROL & INSTRUMENTATION			27,030	138	9,927	550	37,507
	61.00.00		CONSTRUCTION INDIRECT							
		61.15.00	CRAFT PERSONNEL				675	53,372	0	53,372
			CONSTRUCTION INDIRECT				675	53,372	0	53,372
			1 STEAM SUPPLY	605,380	2,635,000	4,268,931	43,006	3,672,829	630,628	11,812,768
2			ELECTRICAL & TRANSMISSION LINE							
	21.00.00		CIVIL WORK							
		21.17.00	EXCAVATION				8	696	110	805
		21.19.00	DISPOSAL				3	278	44	322
		21.20.00	BACKFILL			1,093	7	610	96	1,799
		21.54.00	CAISSON	298,571						298,571
			CIVIL WORK	298,571		1,093	18	1,584	250	301,497
	22.00.00		CONCRETE							

INL/BEA

Estimate No.: 36779B
Project No.: A14248.015
Estimate Date: 5/28/2024
Prep/Rev/App.: CK/JM/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
NUCLEAR & HYDROGEN PLANT INTEGRATION

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
		22.13.00	CONCRETE			2,685	31	2,329	320	5,334
		22.15.00	EMBEDMENT			100	11	833	16	949
		22.17.00	FORMWORK			259	38	3,038	245	3,541
		22.25.00	REINFORCING			1,556	34	2,554	301	4,410
			CONCRETE			4,600	114	8,753	881	14,234
	23.00.00		STEEL							
		23.99.00	STEEL, MISCELLANEOUS			49,438	189	17,831	4,199	71,468
			STEEL			49,438	189	17,831	4,199	71,468
	41.00.00		ELECTRICAL EQUIPMENT							
		41.17.00	COMMUNICATION SYSTEM		50,000		162	11,764	2,047	63,812
		41.31.00	ELECTRICAL EQUIPMENT, GROUNDING			26,336	225	16,609	2,871	45,816
		41.47.00	PANEL: CONTROL, DISTRIBUTION, & RELAY		50,460		259	18,823	3,276	72,559
			ELECTRICAL EQUIPMENT		100,460	26,336	646	47,196	8,194	182,187
	42.00.00		RACEWAY, CABLE TRAY & CONDUIT							
		42.15.33	CONDUIT, PVC			4,551	67	4,680	73	9,305
		42.15.37	CONDUIT, RGS			19,022	546	38,062	594	57,678
			RACEWAY, CABLE TRAY & CONDUIT			23,573	613	42,742	667	66,983
	43.00.00		CABLE							
		43.10.00	CONTROL/INSTRUMENTATION/COMMUNICATION CABLE & TERMINATION			11,761	155	11,466	1,982	25,209
		43.20.00	600V CABLE & TERMINATION			20,845	412	30,458	5,266	56,570
			CABLE			32,606	567	41,924	7,248	81,778
	44.00.00		CONTROL & INSTRUMENTATION							
		44.13.00	CONTROL SYSTEM		30,000		108	7,535	118	37,653
			CONTROL & INSTRUMENTATION		30,000		108	7,535	118	37,653
	51.00.00		SUBSTATION, SWITCHYARD & TRANSMISSION LINE							
		51.13.00	CONDUCTOR & WIRE			22,680	91	6,358	99	29,137
		51.13.02	CONDUCTORS			69,120	547	40,432	6,990	116,543
		51.15.27	CIRCUIT BREAKER		307,600		459	33,833	1,183	342,616
		51.15.37	COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT)		29,973		162	11,941	418	42,332
		51.15.43	METERING		7,725		65	4,776	167	12,668
		51.15.67	INSULATOR			4,555	12	898	155	5,609
		51.21.00	TRANSMISSION TOWER, HARDWARE ASSEMBLY			3,418	61	4,498	778	8,694
		51.25.00	TRANSMISSION TOWER, POLE (STEEL)			55,200	57	4,193	725	60,118
		51.99.00	SUBSTATION, SWITCHYARD & TRANSMISSION LINE, MISCELLANEOUS			252	304	22,456	3,635	26,344
			SUBSTATION, SWITCHYARD & TRANSMISSION LINE		345,298	155,224	1,757	129,387	14,151	644,060
	61.00.00		CONSTRUCTION INDIRECT							
		61.15.00	CRAFT PERSONNEL				675	49,916	0	49,916
			CONSTRUCTION INDIRECT				675	49,916	0	49,916
			2 ELECTRICAL & TRANSMISSION LINE	298,571	475,758	292,871	4,686	346,868	35,707	1,449,776
3			WATER SYSTEMS							
	21.00.00		CIVIL WORK							
		21.17.00	EXCAVATION				932	82,126	12,952	95,078
		21.19.00	DISPOSAL				164	14,487	2,285	16,771
		21.20.00	BACKFILL			32,762	1,856	163,607	25,802	222,171
			CIVIL WORK			32,762	2,952	260,219	41,039	334,020
	31.00.00		MECHANICAL EQUIPMENT							
		31.75.00	PUMP		87,750		144	11,422	1,365	100,537
			MECHANICAL EQUIPMENT		87,750		144	11,422	1,365	100,537
	35.00.00		PIPING							
		35.14.30	HDPE, STRAIGHT RUN			6,270	465	36,885	6,852	50,007
		35.15.30	HDPE, BURIED			162,800	7,452	591,019	109,793	863,612
		35.35.00	PIPE SUPPORTS, HANGERS			14,892	425	33,684	6,257	54,833
		35.49.00	MISCELLANEOUS VALVES			15,750	151	11,992	2,228	29,969
			PIPING			199,712	8,493	673,579	125,130	998,421
	36.00.00		INSULATION							
		36.17.03	PIPE, MINERAL WOOL W/ALUMINUM JACKETING			8,865	204	17,999	1,326	28,191
			INSULATION			8,865	204	17,999	1,326	28,191
	41.00.00		ELECTRICAL EQUIPMENT							
		41.33.00	HEAT TRACING			11,069	548	40,532	7,008	58,609

