Assessments of advanced reactor heat supply to high temperature industrial unit operations

Heat Engines and Heat Pumps

Nuclear Science and Engineering Division
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ABSTRACT

In this report, the feasibility of employing Advanced Nuclear Reactors to supply the necessary high-quality heat to Industrial Processes is investigated. As a first step, the most relevant industrial applications that could benefit from this coupling were identified. Four industries including petroleum refining (distillation, catalyst regeneration, hydro-steam cracking), chemical polymers, steel manufacturing (metals annealing/soaking) and cement manufacturing (calcination of limestone and dolomite industries) were considered. An overview of the heat duties, i.e., the temperatures and thermal powers required by representative plants of the different processes, was provided. Secondly, the thermodynamic conditions of the steam produced by representative designs of Advanced Reactor concepts (Liquid Metal Fast Breeder Reactors, Molten Salt Reactors, and High Temperature Gas-cooled Reactors) were summarized.

The comparison between the requirements of the industrial processes and the capabilities of the candidate nuclear power plants showed that only a few processes could benefit from the coupling. Although Advanced Reactors operate at higher temperatures than Light Water Reactors, the thermodynamic conditions of the generated steam flow rates are generally not suitable for the selected applications. At the same time, data indicate that most of the processes can be suitably supplied if the temperature of steam is elevated to 900 °C. One possible solution to boost the quality of the steam from the nuclear island involves the use of a heat pump. Based on a technology similar to that found in refrigerators and air conditioners, heat pumps extract heat from a source, elevate its temperature and transfer it to where it is needed. A simple numerical example illustrating the viability of this method is described. Specifically, the energy conversion cycle of a conventional Pressurized Water Reactor was extended to incorporate a compressor to raise the heating value of the steam produced by the reactor. Two reference configurations, i.e., one where the industrial process coupled to the nuclear power plant exhausts saturated liquid and the other where it exhausts saturated steam, were considered. The thermal efficiencies achievable by increasing the heating value of the reactor steam in this way are significantly greater than by direct electric heating.
1. INTRODUCTION

Industrial process heat is defined as thermal energy used directly in the preparation or treatment of materials used to produce manufactured goods. Industrial process heat accounts for more than two-thirds of the total global industrial energy consumption [1]. In current practice, the thermal energy sources feeding industrial processes include:

- **Fossil Fuels**: coal, natural gas, and oil are burned to produce heat.
- **Electricity**: Electric heaters are used to convert electrical energy into heat.
- **Nuclear Energy**: thermal power released during fission can be used directly or converted into steam for industrial processes.
- **Renewable Energy Sources**: solar thermal energy, biomass, and geothermal energy can provide heat directly or through conversion processes.
- **Waste Heat Recovery**: utilizing the waste heat from industrial processes or power generation, which would otherwise be lost to the environment.
- **Cogeneration/Combined Heat and Power (CHP)**: systems that produce both electricity and thermal energy from a single fuel source, improving overall efficiency.

These sources are chosen based on factors like cost, availability, environmental impact, and the specific temperature requirements of the industrial process. Approximately 40% of the current industrial energy consumption is covered by natural gas, and approximately 40% by petroleum products [1]. Because of its purity and constant quality, natural gas is used in large quantities in industry when close control is required. It is ideal for continuous processes, such as baking and drying. It is used extensively in the steel industry for annealing and tempering. The relatively high cost limits its use to those processes where fuel costs represent a small portion of the total cost of production [2]. One of the objectives of the IES program consists of evaluating the possibility of coupling the energy conversion cycles of conventional thermal units (i.e., Rankine cycles of nuclear reactors, Brayton cycles of gas turbines, etc.) with industrial processes that require substantial amounts of thermal power at high temperature. It is a convenient scenario for both parties, i.e., the industrial processes obtain the heat they need at a low cost, and the IES unit has an additional degree of freedom that allows to modulate the power production more effectively.

In this report, the feasibility of employing Advanced Nuclear Reactors to supply the necessary heat input to Industrial Processes is investigated. As a first step, the most relevant processes that could benefit from this coupling were identified, and their requirements were characterized. In Section 2, four industries including petroleum refining (distillation, catalyst regeneration, hydro-steam cracking), chemical polymers, steel manufacturing (metals annealing/soaking) and cement manufacturing (calcination of limestone and dolomite) were analyzed. The working temperature ranges for individual processes and the power consumptions for representative plants were identified. In Section 3, the thermal power output and the temperature of the steam produced by
representative designs of Advanced Reactor concepts (Liquid Metal Fast Breeder Reactors, Molten Salt Reactors, and High Temperature Gas-cooled Reactors) were summarized. These analyses provided an overview of the temperature and thermal power that can be directly supplied via steam. A pairing between the required heat loads and the available thermal power sources was then proposed (Section 4).

To expand the flexibility and diversity of applications of advanced nuclear power, the use of heat pumps was considered. Heat pumps provide a means for deploying nuclear reactor technology at operating conditions that have been successfully demonstrated on a commercial scale in the past, while at the same time providing high quality heat for industrial processes that operate at higher temperatures. As a preliminary assessment of the benefits and the added complexity of this technology, the energy conversion cycle of a traditional Pressurized Water Reactor (PWR) was modified by including a compressor increasing the quality of the produced steam (Section 5). Two reference configurations were considered, i.e., the industrial process coupled with the nuclear power plant exhausts either saturated liquid or saturated steam, and the calculated values for the corresponding thermal efficiencies were reported. To obtain a consistent basis for characterization of performance, the heat pumps are set up as closed systems, i.e., the thermal and electrical power absorbed by the heat pump is solely obtained from thermal energy of the steam provided by the Steam Generator (SG).
2. APPLICATION TO INDUSTRIAL PROCESSES

In this Section, the working temperature ranges, and the heat load required by several categories of Industrial Processes are identified. The analyzed industrial processes include Petroleum refinery, Chemical polymers production, Steel manufacturing, and Cement Production. A summary of the analyzed processes, the required temperatures, the required heat loads are listed in Table 2-1.

