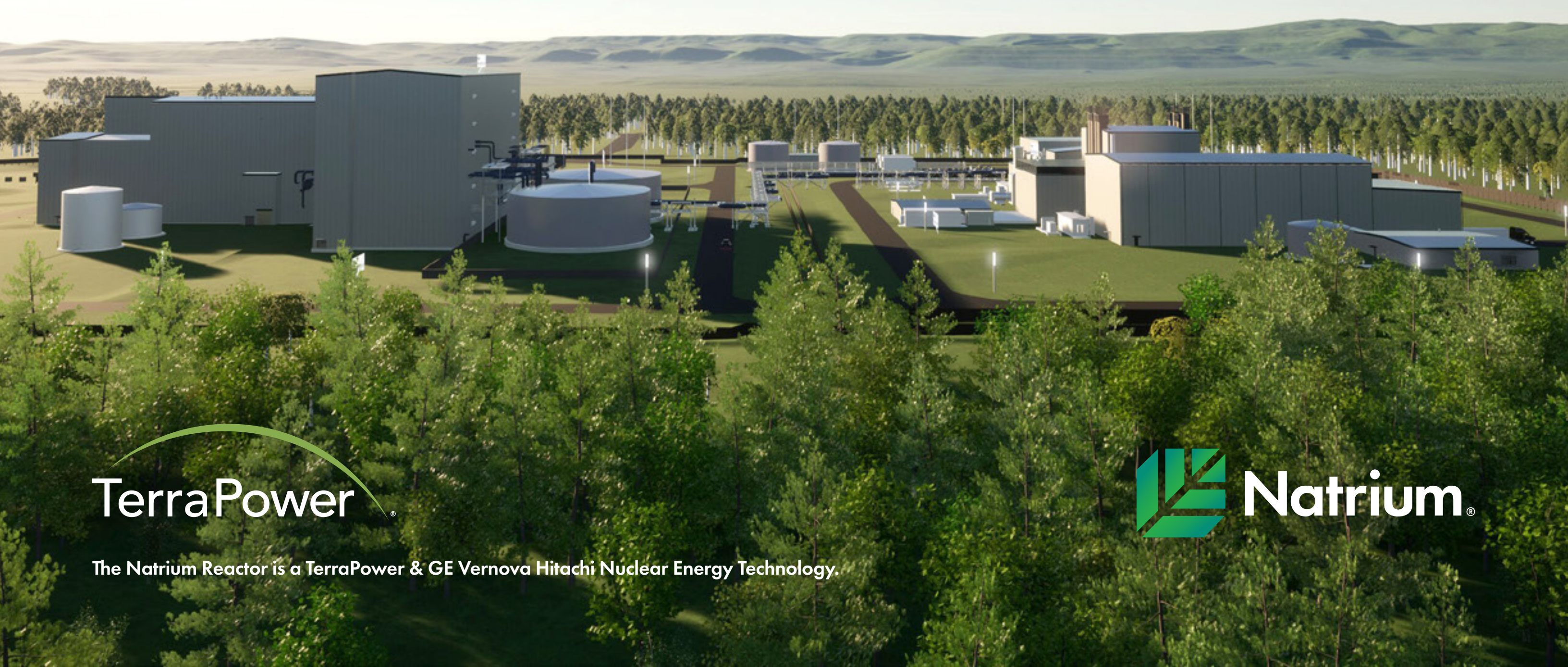
APPLICATION OF NATRIUM® SODIUM FAST REACTOR PLANTS TO SUPPLY HEAT AND POWER TO INDUSTRIAL FACILITIES

Marcel D Berz, PE; Robert Petroski, PhD;
Josh Stuart, PE, Christopher Dayton, PE



TerraPower

Natrium

The Natrium Reactor is a TerraPower & GE Vernova Hitachi Nuclear Energy Technology.

Marcel D Berz, PE; Robert Petroski, PhD; Josh Stuart, PE, Christopher Dayton, PE

ABSTRACT

TerraPower, LLC has developed the Natrium sodium fast reactor (SFR), an advanced nuclear reactor capable of generating carbon-free energy while a thermal energy storage (TES) system provides the ability to peak power output above reactor output for periods with high demand. The Natrium technology has the unique design feature of having a nuclear island that is physically separated and decoupled from a nuclear safety perspective from the energy island portion of the plant that raises steam and generates power. The Natrium technology is uniquely qualified to supply not only power but also heat (for example, in the form of process steam) to existing industrial facilities to replace all or a portion of their fossil fuel fired generating assets, therefore reducing greenhouse gas emissions. TerraPower's demonstration plant, Kemmerer Unit 1, is currently under construction in Kemmerer, Wyoming as part of the Department of Energy's (DOE) Advanced Reactor Demonstration Program (ARDP).