INL/BEA

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Project No.: A14248.015
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BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
NUCLEAR & HYDROGEN PLANT INTEGRATION

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
			ELECTRICAL EQUIPMENT			11,069	548	40,532	7,008	58,609
			3 WATER SYSTEMS		87,750	252,408	12,341	1,003,751	175,868	1,519,778
			TOTAL DIRECT	903,951	3,198,508	4,814,210	60,033	5,023,448	842,204	14,782,321

INL/BEA

Estimate No.: 36779B
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Estimate Date: 5/28/2024
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BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
NUCLEAR & HYDROGEN PLANT INTEGRATION

Estimate Totals

Description	Amount	Totals	Hours
Labor Costs	5,023,448		60,033
Material Costs	4,814,211		
Subcontract Costs	903,951		
Construction Equipment Costs	842,204		
Process Equipment Costs	3,198,508		
Total Direct Cost	**14,782,322**	**14,782,322**	
General Conditions			
Additional Labor Costs			
90-1 Labor Supervision	301,400		
90-2 Show-up Time	100,500		
90-3 Cost Due To OT 5-10's	982,800		
90-5 Per Diem	600,300		
Site Overheads			
91-1 Construction Management	2,344,900		
91-2 Field Office Expenses	722,300		
91-3 Material&Quality Control	183,100		
91-4 Site Services	150,400		
91-5 Safety	115,800		
91-6 Temporary Facilities	88,100		
91-7 Temporary Utilities	96,500		
91-8 Mobilization/Demob.	92,900		
91-9 Legal Expenses/Claims	13,700		
Other Construction Indirects			
92-1 Small Tools & Consumables	210,300		
92-2 Scaffolding	410,400		
92-3 General Liability Insurance	58,600		
92-4 Construction Equipment Mob/Demob	84,200		
92-5 Freight on Material	240,700		
92-6 Freight on Process Equipment	159,900		
92-8 Contractors G&A	2,561,600		
92-9 Contractors Profit	3,659,300		
	13,177,700	**27,960,022**	
Project Indirect Costs			
93-1 Engineering Services	3,914,400		
93-2 Construction Management Support	838,800		
93-3 Start-Up/Commissioning	279,600		
93-4 Start-Up/Spare Parts	10,100		
	5,042,900	**33,002,922**	
Contingency			
94-1 Contingency on Construction Equipment	242,500		
94-3 Contingency on Material	1,354,700		
94-4 Contingency on Labor+General Conditions	3,080,800		
94-5 Contingency on Subcontract	242,300		
94-6 Contingency on Process Equipment	671,700		
94-7 Contingency on Project Indirect	1,008,600		
	6,600,600	**39,603,522**	
Escalation			
		39,603,522	
Total		**39,603,522**	

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PLANT SWITCHYARD

Estimator	LJ
Labor rate table	24ILSPR
Project No.	A14248.015
Estimate Date	5/28/2024
Reviewed By	BA
Approved By	BA
Estimate No.	36780B
Factor table	ILSPR

INL/BEA

Estimate No.: 36780B
Project No.: A14248.015
Estimate Date: 5/28/2024
Prep./Rev/App.: LJ/BA/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PLANT SWITCHYARD

Group	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
21.00.00	CIVIL WORK							
	EXCAVATION				122	10,430	1,272	11,702
	DISPOSAL				38	3,239	322	3,562
	BACKFILL			8,281	112	9,531	1,195	19,007
	EROSION AND SEDIMENTATION CONTROL			53,960	167	13,640	5,914	73,514
	FENCEWORK			26,488	205	15,913	846	43,248
	CAISSON	46,800						46,800
	ROAD, PARKING AREA, & SURFACED AREA	25,000						25,000
	CIVIL WORK	71,800		88,729	644	52,754	9,550	222,832
22.00.00	CONCRETE							
	CONCRETE	93,750		15,225	147	11,401	1,849	122,225
	EMBEDMENT			1,925	49	4,173	89	6,187
	FORMWORK			3,775	573	48,582	4,554	56,912
	REINFORCING			9,428	171	13,363	1,863	24,654
	CONCRETE	93,750		30,353	940	77,520	8,355	209,978
23.00.00	STEEL							
	STEEL, MISCELLANEOUS			160,875	193	18,427	5,277	184,579
	STEEL			160,875	193	18,427	5,277	184,579
41.00.00	ELECTRICAL EQUIPMENT							
	GROUNDING			310,500	1,485	114,149	23,301	447,950
	LIGHTNING PROTECTION			87,500	660	50,337	10,236	148,073
	EXTERIOR LIGHTING			17,500	462	35,236	7,165	59,901
	PANEL: CONTROL, DISTRIBUTION, & RELAY			3,000	53	4,027	819	7,846
	POWER TRANSFORMER / LOAD CENTER		14,750,000		2,266	172,822	35,144	14,957,966
	POWER DISTRIBUTION CENTER (PDC)	360,000			550	52,497	15,035	427,532
	SECURITY SYSTEM			61,250	462	35,236	7,165	103,651
	SWITCHGEAR, COMPONENT			30,000	33	2,517	512	33,029
	ELECTRICAL EQUIPMENT, MISCELLANEOUS			1,750	28	2,097	427	4,274
	ELECTRICAL EQUIPMENT	360,000	14,750,000	511,500	5,999	468,917	99,803	16,190,220
43.00.00	CABLE							
	35KV CABLE AND TERMINATION			978,602	3,788	291,120	59,426	1,329,148
	CABLE			978,602	3,788	291,120	59,426	1,329,148
44.00.00	CONTROL & INSTRUMENTATION							
	INSTRUMENT PANEL AND RACK			140,260	132	10,016	176	150,452
	CONTROL & INSTRUMENTATION			140,260	132	10,016	176	150,452
51.00.00	SUBSTATION, SWITCHYARD & TRANSMISSION LINE							
	BUSBAR			30,700	1,073	81,379	1,433	113,512
	CONDUCTORS			1,616	26	1,995	407	4,019
	CIRCUIT BREAKER			1,010,240	1,100	87,723	3,480	1,101,443
	DISCONNECT SWITCH			227,884	728	58,072	1,357	287,314
	LIGHTNING SURGE ARRESTOR			11,048	20	1,502	26	12,577
	TRANSMISSION TOWER, POLE (STEEL)			43,500	57	4,414	901	48,815
	SUBSTATION, SWITCHYARD & TRANSMISSION LINE			1,324,988	3,004	235,086	7,605	1,567,679
	TOTAL DIRECT	525,550	14,750,000	3,235,306	14,700	1,153,839	190,194	19,854,889