Table 2-1. Summary of the selected Industrial Processes and the corresponding thermal requirements.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Process</th>
<th>Feedstock</th>
<th>Product</th>
<th>Capacity</th>
<th>Temperature range (°C)</th>
<th>Power input (MWth)</th>
<th>Energy input (GJ/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum Refinery</td>
<td>Petroleum Refinery</td>
<td>Crude Oil</td>
<td>Multiple</td>
<td>138,000 barrel/day*</td>
<td>300 - 715</td>
<td>175</td>
<td>15,120</td>
</tr>
<tr>
<td>Chemical Polymers</td>
<td>Olefins via Pyrolysis</td>
<td>Propane</td>
<td>Ethylene and Propylene Monomer</td>
<td>2,720 ton/day</td>
<td>775 - 875</td>
<td>28.0</td>
<td>2,420</td>
</tr>
<tr>
<td></td>
<td>Vinyl Chloride</td>
<td>Ethylene, Chlorine</td>
<td>Vinyl Chloride Monomer</td>
<td>2,000 ton/day</td>
<td>500 - 550</td>
<td>62.5</td>
<td>5,400</td>
</tr>
<tr>
<td></td>
<td>Styrene</td>
<td>Ethylbenzene</td>
<td>Styrene Monomer</td>
<td>1,150 ton/day</td>
<td>620</td>
<td>46.5</td>
<td>4,020</td>
</tr>
<tr>
<td></td>
<td>Polyethylene Terephthalate</td>
<td>Ethylene, P-Xylene</td>
<td>Polyethylene Terephthalate</td>
<td>3,014 ton/day</td>
<td>220 - 275</td>
<td>231.0</td>
<td>19,960</td>
</tr>
<tr>
<td>Steel Making</td>
<td>Steel Refining via BOF</td>
<td>Pig Iron</td>
<td>Crude Steel</td>
<td>3,000 ton/day</td>
<td>1,700</td>
<td>451.4</td>
<td>39,000</td>
</tr>
<tr>
<td></td>
<td>Steel Refining via EAF**</td>
<td>Pig Iron</td>
<td>Crude Steel</td>
<td>3,000 ton/day</td>
<td>1,700</td>
<td>62.5**</td>
<td>5,400**</td>
</tr>
<tr>
<td></td>
<td>Steel Rolling</td>
<td>Crude Steel</td>
<td>Steel Sheets</td>
<td>2,740 ton/day</td>
<td>720 – 1,260</td>
<td>94.9</td>
<td>8,200</td>
</tr>
<tr>
<td></td>
<td>Steel Annealing</td>
<td>Forged Steel</td>
<td>Annealed Steel</td>
<td>1,000 ton/day</td>
<td>670 - 835</td>
<td>16.7</td>
<td>1,440</td>
</tr>
<tr>
<td>Cement Making</td>
<td>Limestone Calcination</td>
<td>Limestone</td>
<td>Lime</td>
<td>200 ton/day</td>
<td>1,000 – 1,600</td>
<td>10.1</td>
<td>874</td>
</tr>
<tr>
<td></td>
<td>Dolomite Calcination</td>
<td>Dolomite</td>
<td>Calcinated Dolomite</td>
<td>60 ton/day</td>
<td>900 – 1,000</td>
<td>3.3</td>
<td>282</td>
</tr>
</tbody>
</table>

*Processing capacity of feedstock
**Consumes electricity
2.1. Petroleum refinery

Petroleum refinery consists of multiple stages occurring at different temperature between 300 °C and 715 °C. A detailed petroleum refinery flow diagram is shown in Figure 2-1 [3]. Some of the processes requiring high-quality heat are discussed in Sections 2.1.1-2.1.7. Modern refineries are rigorously heat-integrated and consume only ~6% of the energy value of their feedstock to provide heat [4]. An average refinery that produces 138,000 barrel/day of crude oil needs a thermal energy input equal to around 15.12 TJ/day [5].

Figure 2-1. Petroleum refinery flow diagram [3].
2.1.1. Crude Oil Distillation

The distillation process is the fundamental separation technique used to separate crude oil into various components or fractions based on their boiling points. This process is crucial for refining crude oil into valuable products like gasoline, diesel, jet fuel, and various petrochemical feedstocks. Two major units are usually used in the distillation process, i.e., Atmospheric Distillation Unit (ADU) and then Vacuum Distillation Unit (VDU). In Figure 2-2, the flow diagram of an ADU is shown. The incoming crude oil is pre-heated to a temperature between 300 °C and 400 °C by exchanging heat with some of the hot, distilled fractions. After the inorganic salts (primarily sodium chloride) are removed, the temperature of crude oil is further increased, then the flow rate is heated in a fuel-fired furnace (fired heater) to a temperature of about 398 °C and routed into the bottom of the ADU which is operated slightly above atmospheric pressure [6]. The cooling and condensing of the distillation tower overhead is provided partially by exchanging heat with the incoming crude oil and partially by either an air-cooled or water-cooled condenser. As a result, petroleum gas, naphtha (to be processed in hydrotreater), Kerosene (jet fuel), middle distillates (to be processed in hydrotreater) and heavy gas oil (for Fluid Catalytic Cracking) are separated from the bottom residue.

Figure 2-2. Flow diagram of an Atmospheric Distillation Unit [7].
The bottom residue from ADU is further processed by the VDU. After being heated in preheat exchangers, the bottom residue is fed to the vacuum flash zone. Thanks to the low pressures (typically below 0.001 MPa), heavier components can be separated at temperatures lower than those needed under normal atmospheric conditions [8]. To avoid thermal cracking of the heavier fractions, the temperature is maintained between 340 °C and 390 °C. As a result, the light vacuum gas oil (for Fluid Catalytic Cracking), heavy vacuum gas oil (to be processed in hydrocracking) are separated from vacuum residue (for delayed coker and visbreaker).

2.1.2. Hydrotreater

As mentioned in Section 2.1.1, the naphtha and middle distillates from ADU are further processed. Hydrotreating, also called hydrodesulfurization (HDS), is a catalytic chemical process widely used to remove sulfur from refined petroleum products. In Eq.(1), the hydrodesulfurization reaction for ethanethiol (C₂H₅SH), a sulfur compound present in some petroleum products, is reported.

\[ \text{C}_2\text{H}_5\text{SH} + \text{H}_2 \rightarrow \text{C}_2\text{H}_6 + \text{H}_2\text{S} \] (1)

In a hydrotreater within a refinery (Figure 2-3), the HDS reaction takes place in a fixed-bed reactor at temperatures ranging from 300 °C to 400 °C and pressures from 3 to 13 MPa, typically in the presence of a catalyst consisting of an alumina base impregnated with cobalt and molybdenum. The desulfurized product is then cooled and separated from the sour gas (H₂S) via gas separator (~ 35 °C and from 0.3 to 0.5 MPa) and a reboiled stripper distillation tower. As a result, the desulfurized naphtha will be further processed via catalytic reforming, and then join the desulfurized middle distillates for final treating and blending.
2.1.3. Catalytic reforming

Catalytic reforming is a chemical process to convert petroleum refinery naphtha with low octane ratings into high-octane liquid products. The latter, also known as reformates, are premium blending stocks for high-octane gasoline. Several categories of chemical reactions occur in the catalytic reforming process in the presence of a catalyst and a high partial pressure of hydrogen (Figure 2-4). The reaction conditions range from 495 °C to 525 °C and from 0.5 to 4.5 MPa, according to the type of catalytic reforming used as well as the desired reaction severity [10].

![Flow diagram of hydrodesulfurization unit](https://www.gnu.org/licenses/gpl-3.0.en.html)

**Figure 2-3. Flow diagram of hydrodesulfurization unit [9] (Figure credit: Wikipedia user “Mbeychok”, under license GFDL, https://www.gnu.org/licenses/fdl-1.3.html. No changes were made).**

2.1.3. Catalytic reforming

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![Flow diagram of Catalytic reforming unit](https://www.gnu.org/licenses/gpl-3.0.en.html)

**Figure 2-4. Flow diagram of Catalytic reforming unit [11].**

Some representative categories of reactions are:

1. The dehydrogenation of naphthene to convert them into aromatics, e.g., the conversion from methylcyclohexane to toluene (Eq.(2)).

   \[
   \text{CH}_3\text{C}_6\text{H}_{11} \rightarrow \text{CH}_3\text{C}_6\text{H}_5 + 3\text{H}_2
   \] (2)

2. The isomerization of normal paraffins to isoparaffins, e.g., the conversion of normal octane to 2,5-Dimethylhexane (Eq.(3)).