As an extension of its demonstration efforts, TerraPower performed a trade study to illustrate how a Natrium plant could supply all or a portion of the necessary process steam and electricity to a chemical production complex on the Gulf Coast of the Southern United States. This study included an evaluation of the impact of steam demand fluctuation on Natrium plant operations as well as the impact of periodically required reactor refueling outages on the ability to supply the necessary steam and power to the chemical plant.

The trade study established initial process sizing for a Natrium plant and evaluates its performance to meet the chemical plant's needs. Two options were considered; the first option proposes replacing all the chemical plant's current power and steam generating assets with a Natrium plant. The second option would replace six of the existing combined cycle units while the chemical plant would maintain operation of its three steam turbine generators. This included establishing preliminary overall plant plot size requirements and an attempt was made to preliminary locate the Natrium plant near the chemical plant location. Results show that Natrium technology is adaptable to serving industrial users by providing not only power but also process steam, and allowing the necessary flexibility to meet the variable demands typical for large industrial users.

INTRODUCTION

The Natrium technology utilizes an advanced modular sodium fast reactor (SFR) with a pool-type architecture and integrated in-line thermal energy storage (TES). SFR's are inherently safer than light water reactors (LWR) because sodium stays liquid at ambient pressure up to 1616 °F (880°C) which allows sodium cooling at pressures near atmospheric during normal operation and when removing decay heat during a loss of electrical power event. TerraPower has been awarded an advanced reactor demonstration program (ARDP) award from the U.S. Department of Energy (DOE) to build a Natrium demonstration plant in Kemmerer, Wyoming that is referred to as Kemmerer Unit 1 (KU1).

A key feature of the Natrium technology is the separation between nuclear island (NI) and energy island (EI) from a nuclear safety case and physical layout perspective. Figure 1 illustrates this division that allows commercial construction scope for the EI part of the plant. This provides reduced construction costs, and operational flexibility making it easier to apply the technology to supply power and heat to industrial users. Each Natrium reactor is designed for 840 MW thermal power which results in up to 345 MW electrical power supply to the grid, or a combination of heat (for example in the form of process steam) and electrical power. The peak power output and energy storage capacity can be customized based on the client's applications. Similarly, the proportion of heat or steam to power can also be customized. Figure 2 shows an artist rendering of a potential plant arrangement with two modular Natrium reactors.

Other key features of Natrium technology compared to LWRs include a smaller emergency planning zone, simplified design leading to reduced cost and shortened construction duration, less radioactive waste per MWhr of power output, and higher thermal cycle energy efficiency. Table 1 shows a comparison of Natrium technology to typical LWRs. One other notable feature is flexibility in Natrium's plant architecture, which enables the NI and EI to be set apart by as much as one kilometer or more depending on cost-benefit analyses and associated use cases.

	Typical LWR	Natrium Technology
Rankine efficiency	~31% net	41% net
Steam Cycle	Saturated high-pressure steam with reheater	Superheated steam high-pressure steam with reheater
Thermal energy storage	no	yes
Fuel utilization (MWd/kg)	68 to 70	150
Radioactive waste	Twice as much as for a Natrium reactor	Reduced by 50% per MW
Primary loop pressure	155 bar/2250 psi PWR 75 bar/1100 psi BWR	Near atmospheric
Primary loop temperature	~345°C/653°F	540°C/1004°F hot leg
Cooling during blackout (w/o external power)	Backup fossil fuel generator is needed to keep the cooling water pressurized to avoid core overheating	Sodium will stay liquid at ambient pressures without the need for backup power
Ramp rate	Slower: Typically 2.5% to 5% per minute	Fast: 10%/per minute
Peaking power	Requires changing reactor power, which negatively impacts economics	Energy Island power can change from 30% to 150% while reactor power stays at 100%