INL/BEA

Estimate No.: 36780B
Project No.: A14248.015
Estimate Date: 5/28/2024
Prep./Rev/App.: LJ/BA/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PLANT SWITCHYARD

Estimate Totals

Description	Amount	Totals	Hours
Labor Costs	1,153,839		14,700
Material Costs	3,235,306		
Subcontract Costs	525,550		
Construction Equipment Costs	190,194		
Process Equipment Costs	14,750,000		
Total Direct Cost	**19,854,889**	**19,854,889**	
General Conditions			
Additional Labor Costs			
90-1 Labor Supervision	69,200		
90-2 Show-up Time	23,100		
90-3 Cost Due To OT 5-10's	225,700		
90-5 Per Diem	147,000		
Site Overheads			
91-1 Construction Management	269,900		
91-2 Field Office Expenses	165,900		
91-3 Material&Quality Control	42,000		
91-4 Site Services	34,500		
91-5 Safety	26,600		
91-6 Temporary Facilities	20,200		
91-7 Temporary Utilities	22,200		
91-8 Mobilization/Demob.	21,300		
91-9 Legal Expenses/Claims	3,200		
Other Construction Indirects			
92-1 Small Tools & Consumables	48,600		
92-2 Scaffolding	40,400		
92-3 General Liability Insurance	13,500		
92-4 Construction Equipment Mob/Demob	9,500		
92-5 Freight on Material	161,800		
92-6 Freight on Process Equipment	737,500		
92-8 Contractors G&A	1,534,900		
92-9 Contractors Profit	2,192,800		
	5,809,800	**25,664,689**	
Project Indirect Costs			
93-1 Engineering Services	1,283,200		
93-2 Construction Management Support	769,900		
93-3 Start-Up/Commissioning	256,600		
93-4 Start-Up/Spare Parts	54,400		
	2,364,100	**28,028,789**	
Contingency			
94-1 Contingency on Construction Equipment	46,400		
94-3 Contingency on Material	794,900		
94-4 Contingency on Labor+General Conditions	544,500		
94-5 Contingency on Subcontract	123,000		
94-6 Contingency on Process Equipment	3,624,100		
94-7 Contingency on Project Indirect	472,800		
	5,605,700	**33,634,489**	
Escalation			
		33,634,489	
Total		**33,634,489**	

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - EARLY ADOPTER

Estimator	CK
Labor rate table	24ILSPR
Project No.	A14248.015
Estimate Date	5/28/2024
Reviewed By	JM
Approved By	BA
Estimate No.	36834B
Factor table	ILSPR

INL/BEA

Estimate No.: 36834B
Project No.: A14248.015
Estimate Date: 5/28/2024
Prep/Rev/App.: CK/JM/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - EARLY ADOPTER