   \[
   \text{CH}_3(\text{CH}_2)_6\text{CH}_3 \rightarrow (\text{CH}_3)_2\text{CH}(\text{CH}_2)_2\text{CH}(\text{CH}_3)_2
   \] (3)

3. The dehydrogenation and aromatization of paraffins to aromatics, e.g., the conversion of normal heptane to toluene (Eq.(4)).

   \[
   \text{CH}_3(\text{CH}_2)_5\text{CH}_3 \rightarrow \text{CH}_3\text{C}_6\text{H}_5 + 4\text{H}_2
   \] (4)

2.1.4. Fluid Catalytic Cracking

As mentioned in Section 2.1.1, the heavy gas oil from ADU and the light vacuum gas oil from VDU need to be further processed in a Fluid Catalytic Cracking (FCC) unit, where the high-boiling point, high-molecular weight hydrocarbon fractions of crude oil are converted into gasoline, alkene gases, and other petroleum products [3]. As shown in Figure 2-5, the heavy gas oil and the light vacuum gas oil feedstock is heated to a temperature between 315 °C and 430 °C and to a moderate pressure, and then is injected to the catalyst riser for vaporization and cracking in the presence of hot, powdered catalyst. After the completion of cracking reaction, the mixture of hydrocarbon vapors and catalyst flows upward to enter the reactor at a temperature close to 535 °C and a pressure of about 0.17 MPa. The cracked product vapors are separated and collected by exiting the...
reactor from top, while the spent catalyst flows downward through a steam stripping section to remove any hydrocarbon vapors before the spent catalyst returns to the catalyst regenerator. The cracking reactions produce some carbonaceous material that deposits on the catalyst, which quickly reduces the catalyst activity. To this aim, the catalyst is regenerated by burning off the deposited coke with air blown into the regenerator, which operates at a temperature of about 715 °C and a pressure of about 0.24 MPa [12][13].

Figure 2-5. Flow diagram of Fluid Catalytic Cracking unit [14] (Figure credit: Wikipedia user “Mbeychok”).

2.1.5. Hydrocracking

The heavy vacuum gas oil from VDU is further processed in the Hydrocracking unit. It is a catalytic cracking process assisted by the presence of added hydrogen gas, which is used to break the C-C bonds of heavier hydrocarbon fractions from vacuum distillation units to produce saturated hydrocarbons as lighter, more valuable products. Depending on the feedstock and the desired product, the temperature can be up to 425 °C for jet fuel, diesel, low sulfur naphtha fractions and LPG (Liquefied Petroleum Gas) production [15]. One example is the cracking of normal heptane into isopentane and ethane (Eq.(5)) [16].

\[
\text{CH}_3(\text{CH}_2)_5\text{CH}_3 + \text{H}_2 \rightarrow (\text{CH}_3)_2\text{CHCH}_2\text{CH}_3 + \text{C}_2\text{H}_6 \tag{5}
\]
The products from hydrocracking will be used for final treating and blending. Because of the high demand for gasoline, fluid catalytic cracking is more common than hydrocracking in U.S.

2.1.6. Visbreaker

Visbreaker upgrades heavy residual oils from the vacuum distillation unit by thermally cracking them into lighter, more valuable products with reduced viscosity. Operating temperature depends on the feedstock and the desired product [17]. For example, Arabian light crude residue would crack only mildly when heating to 425 °C, but crack severely while operating at 500 °C. At 450 °C, Arabian light crude residue would yield around 76% (by weight) of tar, 15% middle distillates, 6% gasolines and 3% gas and LPG [18]. In Figure 2-6, a diagram of a visbreaker unit is shown, and multiple processes are available depending on the desired outputs.

**Figure 2-6. Schematic diagram of a Visbreaker unit.**

1. Furnace visbreaking: Cracking process occurs in the furnace tubes. Material exiting the furnace is quenched to halt the cracking reactions. The quenched mixture then passes to a fractionator where the products of the cracking (gas, LPG, gasoline, gas oil and tar) are separated and recovered. The extent of the cracking reaction is controlled by regulation of the speed of flow of the oil through the furnace tubes.

2. Soaker visbreaking: The cracking reaction occurs in a soaker drum located after the furnace. The oil is held at an elevated temperature (lower than furnace visbreaking) for a longer period of time to allow cracking to occur before being quenched. The oil then passes to a fractionator.

3. Visbreaker tar can be further refined by feeding it to a vacuum fractionator through vacuum flashing. Additional heavy gas oil may be recovered via this method and routed either to catalytic cracking, hydrocracking, or thermal cracking units on the refinery. The vacuum-flashed tar is then routed to fuel oil blending.
2.1.7. *Delayed Coker*

The delayed coker is where the heaviest hydrocarbons from heavy residual oils are raised above their thermal cracking point, so that shorter hydrocarbons and petroleum coke are formed. The flow diagram of a delayed coking unit with two parallel coke drums is shown in Figure 2-7, but more parallel coke drums are available in larger units.

![Flow diagram of a delayed coking unit](image)

*Figure 2-7. Flow diagram of a delayed coking unit [19].*

In Figure 2-7, vacuum residue from the VDU is pumped into the bottom of the main fractionator for distillation purpose. After the vaporization of lighter components, the residues are pumped into the fuel-fired furnace with injected steam and heated to its thermal cracking temperature of about 480 °C. Thermal cracking reaction begins in the pipe between the furnace and the first coke drum and finishes in the coke drum that is on-stream. The injected steam helps to minimize the deposition of coke within the furnace tubes. During the cracking process in the coke drum, gas oil and lighter components are generated in vapor phase and separate from the liquid and solids. The drum effluent vapor is directed to the main fractionator to be separated into the desired boiling point fractions. The solid coke is deposited and remains in the coke drum in a porous structure that allows flow through the pores. After the first drum is full of the solidified...
coke, the hot mixture from the furnace is switched to the second drum. While the second drum is filling, the filled first drum is steamed out to reduce the hydrocarbon content of the petroleum coke, and then quenched with water to cool it. The top and bottom heads of the full coke drum are removed, and the solid petroleum coke is then removed from the coke drum and transported for storage.

2.2. Chemical polymer production

Chemical polymers play an indispensable role in everyday lives, influencing modern society with their versatility and functionality. From clothes, food containers to construction materials, polymers are integral to a myriad of everyday products. According to [20], the largest groups in total non-fiber plastics production are Polyethylene (PE, 36%), Polypropylene (PP, 21%), and Polyvinyl chloride (PVC, 12%), followed by Polystyrene (PS), and Polyethylene Terephthalate (PET) (<10% each). These polymers are usually synthesized from corresponding monomers at temperatures that are easier to achieve (200-350 °C for PE and PET, 40-120 °C for PP, PVC and PS), but the production of monomers requires a higher temperature where the advanced nuclear reactors may be a potential heat supplier. In this section, an overview of the monomer production process and the associated temperature range will be provided.

2.2.1. Olefins production via pyrolysis / steam cracking

The production of olefin usually uses a process that requires large amounts of heat to break down the alkane chains. The two major olefins produced are ethylene (C\(_2\)H\(_4\)) and propylene (C\(_3\)H\(_6\)), which are primarily used in the production of polyethylene and polypropylene, respectively [16]. The first method to produce olefins is pyrolysis or steam cracking, which is the decomposition of hydrocarbon in steam at high temperatures ranging from 775 °C to 875 °C. For example, cracking of propane is described by Eq.(6).

\[
C_3H_8 \rightarrow aH_2 + bCH_4 + cC_2H_4 + dC_3H_6 + eC_4H_8 + fC_5+ \quad (6)
\]

where \(a, b, c, d, e, f\) are characteristic, empirical factors.