Table 1. Comparison of Natrium Technology with Typical LWR Technology

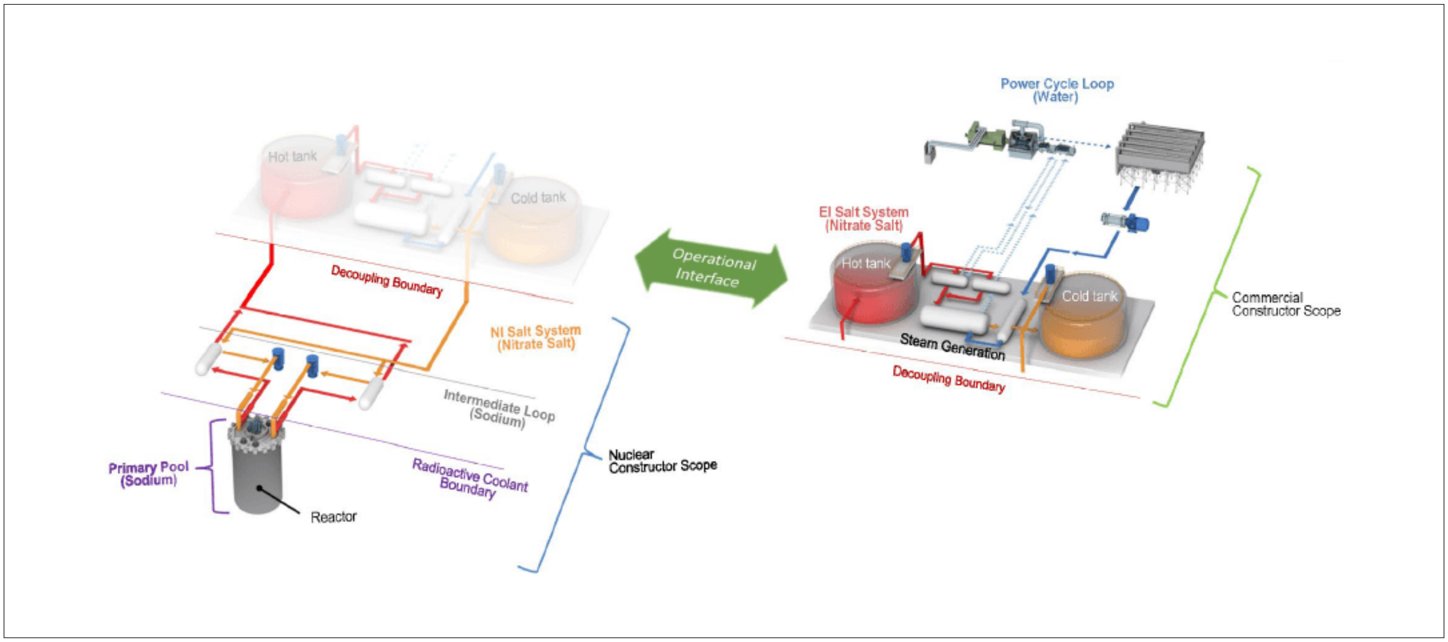


Figure 1: Natrium Heat Transport Loops and Division of Construction Scope

Figure 2: Rendering of Potential Natrium Dual Unit Layout

PURPOSE

A trade study was conducted to illustrate a Natrium plant supplying necessary heat, in the form of process steam, and electrical power to a chemical plant. The purpose was to show how supplying process steam in addition to electricity will impact power generation and to illustrate the adaptability of a Natrium plant to the needs of a chemical plant regarding demand variability for steam and power and impact of a refueling outage on one of multiple reactors.

The chemical plant chosen for this evaluation is located in the Southern United States and manufactures petrochemicals and polymers. The chemical plant owner provided detailed information on power and steam demands for use in this trade study, but under the agreement of anonymity. The use of actual demand data for a chemical plant supports the validity of the conclusions of this study.

The Natrium plant was sized assuming an advanced nuclear fuel product currently under development that is expected to be licensed in the early 2030s. It was further assumed that water availability is not restricted for use in a mechanical evaporative cooling tower, even though designs with air-cooled condensers including dry air cooling or hybrid cooling towers with wet and dry sections can be accommodated. The plant was sized for typical summer conditions based on its location in the Southern USA (2% exceedance ambient conditions). Since cooling occurs with ambient air in the cooling tower, the plant power output is dependent on its location, and the power output will slightly vary with seasonal and daily changes in ambient temperatures and relative humidity.