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
1			BASE ESTIMATE							
	21.00.00		CIVIL WORK							
		21.13.00	CLEARING & GRUBBING				528	45,096	49,608	94,704
		21.14.00	STRIP & STOCKPILE TOPSOIL				1,901	162,345	178,589	340,933
		21.17.00	EXCAVATION				10,094	861,291	172,217	1,033,508
		21.19.00	DISPOSAL				2,042	174,259	34,843	209,102
		21.20.00	BACKFILL			217,831	11,571	987,357	197,424	1,402,612
		21.21.00	MASS FILL				9,010	769,446	846,437	1,615,882
		21.37.00	EQUIPMENT		195,000		352	30,064	33,072	258,136
		21.41.00	EROSION AND SEDIMENTATION CONTROL			583,680	2,887	229,222	50,766	863,668
		21.43.00	FENCEWORK			124,720	911	70,840	3,767	199,327
		21.47.00	LANDSCAPING	18,464			426	36,358	39,996	94,819
		21.57.00	ROAD, PARKING AREA, & SURFACED AREA	1,760,000		19,900	66	5,632	1,126	1,786,659
			CIVIL WORK	1,778,464	195,000	946,131	39,787	3,371,908	1,607,846	7,899,350
	22.00.00		CONCRETE							
		22.13.00	CONCRETE			3,334,382	31,622	2,447,882	396,964	6,179,228
		22.15.00	EMBEDMENT			689,872	12,649	1,072,376	22,881	1,785,128
		22.17.00	FORMWORK			221,151	36,822	3,120,692	292,541	3,634,384
		22.23.00	PRECAST			190,856	1,584	135,176	27,029	353,061
		22.25.00	REINFORCING			1,931,642	34,152	2,676,157	373,152	4,980,950
			CONCRETE			6,367,902	116,830	9,452,283	1,112,566	16,932,752
	23.00.00		STEEL							
		23.25.00	ROLLED SHAPE			918,580	4,748	453,156	129,782	1,501,518
			STEEL			918,580	4,748	453,156	129,782	1,501,518
	24.00.00		ARCHITECTURAL							
		24.35.00	PRE-ENGINEERED BUILDING	3,228,000						3,228,000
			ARCHITECTURAL	3,228,000						3,228,000
	27.00.00		PAINTING & COATING							
		27.17.00	PAINTING			49,535	2,500	244,421	15,294	309,250
			PAINTING & COATING			49,535	2,500	244,421	15,294	309,250
	31.00.00		MECHANICAL EQUIPMENT							
		31.17.00	INSTRUMENT AIR COMPRESSION		1,307,500		1,232	101,059	2,808	1,411,366
		31.23.00	COOLING TOWER		2,102,000		532	43,672	6,176	2,151,848
		31.41.00	FIRE PROTECTION EQUIPMENT & SYSTEM	960,000	14,000		26	2,166	306	976,472
		31.63.00	NITROGEN GENERATOR		106,641		62	5,053	715	112,409
		31.75.00	PUMPS		2,188,000		2,233	183,169	25,903	2,397,072
		31.83.00	TANKS	1,417,500	308,125		64	5,233	740	1,731,598
		31.93.00	WATER TREATING		4,600,000		4,400	360,924	51,040	5,011,964
		31.98.00	HYDROGEN COMPRESSION & DEHYDRATION		57,698,230		13,127	1,076,637	152,252	58,927,119
		31.99.00	ELECTROLYZER		249,600,000		108,691	8,914,825	1,260,688	259,775,513
			MECHANICAL EQUIPMENT	2,377,500	317,924,496		130,367	10,692,737	1,500,627	332,495,361
	34.00.00		HVAC							
		34.15.00	AIR HANDLING UNIT		7,500		24	1,986	178	9,664
			HVAC		7,500		24	1,986	178	9,664
	35.00.00		PIPING							
		35.13.02	SS 316, ABOVE GROUND, PROCESS AREA			3,693,704	37,985	3,126,903	686,764	7,507,371
		35.14.02	SS 316, STRAIGHT RUN			3,673,428	30,332	2,496,937	548,404	6,718,769
		35.14.10	CARBON STEEL, STRAIGHT RUN			627,016	15,984	1,315,843	289,000	2,231,858
		35.15.02	SS 316, BURIED			336,495	1,429	117,666	25,843	480,004
		35.15.30	HDPE, BURIED			370,700	10,641	875,984	192,393	1,439,077
		35.15.31	CHDPE, BURIED			135,931	774	51,867	11,517	199,315
		35.15.37	CAST IRON, BURIED			104,000	1,859	153,048	33,614	290,662
		35.35.00	PIPE SUPPORTS/HANGERS			8,385	226	18,637	4,093	31,116
		35.36.00	PIPE SUPPORTS, RACK			33,986	2,325	191,356	42,028	267,369
		35.45.00	CARBON STEEL VALVES			286,276	1,633	134,393	29,517	450,185
		35.46.00	STAINLESS STEEL VALVES			2,448,400	11,610	955,727	209,907	3,614,034
		35.99.00	MISCELLANEOUS	49,300			394	32,421	7,121	88,841
			PIPING	49,300		11,718,321	115,193	9,470,781	2,080,201	23,318,603
	36.00.00		INSULATION							