The pyrolysis reaction usually occurs in a cracking reactor, whose principal arrangement is shown in Figure 2-8.
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Figure 2-8. Principal arrangement of a cracking reactor.

As shown in Figure 2-8, a hydrocarbon stream is heated by heat exchange against flue gas in the convection section, mixed with steam, and further heated to incipient cracking temperature (500-680 °C, depending on the feedstock). The stream then enters a fired tubular reactor (the “Radiant section”) where it is heated from 500-650 °C to 750-875 °C for 100-500 ms. During this short reaction time hydrocarbons in the feedstock are cracked into smaller molecules including ethylene, other olefins, and diolefins. Since the conversion of saturated hydrocarbons to olefins in the radiant tube is highly endothermic, high energy input rates are needed. The reaction products at 800-850 °C leaves the radiant section, and then they are cooled to 550-650 °C in 20-100ms to prevent degradation of the highly reactive products by secondary reactions. The resulting product mixtures, which can vary widely, depending on feedstock and severity of the cracking operation, are then separated into the desired products by using a complex sequence of separation and chemical-treatment steps. The cooling of the cracked gas in the transfer line exchanger is carried out by vaporization of high-pressure boiler feedwater, which is separated in the steam drum and subsequently superheated in the convection section to high-pressure superheated steam (6-12 MPa).

The olefins production via pyrolysis is an energy intensive process. Since propylene is a co-product in ethylene production, the combined energy consumption is usually normalized by the yield of ethylene. A literature review showed around 20-40 GJ heat (depending on the plant capacity and feedstock) is required per ton of produced ethylene, combining both feed and fuel
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energy [21][22]. For a representative large scale chemical plant that can produce 2720 tons of ethylene per day, the total 55 TJ heat duty is mainly achieved by combustion of pyrolysis oil byproduct, and it only requires about 2.42 TJ of additional fuel [23].

2.2.2. Vinyl Chloride production

Vinyl chloride (C₂H₃Cl) is widely diffused as a chemical building block in the production of polyvinyl chloride (PVC). The most common production pathway for vinyl chloride consists of three steps, characterized by different temperature ranges. These three steps are complementary in producing vinyl chloride.

1. Direct ethylene chlorination: temperatures between 80 °C and 140 °C are preferred in the presence of ferric chloride catalyst [24]. Ethylene reacts with molecular chlorine to produce ethylene dichloride (EDC, Eq. (7)).

\[
\text{Cl}_2 + \text{H}_2\text{C} = \text{CH}_2 \rightarrow \text{Cl} - \text{H}_2\text{C} - \text{CH}_2 - \text{Cl}
\]  

(7)

2. 1,2-dichloroethane cracking: temperatures between 500 °C and 550°C are required [16]. The EDC is cracked, producing vinyl chloride and hydrochloric acid (Eq. (8)).

\[
\text{Cl} - \text{H}_2\text{C} - \text{CH}_2 - \text{Cl} \rightarrow \text{H}_2\text{C} = \text{CH} - \text{Cl} + \text{HCl}
\]  

(8)

3. Ethylene oxychlorination: temperatures between 232 °C and 354 °C are required in the presence of a fixed-bed, supported cupric chloride catalyst [25]. To fully utilize the chlorine, the by-produced hydrochloric acid from Step (2) can be used as a raw material in Step (3). In this process, hydrochloric acid, ethylene, and oxygen are used to manufacture vinyl chloride (Eq. (9)) [26].

\[
\text{HCl} + \text{H}_2\text{C} = \text{CH}_2 + 0.5\text{O}_2 \rightarrow \text{H}_2\text{C} = \text{CH} - \text{Cl} + \text{H}_2\text{O}
\]  

(9)

A typical vinyl chloride monomer manufacture in Germany reports 2.7 GJ heat is provided via fuel gas consumption to produce 1 ton of vinyl chloride monomer [27]. Based on its PVC production capability of 2,000 ton/day, this heat load equals to 5.4 TJ/day [28].

2.2.3. Styrene production

Styrene (C₈H₈) is an important commodity chemical that is used in the production of polystyrene. The process of producing styrene monomer involves the dehydrogenation of ethylbenzene in Eq.(10), like the process used to make chained olefins, however at lower temperatures. The process reaction takes place around 620 °C in the presence of an iron oxide catalyst with excess steam [16].
The heat load is estimated for a representative styrene monomer production plant. According to [29], 420,000 ton of styrene monomer was produced in Innova Plant II in Triunfo (Brazil) in 2022. The average energy consumption was 4.63 GJ/ton, and 75.5% of the energy consumed is from combustion of fuels. From this calculation, 4.02 TJ of heat needs to be supplied to this plant to support the production of styrene monomer at a rate of 1,150 ton/day.

2.2.4. Ethylene Glycol and Terephthalic acid production

Polyethylene terephthalate (PET) is the most common thermoplastic polymer resin of the polyester family and is used in fibres for clothing, containers for liquids and foods. PET is synthesized from two different compounds, i.e., Ethylene Glycol \((\text{C}_2\text{H}_6\text{O}_2)\) and Terephthalic acid \((\text{C}_6\text{H}_4(\text{COOH})_2)\).

- Ethylene Glycol is a useful chemical that is used in anti-freeze and as a building block for polyester fibers. Its production involves reacting ethylene oxide with water at 200 °C using sulfuric acid as a catalyst (Eq. (11)) [16]:

\[
\text{C}_2\text{H}_4\text{O} + \text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_6\text{O}_2 \tag{11}
\]

The precursor, ethylene oxide \((\text{C}_2\text{H}_4\text{O})\), is produced by the oxidation of ethylene between 220°C and 275°C with a silver catalyst (Eq. (12)).

\[
\text{C}_2\text{H}_4 + 0.5\text{O}_2 \rightarrow \text{C}_2\text{H}_4\text{O} \tag{12}
\]

- Terephthalic acid is produced by catalytic oxidation of p-xylene by using acetic acid as solvent, oxygen as an oxidant, and a combination of three ions as homogeneous catalysts, i.e., cobalt, bromide, and manganese (Eq. (13)). The reactor operates at temperatures between 175 °C and 225 °C and at pressures of 1.5-3 MPa [30].

\[
\text{C}_6\text{H}_4(\text{CH}_3)_2 + 3\text{O}_2 \rightarrow \text{C}_6\text{H}_4(\text{COOH})_2 + 2\text{H}_2\text{O} \tag{13}
\]

Ethylene glycol and purified terephthalate can be produced on location in an integrated plant. One representative facility is the Corpus Christi Polymers, which is under construction in Corpus Christi (Texas) [31]. This facility will produce 3,013.7 tons of PET per day. The overall production of ethylene glycol, purified terephthalate and the synthesized PET would utilize 19.96 TJ/day.

2.3. Steel manufacturing: Soaking and annealing

Steel manufacturing begins with the molten iron (also known as pig iron) produced via reduction reaction in blast furnace, and contains three major industrial processes, i.e., (1) Refining
and casting, (2) Rolling and forming, and (3) Heat treatment. Brief descriptions of each process and the associated temperature range will be discussed from Section 2.3.1 to Section 2.3.3.