SCOPE

The scope of the trade study included conducting the initial process design for a Natrium plant located in the Southern United States. Particularly, two options providing steam and power were pursued and compared to a base option providing power only. The first option (Opt. 1) was to supply all process steam and power. The second option (Opt. 2) was to supply high pressure steam to the three existing steam turbine generators and the amount of power currently provided by chemical plant's gas turbines. For Opt. 1, the Natrium SFR plant would replace all current power generating equipment while for Opt. 2 the Natrium plant would only replace the chemical plant's existing combined cycle units and the existing steam turbine generator would continue to operate with high pressure steam although provided by the Natrium SFR plant instead of the combined cycle units.

The process design for Opt. 1 was then used to show performance at several scenarios, including periods when steam demand differs from normal averages and during a refueling outage of one of the several Natrium units. The goal of this was to illustrate how a Natrium plant would handle these situations and how it would impact performance. An example of the Natrium plant layout and size is also provided for Opt. 1 including locating it near the existing chemical plant.

DESCRIPTION OF CHEMICAL PLANT STEAM AND POWER DEMAND

Power and Steam Generating Units:

The chemical plant's power and steam generating equipment includes the following:

- Six combined cycle units each consisting of a gas turbine that generates power and either a heat recovery steam generator (HRSG) or a boiler to raise steam from the gas turbine exhaust.
- Three steam turbine generators. Two of them use high pressure steam from the HRSGs and boilers to generate power. One of the high-pressure steam turbines is a condensing turbine, and the other is a backpressure turbine that supplies process steam from the exhaust. Both are equipped with extractions. The extraction of the high-pressure condensing turbine provides steam for process usage and to a third lower pressure steam turbine generator.

Normal power generation is 700 MWe with approximately 81% provided by the six gas turbines and the remaining 19% by the three steam turbine generators. Most of the generated power is used internally by the plant, but 32% or 225 MWe is normally exported. Variations in internal power usage are typical due to equipment coming online or going offline for maintenance. Maximum and minimum typical power generation was reported to be 785 MWe and 500 MWe, respectively.

Each power generating asset has planned maintenance down times every 12 to 14 months with a duration of 21 to 60 days. These maintenance outages are typically scheduled assuring that never more than one unit undergoes a planned maintenance outage at the same time. Steam supply is typically made up by other assets during a generating unit down for maintenance, but power generation from combined cycle units is not compensated for by other units generating more power; rather, the plant exports less power during these times. Typically, power generation during maintenance outages can be as low as 500 MWe with almost 100% used internally.

Steam Demand

Table 2 shows the plant's normal process steam usage by steam header pressure. Also, shown are typical ranges. Note that the table does not show high-pressure steam supplied to steam turbine generators. Approximately 38% of the normal 600 psi steam and 17% of the normal 175 psi steam is typically supplied to external customers.

All process steam usage is relatively steady outside of planned unit outages. Steam fluctuations occur during equipment cleaning and affect the 175-psig steam header. This steam fluctuation is typically a curtailment of 450 kpph every 7 to 9 days for roughly 4 to 6 hours. Additionally, the 175-psig external customer demand swings often from 80 to 220 kpph (kilo pounds per hour) within several minutes.

Steam normally produced by the HRSGs and gas boilers is listed below. All 1900 psi and 1200 psig steam is supplied to the two high pressure steam turbine generators and extraction from the 1900 psi turbine is supplied to the third condensing steam turbine generator.

- 1900 psig (131 bar) Steam: 1000 kpph (126.0 kg/s)
- 1250 psig (86 bar) Steam: 1425 kpph (179.5 kg/s)
- 175 psig (12.1 bar) Steam: 120 kpph (15.12 kg/s) (from HRSG low pressure drums)

As seen, 2,545 kpph of steam is normally generated, of which 850 kpph is condensed in the two condensing turbines and the remainder is supplied as process steam to the chemical plant and exported to external users.