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
		36.17.01	PIPE, CALCIUM SILICATE W/ALUMINUM JACKETING			1,583,289	13,011	1,097,834	103,720	2,784,843
			INSULATION			1,583,289	13,011	1,097,834	103,720	2,784,843
	41.00.00		ELECTRICAL EQUIPMENT							
		41.15.00	CATHODIC PROTECTION			9,000	20	1,510	307	10,817
		41.21.00	CONTROL & BACKUP POWER		31,821,700		28,783	2,195,013	446,358	34,463,071
		41.33.00	HEAT TRACING			211,553	9,300	714,806	145,913	1,072,272
		41.51.00	POWER TRANSFORMER / LOAD CENTER		31,120,000		6,363	485,245	98,675	31,703,920
		41.52.00	POWER DISTRIBUTION CENTER (PDC)		19,358,750		13,762	1,313,481	376,176	21,048,407
		41.99.00	ELECTRICAL EQUIPMENT, MISCELLANEOUS		100,000		48	3,691	751	104,442
			ELECTRICAL EQUIPMENT		82,400,450	220,553	58,277	4,713,747	1,068,179	88,402,928
	42.00.00		RACEWAY, CABLE TRAY & CONDUIT							
		42.15.33	CONDUIT, PVC			79,056	3,102	235,339	4,145	318,540
			RACEWAY, CABLE TRAY & CONDUIT			79,056	3,102	235,339	4,145	318,540
	43.00.00		CABLE							
		43.10.00	CONTROL/INSTRUMENTATION/COMMUNICATION CABLE & TERMINATION			37,500	495	38,050	7,767	83,317
		43.40.00	5/8KV CABLE & TERMINATION			495,560	2,926	224,915	45,912	766,387
		43.50.00	15KV CABLE & TERMINATION			496,890	4,635	356,228	72,716	925,834
			CABLE			1,029,950	8,056	619,192	126,395	1,775,538
	44.00.00		CONTROL & INSTRUMENTATION							
		44.13.00	CONTROL SYSTEM	50,000	1,534,000		35	2,671	47	1,586,718
		44.17.00	INSTRUMENT PANEL, RACK, TUBING AND COMPONENTS			251,500	1,238	94,063	2,065	347,628
		44.21.10	ANALYTICAL DEVICES			4,000	11	850	54	4,904
		44.21.20	FLOW DEVICES			42,072	43	3,316	210	45,598
		44.21.30	LEVEL DEVICES			33,146	141	10,884	690	44,719
		44.21.40	PRESSURE DEVICES			357,994	1,047	80,946	5,131	444,071
		44.21.50	TEMPERATURE DEVICES			313,700	1,101	85,511	6,439	405,650
		44.25.00	MONITORING EQUIPMENT			3,000	18	1,360	60	4,420
		44.98.00	CONTROL & INSTRUMENTATION, TESTING				3,846	297,256	18,843	316,100
		44.99.00	CONTROL & INSTRUMENTATION, MISCELLANEOUS	140,000					151	140,151
			CONTROL & INSTRUMENTATION	190,000	1,534,000	1,005,412	7,480	576,857	33,691	3,339,960
	51.00.00		SUBSTATION, SWITCHYARD & TRANSMISSION LINE							
		51.15.23	CAPACITOR BANK		168,000		264	21,053	1	189,054
			SUBSTATION, SWITCHYARD & TRANSMISSION LINE		168,000		264	21,053	1	189,054
	61.00.00		CONSTRUCTION INDIRECT							
		61.15.00	CRAFT PERSONNEL				22,002	1,804,620	255,200	2,059,820
			CONSTRUCTION INDIRECT				22,002	1,804,620	255,200	2,059,820
			1 BASE ESTIMATE	7,623,264	402,229,446	23,918,730	521,641	42,755,916	8,037,825	484,565,181
2			HIGH PRESSURE COMPRESSION (HPC)							
	21.00.00		CIVIL WORK							
		21.17.00	EXCAVATION				44	3,782	756	4,538
		21.19.00	DISPOSAL				11	963	193	1,156
		21.20.00	BACKFILL				16	1,373	275	1,648
			CIVIL WORK				72	6,118	1,223	7,342
	22.00.00		CONCRETE							
		22.13.00	CONCRETE			31,973	303	23,472	3,806	59,251
		22.15.00	EMBEDMENT			6,615	121	10,283	219	17,117
		22.17.00	FORMWORK			1,399	233	19,736	1,850	22,985
		22.25.00	REINFORCING			18,523	327	25,662	3,578	47,762
			CONCRETE			58,509	985	79,152	9,454	147,115
	31.00.00		MECHANICAL EQUIPMENT							
		31.98.00	HYDROGEN COMPRESSION & DEHYDRATION		14,000,000		5,721	469,201	66,352	14,535,553
			MECHANICAL EQUIPMENT		14,000,000		5,721	469,201	66,352	14,535,553
			2 HIGH PRESSURE COMPRESSION (HPC)		14,000,000	58,509	6,777	554,472	77,029	14,690,010
3			HPC EXCLUDED							
	21.00.00		CIVIL WORK							
		21.17.00	EXCAVATION				-44	(3,782)	(756)	(4,538)
		21.19.00	DISPOSAL				-11	(963)	(193)	(1,156)
		21.20.00	BACKFILL				-16	(1,373)	(275)	(1,648)
			CIVIL WORK				-72	(6,118)	(1,223)	(7,342)
	22.00.00		CONCRETE							

INL/BEA

Estimate No.: 36834B
Project No.: A14248.015
Estimate Date: 5/28/2024
Prep/Rev/App.: CK/JM/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - EARLY ADOPTER

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
		22.13.00	CONCRETE			(31,973)	-303	(23,472)	(3,806)	(59,251)
		22.15.00	EMBEDMENT			(6,615)	-121	(10,283)	(219)	(17,117)
		22.17.00	FORMWORK			(1,399)	-233	(19,736)	(1,850)	(22,985)
		22.25.00	REINFORCING			(18,525)	-328	(25,665)	(3,579)	(47,768)
			CONCRETE			(58,511)	-985	(79,155)	(9,454)	(147,121)
	31.00.00		MECHANICAL EQUIPMENT							
		31.98.00	HYDROGEN COMPRESSION & DEHYDRATION		(14,000,000)		-5,721	(469,201)	(66,352)	(14,535,553)
			MECHANICAL EQUIPMENT		(14,000,000)		-5,721	(469,201)	(66,352)	(14,535,553)
			3 HPC EXCLUDED		(14,000,000)	(58,511)	-6,777	(554,475)	(77,030)	(14,690,016)
			TOTAL DIRECT COST	7,623,264	402,229,446	23,918,728	521,641	42,755,913	8,037,824	484,565,175

INL/BEA

Estimate No.: 36834B
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Estimate Date: 5/28/2024
Prep/Rev/App.: CK/JM/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - EARLY ADOPTER