2.3.1. Refining and Casting

The molten iron from the blast furnace is refined in a basic oxygen furnace (BOF) or an electric arc furnace (EAF) [32]. During refining, excessive carbon and other impurities are removed, while alloying elements are added to produce steel. The refined steel is then cast into various forms, such as slabs, billets, or ingots. In BOF, oxygen is used to lower the carbon content of the alloy and change it into low-carbon steel. The process is known as basic because fluxes of burnt lime or dolomite, which are chemical bases, are added to promote the removal of impurities and protect the lining of the converter [33]. The key component, LD converter. Its working principle is shown in Figure 2-9. Pure oxygen was blown over the hot metal, igniting the carbon dissolved in the steel, to form carbon monoxide and carbon dioxide, causing the temperature to rise to about 1700 °C. This melts the scrap, lowers the carbon content of the molten iron, and helps remove unwanted chemical elements. For a medium-sized BOF (3,000-ton of crude steel daily production rate), the energy consumption is about 30-39 TJ/day [34].

![Figure 2-9. The principle of LD converter [35].](image)

In EAF, steel is manufactured from scrap or reduced iron melted by electric arcs. When a batch of iron is loaded into the furnace, multiple graphite electrodes contact the molten bath and generate electric arc using the three-phase electrical supply [36]. The EAF usually operates at a temperature up to 1700 °C, and gas burners may be used to assist with the melt. As in basic oxygen steelmaking, fluxes are also added to protect the lining of the vessel and help improve the removal of impurities. For a medium-sized EAF (3,000-ton of crude steel daily production rate), the energy consumption is about 4.32-5.40 TJ/day [37].
2.3.2. Rolling and forming

Steel products are shaped and formed into various final products, such as sheets, bars, and structural shapes, using rolling mills and other forming techniques. Rolling is classified into hot rolling and cold rolling according to the temperature of the metal rolled.

In the former, the metal temperature is above its recrystallization temperature (between 720 °C and 1260 °C for various types of steel). At such elevated temperatures, the steel is in the austenitic state, and the iron atoms are arranged face-centered in cubic form allowing for strong deformation. In addition, the internal stress of the hot rolled steel is neglectable [38]. For a large sized rolling mill with 2,700-ton daily production rate, the heat consumption for this process is about to 4.10-8.22 TJ/day [39]. In the latter, the metal temperature is below its recrystallization temperature. The strength of cold rolled steel can be increased via strain hardening by up to 20%.

2.3.3. Annealing

Some steel products undergo heat treatment processes such as annealing to achieve specific mechanical properties. Annealing process involves heating the steel to a specific temperature and then cooling it at a controlled rate. Annealing is employed to relieve internal stresses, improve machinability, enhance cold working properties, and refine the microstructure of steel. Annealing is composed of three major steps, i.e., Heating, Soaking and Cooling.

- The heating is typically done in a furnace, kiln, or controlled atmosphere to ensure uniform temperature distribution throughout the workpiece. The temperature is carefully controlled to achieve the desired metallurgical effects. Depending on the level of microstructure changes, the temperature range can be divided into three segments [40]:
  - Subcritical annealing (260 °C - 649 °C): No crystal structure change
  - Intermediate annealing (649 °C - 760 °C): Some transformation to austenite
  - Full annealing (higher than 816 °C): Completely austenitizing

- Once the steel reaches the annealing temperature, it is held at that temperature for a predetermined period, known as the soaking time. This time can vary from minutes to hours, depending on the steel grade, thickness, and desired properties.

- The cooling begins after soaking, and there are several types of annealing processes, each with its own cooling method:
  - Subcritical and Intermediate Annealing: The steel is cooled to room temperature in still air or a controlled atmosphere.
  - Full Annealing: The steel is cooled slowly in the furnace or kiln. This gradual cooling helps in achieving a refined grain structure.
Multiple technologies have emerged and been deployed in industry for mass steel annealing. One representative technology is the continuous annealing line. As shown in Figure 2-10, the rolls of steel plates are welded before entering annealing line, and the flat steel passes through a degreasing section and a furnace at the core of the process, where it is annealed at a constant speed and temperature that typically ranges between 670 °C and 835 °C. Every day, a single line that is capable of annealing 1,000 tons of steel consumes 1.44 TJ of heat [41].

Figure 2-10. A schematic of continuous steel annealing line [42].

2.4. Cement and Lime Making

Cement manufacturing is a complex industrial process whose output is a key construction material in the construction of buildings, roads, and infrastructure. The most common type of cement is hydraulic cement, which hardens by hydration of the clinker minerals when water is added. Hydraulic cements are made of a mixture of silicates and oxides, and the four main mineral phases of the clinker are Alite (3CaO・SiO₂), Belite (2CaO・SiO₂), Tricalcium aluminate (3CaO・Al₂O₃), and Brownmillerite (4CaO・Al₂O₃・Fe₂O₃) [43].

Lime (CaO) is the common fraction of all the four main minerals, and the production of Lime is a heat-intensive process called calcination. Calcination is conducted in furnaces or reactors (also known as kilns or calciners) of various designs. In a typical shaft furnace configuration, the feedstock (limestone) is fed from the top and then it is heated by the combustion of fuel. Carbon dioxide is removed during the calcination process and is exhausted to the atmosphere by a fan on the top of the furnace. Depending on the material being processed and the desired outcome, the specific temperature range for calcination may vary.

1. Calcination of Limestone: Limestone (CaCO₃) is decomposed into calcium oxide (CaO) and carbon dioxide (CO₂) (Eq.(14)). At temperature higher than 898°C, the decomposition of limestone happens quickly at atmospheric pressure [44]. In industrial practice, the temperature of furnace is controlled between 1000 °C and 1600 °C for efficient decomposition [16][45][46].

\[
CaCO_3 \rightarrow CaO + CO_2
\]  

(14)

The energy consumption in limestone calcination depends on the operating temperature. At 1600 °C, the energy consumption is about 4.36 GJ per ton of lime produced. This equals 873.6 GJ for a typical kiln with 200-ton daily lime production rate.
2. Calcination of Dolomite: Dolomite (CaMg(CO$_3$)$_2$) is a carbonate mineral composed of calcium carbonate (CaCO$_3$) and magnesium carbonate (MgCO$_3$). Decomposition takes place in two stages, starting at approximately 550 °C for the MgCO$_3$ portion. Dolomite decomposes completely above 900 °C. In industrial practice, the temperature is usually kept above 1000 °C for efficient decomposition. The product resulting from this relatively low temperature calcination is highly porous and reactive and is known as calcinated dolomite, which is a mixture of CaO and MgO (Eq. (15)).

$$\text{CaMg(CO}_3\text{)}_2 \rightarrow \text{CaO} + \text{MgO} + 2\text{CO}_2$$  \hspace{1cm} (15)

In a small-sized furnace that can produce 60 tons of calcinated dolomite [47], the energy consumption is 282 GJ/day.
3. OVERVIEW OF ADVANCED REACTOR DESIGNS SUITABLE FOR INTEGRATION WITH INDUSTRIAL PROCESSES

In this Section, the thermodynamic conditions of the steam produced by the energy conversion cycles of representative Advanced Reactor designs are characterized, and the corresponding technical specifications are collected. The results of the performed literature review are summarized in Table 3-1. The goal is to obtain an overview of the quality of the heat produced by these reactors to identify the most appropriate designs for the integration with the industrial processes described in Section 2. To this aim, the following criteria were applied:

- For each reactor concept, we selected designs that are representative of the state-of-the-art.
- Given the nature of our analysis, the designs that were licensed and that were or are in operation are identified (conceptual reactor designs that were never put into operation tended to be excluded).
- Due to licensing issues, we made every effort to select U.S. units, despite the existence of more representative candidates. In particular, the minimum requirement for a reactor design to be integrated with an industrial process is that it had previously received approval or licensing from the U.S. Nuclear Regulatory Commission (NRC). For completeness, the performance of other reactor designs is reported as well.