	Units	Normal	Max	Min
600 psi Steam	kpph	400	900	330
400 psi Steam	kpph	540	565	365
175 psi Steam	kpph	690	870	210
30 psi Steam	kpph	65	120	0
Total	kpph	1695	2455	905

Table 2. Chemical Plant Process Steam Usage Supplied from Current Steam Generators

RESULTS

New Natrium Plant Providing all Process Steam and Power (Opt. 1)

In this scenario, a new Natrium plant would replace all existing power and steam generating equipment at the chemical facility. The new Natrium plant would have to supply the normal process steam flow listed in Table 2 and at least 700 MWe of electrical power, which is the normal power consumption including power currently exported.

The Natrium plant would consist of three 840 MWth reactors and associated cooling loops. The nuclear fuel assumed for this study is an advanced fuel product currently under development that is expected to be licensed in the early 2030's. There is no need for significant TES based on the current chemical plant demand which typically is not significantly fluctuating throughout a typical day of operation. Changes in process steam demand can easily be accommodated by the steam turbine extractions and adjustments to power produced. Therefore, the Natrium plant would include a minimum thermal storage capacity to allow for short-term fluctuations and hold the salt needed to fill the piping upon startup. Steam generated by each reactor's salt-to-steam generators will be fed to two identical steam turbine generators, each consisting of a high-pressure (HP), an intermediate-pressure (IP), and two low-pressure (LP) turbine sections including reheating between the HP and IP sections. Note, that it could be possible for a three-reactor plant to feed steam to a single steam turbine generator, but for redundancy purposes two steam generators were chosen for this example.

Thermodynamic software from Thermoflow Inc. was used to model the Rankine cycle performance. Figure 3 shows a schematic model output, and some of the projected key parameters are summarized in Table 3 and compared to a Natrium plant that produces electric power only and does not provide process steam (designated Opt. 0 for comparison purposes). As seen from Table 3, a three-reactor Natrium plant was projected to generate 961 MWe net (which averages 320 MWe per reactor) without supplying process steam. Note that this is at summer conditions (2% exceedance values) and will vary by some degree based on the plant location due to plant's cooling tower relying on ambient air for cooling.

The Natrium plant (Opt. 1) would provide 807 MWe net, which is 107 MWe and 22 MWe more than the current normal and maximum power demand of the chemical plant, respectively. The higher power output is a consequence of the modular reactor design with a single reactor size of 840 MW thermal. However, this allows some flexibility to meeting the process heat demands during times when more process steam is needed.