Estimate Totals

Description	Amount	Totals	Hours
Labor Costs	42,755,913		521,641
Material Costs	23,918,728		
Subcontract Costs	7,623,264		
Construction Equipment Costs	8,037,824		
Process Equipment Costs	402,229,446		
Total Direct Cost	**484,565,175**	**484,565,175**	
General Conditions			
Additional Labor Costs			
90-1 Labor Supervision	2,565,400		
90-2 Show-up Time	855,100		
90-3 Cost Due To OT 5-10's	8,365,300		
90-5 Per Diem	5,216,400		
Site Overheads			
91-1 Construction Management	10,000,300		
91-2 Field Office Expenses	6,147,500		
91-3 Material&Quality Control	1,558,200		
91-4 Site Services	1,279,800		
91-5 Safety	985,700		
91-6 Temporary Facilities	749,900		
91-7 Temporary Utilities	821,800		
91-8 Mobilization/Demob.	790,300		
91-9 Legal Expenses/Claims	116,800		
Other Construction Indirects			
92-1 Small Tools & Consumables	1,792,700		
92-2 Scaffolding	1,496,800		
92-3 General Liability Insurance	498,900		
92-4 Construction Equipment Mob/Demob	401,900		
92-5 Freight on Material	1,195,900		
92-6 Freight on Process Equipment	20,111,500		
92-8 Contractors G&A	30,949,900		
92-9 Contractors Profit	39,935,400		
	135,835,500	**620,400,675**	
Project Indirect Costs			
93-1 Engineering Services	28,160,000		
93-2 Construction Management Support	21,120,000		
93-3 Start-Up/Commissioning	7,040,000		
93-4 Start-Up/Spare Parts	1,415,000		
	57,735,000	**678,135,675**	
Contingency			
94-1 Contingency on Construction Equipment	1,961,200		
94-3 Contingency on Material	5,876,800		
94-4 Contingency on Labor+General Conditions	20,123,300		
94-5 Contingency on Subcontract	1,783,800		
94-6 Contingency on Process Equipment	44,415,000		
94-7 Contingency on Project Indirect	11,547,000		
	85,707,100	**763,842,775**	
Escalation			
		763,842,775	
Total		**763,842,775**	

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - LARGE MODULE

Estimator	CK
Labor rate table	24ILSPR
Project No.	A14248.015
Estimate Date	5/28/2024
Reviewed By	JM
Approved By	BA
Estimate No.	36835B
Factor table	ILSPR

INL/BEA

Estimate No.: 36835B
Project No.: A14248.015
Estimate Date: 5/28/2024
Prep/Rev/App.: CK/JM/BA

BATELLE ENERGY ALLIANCE - IDAHO NATIONAL LABORATORY
500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - LARGE MODULE

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
1			BASE ESTIMATE							
	21.00.00		CIVIL WORK							
		21.13.00	CLEARING & GRUBBING				528	45,096	49,608	94,704
		21.14.00	STRIP & STOCKPILE TOPSOIL				1,901	162,345	178,589	340,933
		21.17.00	EXCAVATION				10,094	861,291	172,217	1,033,508
		21.19.00	DISPOSAL				2,042	174,259	34,843	209,102
		21.20.00	BACKFILL			217,831	11,571	987,357	197,424	1,402,612
		21.21.00	MASS FILL				9,010	769,446	846,437	1,615,882
		21.37.00	EQUIPMENT		195,000		352	30,064	33,072	258,136
		21.41.00	EROSION AND SEDIMENTATION CONTROL			583,680	2,887	229,222	50,766	863,668
		21.43.00	FENCEWORK			124,720	911	70,840	3,767	199,327
		21.47.00	LANDSCAPING	18,464			426	36,358	39,996	94,819
		21.57.00	ROAD, PARKING AREA, & SURFACED AREA	1,760,000		19,900	66	5,632	1,126	1,786,659
			CIVIL WORK	1,778,464	195,000	946,131	39,787	3,371,908	1,607,846	7,899,350
	22.00.00		CONCRETE							
		22.13.00	CONCRETE			3,334,382	31,622	2,447,882	396,964	6,179,228
		22.15.00	EMBEDMENT			689,872	12,649	1,072,376	22,881	1,785,128
		22.17.00	FORMWORK			221,151	36,822	3,120,692	292,541	3,634,384
		22.23.00	PRECAST			190,856	1,584	135,176	27,029	353,061
		22.25.00	REINFORCING			1,931,642	34,152	2,676,157	373,152	4,980,950
			CONCRETE			6,367,902	116,830	9,452,283	1,112,566	16,932,752
	23.00.00		STEEL							
		23.25.00	ROLLED SHAPE			918,580	4,748	453,156	129,782	1,501,518
			STEEL			918,580	4,748	453,156	129,782	1,501,518
	24.00.00		ARCHITECTURAL							
		24.35.00	PRE-ENGINEERED BUILDING	3,228,000						3,228,000
			ARCHITECTURAL	3,228,000						3,228,000
	27.00.00		PAINTING & COATING							
		27.17.00	PAINTING			49,535	2,500	244,421	15,294	309,250
			PAINTING & COATING			49,535	2,500	244,421	15,294	309,250
	31.00.00		MECHANICAL EQUIPMENT							
		31.17.00	INSTRUMENT AIR COMPRESSION		1,307,500		1,232	101,059	2,808	1,411,366
		31.23.00	COOLING TOWER		2,102,000		532	43,672	6,176	2,151,848
		31.41.00	FIRE PROTECTION EQUIPMENT & SYSTEM	960,000	14,000		26	2,166	306	976,472
		31.63.00	NITROGEN GENERATOR		106,641		62	5,053	715	112,409
		31.75.00	PUMPS		2,188,000		2,233	183,169	25,903	2,397,072
		31.83.00	TANKS	1,417,500	308,125		64	5,233	740	1,731,598
		31.93.00	WATER TREATING		4,600,000		4,400	360,924	51,040	5,011,964
		31.98.00	HYDROGEN COMPRESSION & DEHYDRATION		57,698,230		13,127	1,076,637	152,252	58,927,119
		31.99.00	ELECTROLYZER		124,800,000		108,691	8,914,825	1,260,688	134,975,513
			MECHANICAL EQUIPMENT	2,377,500	193,124,496		130,367	10,692,737	1,500,627	207,695,361
	34.00.00		HVAC							
		34.15.00	AIR HANDLING UNIT		7,500		24	1,986	178	9,664
			HVAC		7,500		24	1,986	178	9,664
	35.00.00		PIPING							
		35.13.02	SS 316, ABOVE GROUND, PROCESS AREA			3,693,704	37,985	3,126,903	686,764	7,507,371
		35.14.02	SS 316, STRAIGHT RUN			3,673,428	30,332	2,496,937	548,404	6,718,769
		35.14.10	CARBON STEEL, STRAIGHT RUN			627,016	15,984	1,315,843	289,000	2,231,858
		35.15.02	SS 316, BURIED			336,495	1,429	117,666	25,843	480,004
		35.15.30	HDPE, BURIED			370,700	10,641	875,984	192,393	1,439,077
		35.15.31	CHDPE, BURIED			135,931	774	51,867	11,517	199,315
		35.15.37	CAST IRON, BURIED			104,000	1,859	153,048	33,614	290,662
		35.35.00	PIPE SUPPORTS/HANGERS			8,385	226	18,637	4,093	31,116
		35.36.00	PIPE SUPPORTS, RACK			33,986	2,325	191,356	42,028	267,369
		35.45.00	CARBON STEEL VALVES			286,276	1,633	134,393	29,517	450,185
		35.46.00	STAINLESS STEEL VALVES			2,448,400	11,610	955,727	209,907	3,614,034
		35.99.00	MISCELLANEOUS	49,300			394	32,421	7,121	88,841
			PIPING	49,300		11,718,321	115,193	9,470,781	2,080,201	23,318,603
	36.00.00		INSULATION							