Table 3-1. Thermodynamic conditions of the steam produced by the energy conversion cycles of representative Advanced Reactor designs.

<table>
<thead>
<tr>
<th>Reactor Concept</th>
<th>Design</th>
<th>Operational period</th>
<th>Installed capacity</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>Liquid Metal Fast Breeder Reactor (LMFBR)</td>
<td>EBR-II (United States)</td>
<td>1964 - 1994</td>
<td>62.5 MW(<em>{th}) (20 MW(</em>{e}))</td>
<td>438</td>
</tr>
<tr>
<td></td>
<td>BN-800 (Russia)</td>
<td>2014 - Present</td>
<td>2.100 MW(<em>{th}) (880 MW(</em>{e}))</td>
<td>490</td>
</tr>
<tr>
<td>Molten Salt Reactor (MSR)</td>
<td>MSBR (United States)</td>
<td>Never built</td>
<td>2,250 MW(<em>{th}) (1,000 MW(</em>{e}))</td>
<td>537</td>
</tr>
<tr>
<td></td>
<td>KP-FHR (United States)</td>
<td>From 2026</td>
<td>320 MW(<em>{th}) (140 MW(</em>{e}))</td>
<td>585</td>
</tr>
<tr>
<td>High Temperature Gas-cooled Reactor (HTGR)</td>
<td>FSV HTGR (United States)</td>
<td>1976 - 1989</td>
<td>842 MW(<em>{th}) (330 MW(</em>{e}))</td>
<td>540.5</td>
</tr>
<tr>
<td></td>
<td>Xe-100 (United States)</td>
<td>From 2025</td>
<td>200 MW(<em>{th}) (80 MW(</em>{e}))</td>
<td>565.5</td>
</tr>
<tr>
<td></td>
<td>HTR-PM (China)</td>
<td>2021 - Present</td>
<td>500 MW(<em>{th}) (210 MW(</em>{e}))</td>
<td>566</td>
</tr>
</tbody>
</table>
3.1. **Liquid Metal Fast Breeder Reactors (LMFBRs)**

The concept of a liquid-metal fast breeder reactor (LMFBR) dates back to the genesis of nuclear energy. The first nuclear reactor to generate electricity was the liquid sodium potassium-cooled fast reactor Experimental Breeder Reactor I (EBR-I). Its successor, the sodium-cooled fast reactor (SFR) Experimental Breeder Reactor II (EBR-II), was operated successfully for more than 30 years. In the 1980s and 1990s, General Electric (GE) led an industrial team that pursued commercial deployment of an SFR called Power Reactor Innovative Small Module (PRISM) as part of the U.S. Advanced Liquid Metal Reactor (ALMR) program administered by the U.S. Department of Energy [48]. In this regard, EBR-II reactor design and operational experience played a key role in the deployment of LMFBRs. In Section 3.1.1, the main technical specifications of EBR-II are summarized.

3.1.1. **Experimental Breeder Reactor (EBR-II)**

Experimental Breeder Reactor-II (EBR-II) was a sodium-cooled fast reactor designed, built, and operated by Argonne National Laboratory at the National Reactor Testing Station near Idaho Falls (Idaho). Initial operations began in July 1964, and criticality was achieved in 1965. It was shut down in late 1994, after 30 years of successful operation. EBR-II was a pool-type reactor with integrated power plant. It consisted of an unmoderated, heterogeneous, sodium-cooled reactor (nominal thermal power output equal to 62.5 MW(th)), an intermediate closed loop of secondary sodium coolant, and a steam energy conversion cycle that produced 20 MW(e) through a conventional turbine generator [49][50].

The configuration of the SG system is shown in Figure 3-1. Originally, it consisted of eight natural-circulation evaporators, two once-through superheaters, and a single steam drum (no reheaters were present). The evaporators were arranged in two rows of four each and are connected to the steam drum by individual risers and downcomers. The designs of the evaporators and superheaters were essentially identical (both are counterflow units) [49]. The steam drum was located horizontally above the evaporators and superheaters. Primary and secondary steam separation took place within the drum and dry-saturated steam was routed from the top of the drum, through the parallel connected superheaters to a common header to the turbine. Feedwater was supplied to the drum, where it mixes with the saturated steam water mixture before entering the downcomers. Blowdown was taken from a collection header located within and near the bottom of the drum.

In EBR-II, the secondary sodium flowed from the intermediate heat exchanger (IHX) located in the primary-sodium tank to the SG, thereby producing a saturated steam mass flow rate of 30.9 kg/s. Then, the sodium passes through the superheaters, where it raises the steam temperature from 304 °C to 438 °C (superheated steam conditions) at 8.8 MPa. The secondary sodium then passes on to the evaporator inlet headers and then passes through the evaporators, heating steam-drum water in an almost isothermal process to 304 °C wet steam, which returns to the drum. The feedwater is normally supplied to the steam drum at 33.4 kg/s and 288 °C. This accounts for a
continuous blowdown flow of 2.5 kg/s, which is extracted from the steam drum. A detailed representation of the SG system design is shown in Figure 3-2. The feedwater and the steam reference operating conditions are reported as well. The technical specifications of the SG system of EBR-II and the thermodynamic conditions of the produced steam are reported in Table 3-2.

Figure 3-1. Representation of (a) the general arrangement of the system and (b) the schematic of the SG system [50].

Figure 3-2. Detailed scheme of the general layout of the system [49].
Table 3-2. Technical specifications of the SG system of EBR-II and the turbine generator throttle conditions.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBR-II</td>
<td>1964-1994</td>
<td>Recirculation</td>
<td>62.5 MW(<em>{th}) (20.0 MW(</em>{e}))</td>
<td>8 Evaporators, 2 Superheaters</td>
<td>No</td>
<td>438 °C 8.8 MPa 30.9 kg/s</td>
</tr>
</tbody>
</table>

3.1.2. Clinch River Breeder Reactor (CRBR)

Originally, EBR-II was designed as an engineering facility to demonstrate the feasibility of fast reactors for central station power plant applications. To this aim, the associated Rankine cycle was not designed to optimize thermal efficiency or to maximize the electrical power output. To this aim, in June 1970, the United States Congress authorized the Atomic Energy Commission (AEC) and a successor agency, the U.S. Energy Research and Development Administration (ERDA) to undertake the design, construction, and operation of the Clinch River Breeder Reactor plant (CRBR), the U.S.’s first large-scale demonstration breeder nuclear power plant, which was supposed to be in Oak Ridge (TN). The project was intended as a prototype and demonstration for building a class of LMFBRs. After initial appropriations were provided in 1972, work continued until the U.S. Congress terminated funding in October 1983. The reactor would have been a sodium-cooled, fast-neutron reactor fueled with a mixture of plutonium and uranium oxides, rated at 975 MW\(_{th}\) with a net electrical power output of 380 MW\(_{e}\). The plant would have been an integrated electric generation facility, designed to operate as a part of the Tennessee Valley Authority (TVA) power distribution network [52].