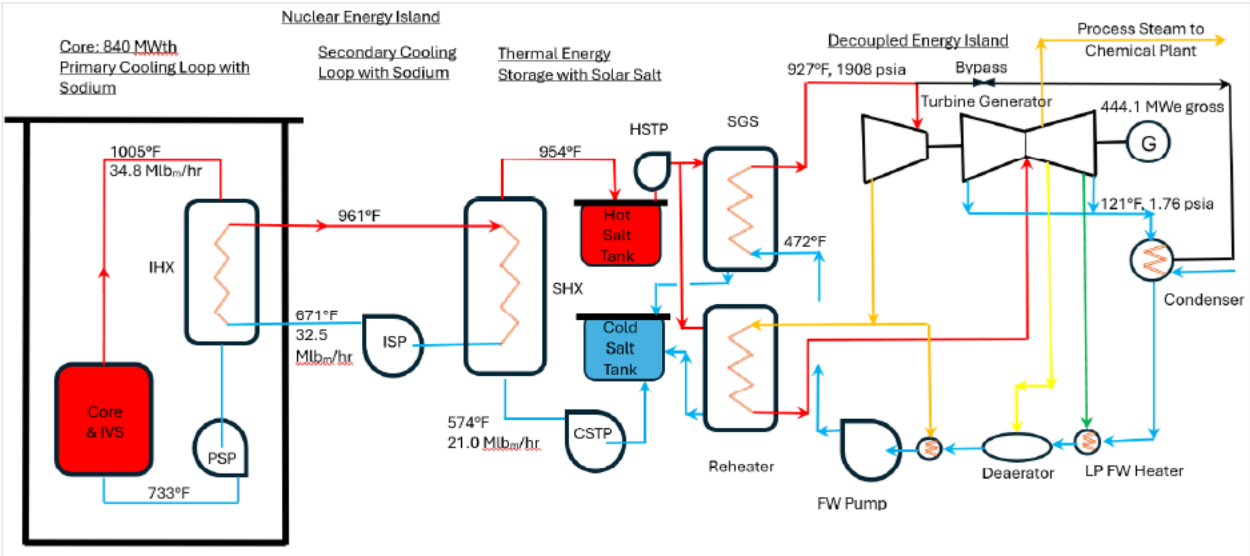


Figure 3: Natrium Heat Transport Loops and Division of Construction Scope

		Option 0: Power only	Option 1: Normal	Option 2: Normal	Option 1: High Steam Need	Option 1: Refueling Outage
Number of reactors in operation	#	3	3	3	3	2
Total gross power	MWe	1,059	888	710	812	529
Total projected net power	MWe	961	807	630*	731	468
Total reactor thermal power	MWth	2,520	2,520	2,520	2,520	1,680
Gross Rankine efficiency	%	41.86	35.09	28.06	32.08	31.36
Combined gross efficiency**	%	NA	58.39	65.67	65.79	66.22
Total high-pressure steam	kpph	7,033	7,636	7,962	7,564	4,742
Reheater steam flow	kpph	6,683	6,768	4,931	6,202	4,088
Total steam flow to chemical facility	kpph	0	1,695	2,545	2,455	1,695

*Not including 137 MWe generated by the chemical plants existing steam turbine generators.
** Gross power plus process steam heat minus return condensate heat, all divided by reactor thermal power.

Table 3. Predicted Performance Parameters for a Three-Reactor Natrium Plant (Summer C onditions)

New Natrium Plant Providing Steam to Existing Steam Turbine Generators and Power to Replace Combined Cycle Units (Opt. 2)

In this scenario, a new Natrium plant would replace all existing combined cycle units (gas turbines and heat recovery steam generators) at the chemical facility. The new Natrium plant would supply high-pressure steam to the existing steam turbine generators and sufficient power to achieve at least 700 MWe of electrical power together with the power generated by the existing three steam turbine generators. Process steam would be supplied similarly as currently from steam turbine extractions and/or exhausts in the case of the back-pressure turbine. The 175-psig steam currently generated by the low-pressure section of the HRSG would be supplied by the backpressure steam turbine. The additional high-pressure steam flow to this backpressure turbine was estimated to increase its power generation from normally 35 MWe to about 42 MWe, which is still lower than the unit's design rating of 60 MWe.

Since the Natrium plant is most efficient generating steam at approximately 1900 psig and 926°F, high-pressure steam supply to the existing steam turbine that currently uses 1900 psig steam would be at lower pressure due to pressure losses in the steam piping. It was estimated that this would reduce the power normally generated from that turbine generator from 70 MWe to approximately 65 MWe. In total, the three steam turbine generators would generate 137 MWe in this scenario, which would require the Natrium plant to provide at least the remaining 563 MWe to maintain the current normal power generation rate.

Like Opt. 1 above, the Natrium plant would consist of three 840 MWth size reactors and associated cooling loops, minimum TES capacity, and would feed steam to two new steam turbine generators with HP, IP, and two LP stages and reheating between HP and IP turbines. A portion of the HP-steam would be supplied to the chemical plant's existing HP condensing steam turbine generator, and HP turbine extraction steam would be supplied to the chemical plant's existing backpressure turbine that uses 1200 psig inlet steam.

Table 3 summarizes some of the key performance parameters for this option. The results indicate 630 MWe from the new Natrium plant steam turbines which together with the power generation from the existing steam turbine would result in a total of 765 MWe. This is less than the winter demand of 785 MWe for the chemical plant, and 5% less than predicted for Opt. 1. This is not unexpected, indicating that the efficiency of the Natrium plant steam turbine generator is higher than for the existing smaller steam turbine in the chemical facility. Therefore, supplying lower pressure process steam and replacing all 6 combined cycle and 3 steam turbine generators with a Natrium plant would be preferred from a performance consideration.

Natrium Plant at Times with Deviation from Normal Steam Demand and During Reactor Refueling

Table 2 indicates not only the normal process steam flow but also gives minimum and maximum values. Note that the maximums at each steam supply pressure may not necessarily occur simultaneously since these are impacted by generating asset and user down times, and the same is true for the minimums. To explore the impact of process steam usage on power generation of a Natrium plant, a case with simultaneous maximum process steam demand at all four pressures was considered for Option 1. Key performance parameters are included in Table 2 (4th data column from the left). As seen, net power output was predicted to decrease by 76 MWe or 9% but remains 4% above the normal demand of 700 MWe. This demonstrates that the Natrium plant sizing can accommodate the current range of process steam demand while supplying the normal power demand of the chemical plant.