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500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - LARGE MODULE

Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
		36.17.01	PIPE, CALCIUM SILICATE W/ALUMINUM JACKETING			1,583,289	13,011	1,097,834	103,720	2,784,843
			INSULATION			1,583,289	13,011	1,097,834	103,720	2,784,843
	41.00.00		ELECTRICAL EQUIPMENT							
		41.15.00	CATHODIC PROTECTION			9,000	20	1,510	307	10,817
		41.21.00	CONTROL & BACKUP POWER		31,821,700		28,783	2,195,013	446,358	34,463,071
		41.33.00	HEAT TRACING			211,553	9,300	714,806	145,913	1,072,272
		41.51.00	POWER TRANSFORMER / LOAD CENTER		31,120,000		6,363	485,245	98,675	31,703,920
		41.52.00	POWER DISTRIBUTION CENTER (PDC)		19,358,750		13,762	1,313,481	376,176	21,048,407
		41.99.00	ELECTRICAL EQUIPMENT, MISCELLANEOUS		100,000		48	3,691	751	104,442
			ELECTRICAL EQUIPMENT		82,400,450	220,553	58,277	4,713,747	1,068,179	88,402,928
	42.00.00		RACEWAY, CABLE TRAY & CONDUIT							
		42.15.33	CONDUIT, PVC			79,056	3,102	235,339	4,145	318,540
			RACEWAY, CABLE TRAY & CONDUIT			79,056	3,102	235,339	4,145	318,540
	43.00.00		CABLE							
		43.10.00	CONTROL/INSTRUMENTATION/COMMUNICATION CABLE & TERMINATION			37,500	495	38,050	7,767	83,317
		43.40.00	5/8KV CABLE & TERMINATION			495,560	2,926	224,915	45,912	766,387
		43.50.00	15KV CABLE & TERMINATION			496,890	4,635	356,228	72,716	925,834
			CABLE			1,029,950	8,056	619,192	126,395	1,775,538
	44.00.00		CONTROL & INSTRUMENTATION							
		44.13.00	CONTROL SYSTEM	50,000	1,534,000		35	2,671	47	1,586,718
		44.17.00	INSTRUMENT PANEL, RACK, TUBING AND COMPONENTS			251,500	1,238	94,063	2,065	347,628
		44.21.10	ANALYTICAL DEVICES			4,000	11	850	54	4,904
		44.21.20	FLOW DEVICES			42,072	43	3,316	210	45,598
		44.21.30	LEVEL DEVICES			33,146	141	10,884	690	44,719
		44.21.40	PRESSURE DEVICES			357,994	1,047	80,946	5,131	444,071
		44.21.50	TEMPERATURE DEVICES			313,700	1,101	85,511	6,439	405,650
		44.25.00	MONITORING EQUIPMENT			3,000	18	1,360	60	4,420
		44.98.00	CONTROL & INSTRUMENTATION, TESTING				3,846	297,256	18,843	316,100
		44.99.00	CONTROL & INSTRUMENTATION, MISCELLANEOUS	140,000					151	140,151
			CONTROL & INSTRUMENTATION	190,000	1,534,000	1,005,412	7,480	576,857	33,691	3,339,960
	51.00.00		SUBSTATION, SWITCHYARD & TRANSMISSION LINE							
		51.15.23	CAPACITOR BANK		168,000		264	21,053	1	189,054
			SUBSTATION, SWITCHYARD & TRANSMISSION LINE		168,000		264	21,053	1	189,054
	61.00.00		CONSTRUCTION INDIRECT							
		61.15.00	CRAFT PERSONNEL				22,002	1,804,620	255,200	2,059,820
			CONSTRUCTION INDIRECT				22,002	1,804,620	255,200	2,059,820
			1 BASE ESTIMATE	7,623,264	277,429,446	23,918,730	521,641	42,755,916	8,037,825	359,765,181
2			HIGH PRESSURE COMPRESSION (HPC)							
	21.00.00		CIVIL WORK							
		21.17.00	EXCAVATION				44	3,782	756	4,538
		21.19.00	DISPOSAL				11	963	193	1,156
		21.20.00	BACKFILL				16	1,373	275	1,648
			CIVIL WORK				72	6,118	1,223	7,342
	22.00.00		CONCRETE							
		22.13.00	CONCRETE			31,973	303	23,472	3,806	59,251
		22.15.00	EMBEDMENT			6,615	121	10,283	219	17,117
		22.17.00	FORMWORK			1,399	233	19,736	1,850	22,985
		22.25.00	REINFORCING			18,523	327	25,662	3,578	47,762
			CONCRETE			58,509	985	79,152	9,454	147,115
	31.00.00		MECHANICAL EQUIPMENT							
		31.98.00	HYDROGEN COMPRESSION & DEHYDRATION		14,000,000		5,721	469,201	66,352	14,535,553
			MECHANICAL EQUIPMENT		14,000,000		5,721	469,201	66,352	14,535,553
			2 HIGH PRESSURE COMPRESSION (HPC)		14,000,000	58,509	6,777	554,472	77,029	14,690,010
3			HPC EXCLUDED							
	21.00.00		CIVIL WORK							
		21.17.00	EXCAVATION				-44	(3,782)	(756)	(4,538)
		21.19.00	DISPOSAL				-11	(963)	(193)	(1,156)
		21.20.00	BACKFILL				-16	(1,373)	(275)	(1,648)
			CIVIL WORK				-72	(6,118)	(1,223)	(7,342)
	22.00.00		CONCRETE							