The heat transport system of CRBR consisted of three, independent and identical steam generation systems (SGS) with forced recirculation coupled to a conventional non-reheat turbine. The scheme of an SGS is shown in Figure 3-3. The SG modules in each of the three SGS comprised two parallel operating evaporators, one superheater, one steam drum and one water recirculation pump. The evaporators and superheaters were vertically oriented shell and tube heat exchangers arranged in a “hockey stick” configuration with a 90-deg bend in the shell and tubes to provide for differential thermal expansion between the tube bundle and shell. The SGSs accepted flowing sodium at 502 °C, cooled it to 344 °C, and converted feedwater at 232 °C to superheated steam that was delivered to the turbine throttle at 482 °C and 10.51 MPa. Each SGS was designed to transfer 325 MW\(_{th}\) at full power, with a load following range from 40% to 100% of full power. The technical specifications of CRBR SGS are reported in Table 3-3. At the full-power conditions, water was pumped from the steam drum at a 2-to-1 recirculation ratio to the two evaporators where it was boiled to a two-phase mixture and was then returned to the steam drum for separation of saturated steam that went from the drum to the superheater. A portion of the saturated liquid water was continuously drained from the drum to the feedwater treatment system for return to the drum as part of the feedwater flow after full-flow demineralization treatment [53].
Table 3-3. Technical specifications of the SG system of CRBR and the turbine generator throttle conditions.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRBR</td>
<td>[52][53] Never built</td>
<td>Recirculation</td>
<td>975 MW_{th} (380 MW_{e}) 3 Loops</td>
<td>2 Evaporators, 1 Superheater</td>
<td>No</td>
<td>482 °C 10.51 MPa 420.83 kg/s</td>
</tr>
</tbody>
</table>

3.1.3. Overview of steam generation capabilities of representative SFR designs

In the following years, once the SFR technology was assessed, other units were designed, licensed, and operated all over the world. In Table 3-4, the technical specifications of the steam systems coupled with representative sodium-cooled reactors that were operated in the last decades are reported. As for the steam system designs, it can be observed that recirculation SG with no reheating coolant circuit were adopted in the early years of this technology, and then later Once Through Steam Generator (OTSG). In addition to the more complex designs of SG systems and the larger installed capacities, as material capabilities advance, newer designs tend to adopt higher temperatures and higher pressures to obtain superior energy conversion performance (Figure 3-4). From the perspective of using the steam generated by these systems for industrial applications, this design solution broadens the scope of potential applications.
Table 3-4. Technical specifications of the SG systems of the considered SFR designs.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBR-II [51]</td>
<td>1964 - 1994</td>
<td>Recirculation</td>
<td>62.5 MW&lt;sub&gt;a&lt;/sub&gt; (20 MW&lt;sub&gt;e&lt;/sub&gt;)</td>
<td>8 Evaporators, 2 Superheaters</td>
<td>No</td>
<td>438 °C, 8.8 MPa, 30.9 kg/s</td>
</tr>
<tr>
<td>BN-350 [51]</td>
<td>1973 - 1999</td>
<td>Recirculation</td>
<td>1,000 MW&lt;sub&gt;th&lt;/sub&gt; (350 MW&lt;sub&gt;e&lt;/sub&gt;)</td>
<td>2 Evaporators, 2 Superheaters</td>
<td>No</td>
<td>435 °C, 5 MPa</td>
</tr>
<tr>
<td>CRBR [52][53]</td>
<td>Never built</td>
<td>Recirculation</td>
<td>975 MW&lt;sub&gt;th&lt;/sub&gt; (380 MW&lt;sub&gt;e&lt;/sub&gt;)</td>
<td>2 Evaporators, 1 Superheater</td>
<td>No</td>
<td>482 °C, 10.51 MPa, 420.83 kg/s</td>
</tr>
<tr>
<td>BN-600 [55][56]</td>
<td>1980 - Present</td>
<td>Straight tube, modular-staged OTSG</td>
<td>1,470 MW&lt;sub&gt;th&lt;/sub&gt; (600 MW&lt;sub&gt;e&lt;/sub&gt;)</td>
<td>8 Evaporators, 8 Superheaters</td>
<td>Sodium</td>
<td>507 °C, 13.7 MPa, 180 kg/s</td>
</tr>
<tr>
<td>Superphénix [57][58]</td>
<td>1985 - 1998</td>
<td>Helical coil OTSG</td>
<td>3,000 MW&lt;sub&gt;th&lt;/sub&gt; (1,242 MW&lt;sub&gt;e&lt;/sub&gt;)</td>
<td>1 Economizer/ Evaporator, 1 Superheater, No Reheat</td>
<td>Steam</td>
<td>490 °C, 18.4 MPa, 338.7 kg/s</td>
</tr>
<tr>
<td>BN-800 [55][56]</td>
<td>2014 - Present</td>
<td>Modular-staged OTSG</td>
<td>2,100 MW&lt;sub&gt;th&lt;/sub&gt; (880 MW&lt;sub&gt;e&lt;/sub&gt;)</td>
<td>8 Evaporators, 8 Superheaters</td>
<td>Steam</td>
<td>490 °C, 14 MPa, 876 kg/s</td>
</tr>
</tbody>
</table>

Figure 3-4. Thermodynamic conditions of the steam generated in the energy conversion cycles of the selected SFR designs (“Turbine generator throttle conditions”).
3.1.4. Westinghouse Demonstration LFR (DLFR)

In the last few years, there has been a renewed attention towards Lead-cooled Fast Reactors (LFRs). Among vendors, Westinghouse Electric Company LLC (WEC) has been developing its own design. The benefits of lead cooling over sodium cooling are its high boiling point and lack of chemical activity. In particular, the latter offers several benefits. It not only provides additional flexibility for the technology used in SGs and the balance of plant, but it also enables the use of water as a coolant in an emergency. The Westinghouse Demonstration Lead Fast Reactor (DLFR) is a lead-cooled, pool-type fast reactor, targeting operation by 2030 and intended for demonstrating feasibility and basic performance of DLFR-based technology for the ensuing commercial deployment [59][60]. The Westinghouse DLFR is a ~ 465 MW_e (950 MW_th), highly simplified, passively safe, scalable, lead-cooled fast neutron spectrum reactor. DLFR features a compact, pool-type, primary system, with the main vessel containing all primary circuit components immersed in molten lead. The reactor is envisioned to be developed through a staged approach starting with a lower-power Prototype LFR (PLFR) unit adopting higher technology readiness solutions and materials to accelerate its deployment. After the first few years of operation and testing, the PLFR unit is envisioned to be uprated to achieve the ~ 465 MW_e power output thus transitioning to the First Of A Kind (FOAK) of the commercial fleet.