Each Natrium reactor requires refueling outages every 24 months. The outages can be scheduled to occur staggered with two refueling outages every second year and one refueling outage between. On average, a three-unit Natrium plant would operate with one reactor in refueling outage approximately 17.3% of the time. This compares favorably to the existing six combined cycle asset's outage requirements of approximately every 13 months for 21 to 60 days or operating with one unit in maintenance approximately 61% of the time. The current annual power generation of the chemical plant was estimated to be approximately 5,726 GWhr per year when considering outages and higher demands in winter.

Key performance parameters for a Natrium plant operating with one of three reactors in refueling outage, while still supplying the normal quantity of process steam, are included in the far-right column in Table 2. As expected, hot weather power generation during those periods would be less than normal demand and slightly lower than the normal inhouse power demand excluding power supplied to external clients. However, even when considering the refueling outages, a Natrium plant would generate an average of 6,557 GWhr annually which is 14.5% higher than the chemical plant's current power generation. The chemical plant could either purchase the additional power from the grid during refueling outages or alternatively choose to keep at least one natural gas fired unit and one turbine generator operable for times of a Natrium plant refueling outage.

EXAMPLE LAYOUT AND SIZE OF NATRIUM PLANT

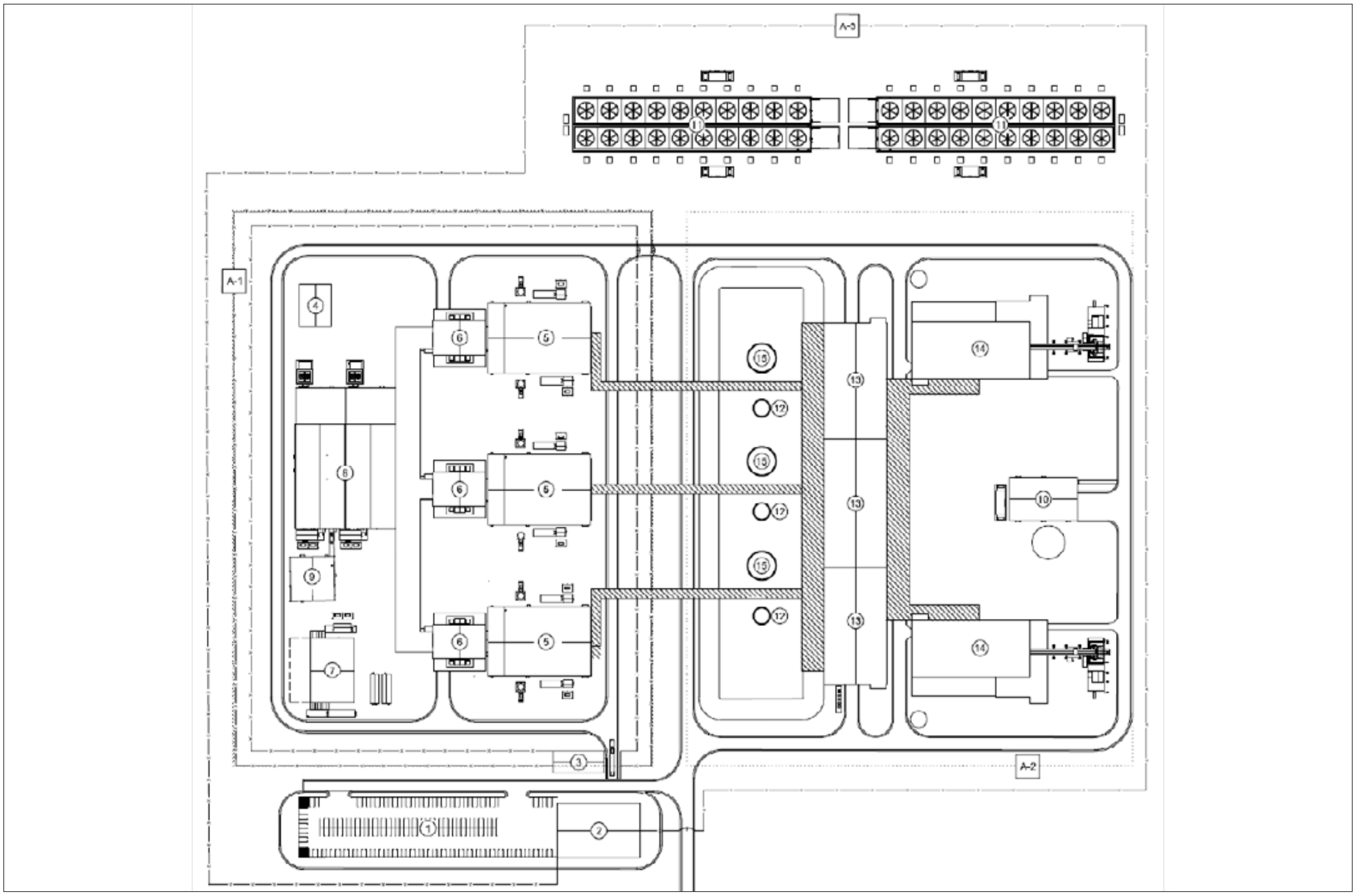


Figure 4. Conceptual Arrangement of a Three-Reactor Natrium Plant

The space requirement of a three-reactor Natrium plant would be approximately 77 acres (3.35 million square feet). Figure 4 shows an example conceptual arrangement of a three-reactor Natrium plant labeled "A-3". The area labeled "A-1" represents the Nuclear Island, and the area labeled "A-2" indicates the Energy Island. Major structures shown include the wet cooling towers (No. 11), the turbine buildings (No. 14), the steam generation buildings (No. 13), and the salt tanks for the thermal energy storage system (Nos. 12 and 15). The required plot area is approximately 1920 ft by 1750 ft. This example layout includes additional space to enhance constructability. Due to the distributed nature of the Natrium plant's structures, this layout can be customized to meet the size and shape constraints of specific sites.