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Area	Group	Phase	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Construction Equipment Cost	Total Cost
		22.13.00	CONCRETE			(31,973)	-303	(23,472)	(3,806)	(59,251)
		22.15.00	EMBEDMENT			(6,615)	-121	(10,283)	(219)	(17,117)
		22.17.00	FORMWORK			(1,399)	-233	(19,736)	(1,850)	(22,985)
		22.25.00	REINFORCING			(18,525)	-328	(25,665)	(3,579)	(47,768)
			CONCRETE			(58,511)	-985	(79,155)	(9,454)	(147,121)
	31.00.00		MECHANICAL EQUIPMENT							
		31.98.00	HYDROGEN COMPRESSION & DEHYDRATION		(14,000,000)		-5,721	(469,201)	(66,352)	(14,535,553)
			MECHANICAL EQUIPMENT		(14,000,000)		-5,721	(469,201)	(66,352)	(14,535,553)
			3 HPC EXCLUDED		(14,000,000)	(58,511)	-6,777	(554,475)	(77,030)	(14,690,016)
			TOTAL DIRECT COST	7,623,264	277,429,446	23,918,728	521,641	42,755,913	8,037,824	359,765,175

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500 MW REFERENCE PLANT
HYDROGEN PRODUCTION FACILITY - LARGE MODULE

Estimate Totals

Description	Amount	Totals	Hours
Labor Costs	42,755,913		521,641
Material Costs	23,918,728		
Subcontract Costs	7,623,264		
Construction Equipment Costs	8,037,824		
Process Equipment Costs	277,429,446		
Total Direct Cost	**359,765,175**	**359,765,175**	
General Conditions			
Additional Labor Costs			
90-1 Labor Supervision	2,565,400		
90-2 Show-up Time	855,100		
90-3 Cost Due To OT 5-10's	8,365,300		
90-5 Per Diem	5,216,400		
Site Overheads			
91-1 Construction Management	10,000,300		
91-2 Field Office Expenses	6,147,500		
91-3 Material&Quality Control	1,558,200		
91-4 Site Services	1,279,800		
91-5 Safety	985,700		
91-6 Temporary Facilities	749,900		
91-7 Temporary Utilities	821,800		
91-8 Mobilization/Demob.	790,300		
91-9 Legal Expenses/Claims	116,800		
Other Construction Indirects			
92-1 Small Tools & Consumables	1,792,700		
92-2 Scaffolding	1,496,800		
92-3 General Liability Insurance	498,900		
92-4 Construction Equipment Mob/Demob	401,900		
92-5 Freight on Material	1,195,900		
92-6 Freight on Process Equipment	13,871,500		
92-8 Contractors G&A	25,521,100		
92-9 Contractors Profit	34,319,400		
	118,550,700	**478,315,875**	
Project Indirect Costs			
93-1 Engineering Services	26,240,000		
93-2 Construction Management Support	19,680,000		
93-3 Start-Up/Commissioning	6,560,000		
93-4 Start-Up/Spare Parts	988,800		
	53,468,800	**531,784,675**	
Contingency			
94-1 Contingency on Construction Equipment	1,961,200		
94-3 Contingency on Material	5,876,800		
94-4 Contingency on Labor+General Conditions	20,123,300		
94-5 Contingency on Subcontract	1,783,800		
94-6 Contingency on Process Equipment	40,958,000		
94-7 Contingency on Project Indirect	10,693,800		
	81,396,900	**613,181,575**	
Escalation			
		613,181,575	
Total		**613,181,575**	