One of the challenges of retrofitting an existing chemical plant with a new Natrium plant is finding an adequate location close to the chemical plant to minimize heat and pressure losses in steam and condensate piping between the locations. This is especially challenging for chemical plants located in a relatively densely industrialized area. Also, chemical plants are often located near water access such as rivers, lakes, and oceans, which can be prone to flooding. One potential solution lies in Natrium's innovative plant architecture, which enables the nuclear island and energy islands to be set apart by as much as one kilometer or more depending on cost-benefit analyses and associated use cases. All this needs to be considered when planning construction of a nuclear plant to replace fossil fuel units at existing chemical facilities.

FINDINGS AND CONCLUSIONS

This trade study gives an example how an advanced modular reactor using Natrium technology could replace the existing natural gas fired generating assets at a chemical facility on the Gulf Coast of the Southern USA. A three-reactor Natrium plant could replace the existing six combined cycle units and three gas turbine generators and be able to adapt the normal swings in process steam demand. Even at the maximum process steam demand the Natrium plant power output would still be able to meet the facility's normal demands. Power generation from a Natrium plant would exceed the current normal usage at normal process steam demand by 15% and the peak power demand by 3%. This would give the opportunity to export more power to adjacent industries and/or alternatively reduce reactor power output at times to reduce nuclear fuel burnup.

Nuclear reactors typically require longer, but less frequent, scheduled outages for refueling than combined cycle units and steam turbine generators. A three-reactor Natrium plant would on average operate approximately 17.3% of the time with one reactor in refueling outage, generating less power than needed but still providing all required process steam. The potential lower power output during refueling outages could be more than offset by the higher power output during the remaining time also provides a benefit if this extra power can be sold to the grid or other users. Overall, the Natrium plant would generate 713 GWhr per year more power than the plant currently generates. The chemical facility could also choose to keep at least one natural gas fired unit and turbine generator operable for redundancy and during times of a Natrium plant refueling outage.

In summary, the use of advanced modular nuclear reactors with Natrium technology provides an excellent option to reduce carbon dioxide emissions by supplying electrical power and process steam to a variety of industrial users, including but not limited to petrochemicals and polymers producers. Industrial users with combined process heat and electrical power demand (with 38 to 41% net efficiency for electrical to thermal conversion) of at least approximately 840 MW thermal are in the size range to consider a Natrium modular reactor to reduce their carbon footprint.

TerraPower Natrium

The Natrium Reactor is a TerraPower & GE Vernova Hitachi Nuclear Energy Technology.

TerraPower

Natrium®