DLFR design is still in pre-conceptual design phase. Multiple configurations are currently being considered for the energy conversion cycle. Supercritical carbon dioxide is the main candidate for the coolant in the secondary side, with supercritical water also being considered for the PLFR, given its higher technology readiness. The possibility of extracting high-grade heat for hydrogen production has been considered by WEC designers. Feasibility studies were performed to explore whether high-grade steam could be used for meaningful efficiency advantage in the process. At this stage, the main goal consists of identifying the desired performance of the energy conversion cycle that ensures the financial sustainability of DLFRs, i.e., the final arrangement of the system’s components is yet to be determined. In Table 3-5, the thermodynamic conditions of the steam flow rate in the Westinghouse DLFR energy conversion cycle adopting supercritical water are reported [61].

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westinghouse DLFR [59][61]</td>
<td>From 2030</td>
<td>N/A</td>
<td>950 MW_th (465 MW_e)</td>
<td>N/A</td>
<td>N/A</td>
<td>633 °C 33 MPa 480-520 kg/s</td>
</tr>
</tbody>
</table>

Table 3-5. Thermodynamic conditions of the generated steam in the energy conversion cycle of Westinghouse DLFR.
3.2. Molten Salt Reactors (MSRs)

3.2.1. Molten-Salt Breeder Reactor (MSBR)

Molten salt reactors (MSRs) are a class of nuclear fission reactor in which the primary nuclear reactor coolant and/or the fuel is a mixture of molten salt with a fissionable material. In 1960, the construction of the Molten Salt Reactor Experiment (MSRE) was authorized. The MSRE was a 7.4 MWth test reactor simulating the neutronic “kernel” of a type of inherently safer epithermal thorium breeder reactor. The MSRE became critical at Oak Ridge in 1965 and, after a successful operating experience, was shut down in late 1969. The MSRE experience was of major importance to the molten-salt concept. It demonstrated that the issues of control, pumping, heat removal, radioactivity containment, and corrosion could be managed. As of today, the Aircraft Reactor Experiment (ARE) and the MSRE remained the only molten-salt reactors ever operated in United States [62][63]. In the MSRE, the heat from the reactor core was shed via a cooling system using air blown over radiators, i.e., no power cycle was foreseen. For this reason, in this Section, technical specifications about the designed energy conversion cycle for Molten-Salt Breeder Reactor (MSBR) are reported.

![Figure 3-5. Flow Diagram of MSBR Plant [64].](image)

From 1970 to 1976, ORNL researchers studied MSBR design. The MSR program closed in the early 1970s in favor of LMFBRs, after which research stagnated in the United States. The proposed 1,000-MWth MSBR steam-electric generating plant consisted of a 2,250-MWth graphite-moderated molten-salt reactor, 4 shell-and-tube primary heat exchangers, and 16 shell-and-tube supercritical SGs (Figure 3-5). Electricity was meant to be produced from supercritical steam with an overall efficiency of 44%. The heat generated in the primary salt in the core was transferred from the tube side of the primary heat exchangers to a countercurrent secondary salt passing through the shell side. To each primary heat exchanger, a secondary loop was associated. The four secondary loops were independent of each other, with each loop supplying heat to four supercritical SGs. The SGs were countercurrent single-pass U-tube exchangers. Feedwater entered
the SGs at the design point at 372 °C and a pressure of about 25.9 MPa. The outlet steam conditions at the design point were 538 °C and 24.82 MPa. Each of the 16 SGs produced steam at the design point at a rate of 78.75 kg/s [64]. The main details of the SG system of MSBR are summarized in Table 3-6.

### Table 3-6. Technical specifications of the SG system of MSBR and the turbine generator throttle conditions.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSBR [63][64]</td>
<td>Never built</td>
<td>U-tube OTSG</td>
<td>2,250 MWth (1,000 MWe)</td>
<td>4 Secondary Loops</td>
<td>Molten Salt</td>
<td>537 °C 24.8 MPa 1,260 kg/s</td>
</tr>
</tbody>
</table>

3.2.2. **Kairos Power Fluoride salt-cooled High temperature Reactor (KP-FHR)**

The Kairos Power (KP) Fluoride salt-cooled High temperature Reactor (KP-FHR) is a new, U.S.-developed advanced reactor technology based on rapid progress in the last decade. KP builds on the foundation laid by DOE-sponsored university Integrated Research Projects (IRPs) on FHRs to develop the KP-FHR. The reference thermal power for a commercial KP-FHR reactor is 320 MWth (140 MWe). The fundamental concept of FHR is the novel combination of robust tristructural isotropic (TRISO) particle fuel, and chemically inert and transparent fluoride salt coolant Flibe (Li-7 enriched Li2BeF4). The TRISO particle fuel in the KP-FHR is a high-temperature graphite-matrix coated particle fuel developed for high-temperature gas reactors, with allows for fuel temperatures exceeding 1,600 °C. The coolant is a chemically stable, low vapor pressure molten fluoride salt mixture (Flibe) with a boiling point of 1,430 °C. The intrinsic low pressure enhances safety and eliminates the need for bulky and expensive high-pressure containment structures. At the same time, the high reactor normal operating outlet temperatures (up to 750 °C) enabled by this combination allow the KP-FHR to leverage high-efficiency, flexible power conversion systems.

Currently, the KP-FHR is in the conceptual design stage, and a detailed configuration is still under development. In [65], a diagram showing the current overall reference system configuration is provided, and the major design options/parameters are reported. KP plans on using currently available technology for near-term deployment. Accordingly, the tentative layout of the energy conversion cycle foresees a traditional Rankine cycle. The steam flow rate from the SG at a temperature equal to 585 °C and a pressure equal to 19 MPa is expanded in a subcritical, steam turbine with High Pressure (HP), Medium Pressure (MP), and Low Pressure (LP) stages (Table 3-7).
Table 3-7. Thermodynamic conditions of the generated steam in the energy conversion cycle of KP-FHR.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>KP-FHR</td>
<td>From 2026</td>
<td>N/A</td>
<td>320 MWth (140 MWe)</td>
<td>N/A</td>
<td>N/A</td>
<td>585 °C 19 MPa</td>
</tr>
</tbody>
</table>

### 3.3. High Temperature Gas-cooled Reactors (HTGRs)

#### 3.3.1. Fort St. Vrain (FSV) High Temperature Gas-cooled Reactor

High-Temperature Gas-cooled Reactor (HTGR) is the most mature Generation-IV Advanced Reactor Technology, both in terms of reactor and fuel. To represent this category of nuclear power plants, Fort St. Vrain (FSV) generating station was selected. Owned and operated by Public Service company of Colorado between 1976 and 1989, it was situated approximately 40 miles north of Denver. Designed by General Atomics in the mid-1960s as part of the U.S. Atomic Energy Commission’s Reactor Demonstration Program, it was the only HTGR in the United States, and it featured a uranium-thorium fuel cycle with helium as primary coolant [67]. Despite being shut down in 1989, FSV reactor design and operational experience played and keeps playing a key role in the deployment of HTGRs, and it is still representative of this technology.

The entire primary coolant system of FSV, including the reactor, the SGs, and the helium circulators, was housed within a prestressed concrete reactor vessel (PCRV). Integration of these items reduces the primary coolant inventory, eliminates external piping, removes the requirements for SG pressure shells, provides a single integral radiation shield, and results in a minimum building size. The reactor was graphite moderated and reflected. The active core consisted of 1,482 hexagonal fuel elements loaded with TRISO-coated uranium and thorium particles cast into cylindrical rods. At rate power conditions, helium was discharged from four circulators and passed down through the core removing heat that was then distributed equally through 12 SG modules [67]. The use of helium as the primary coolant and graphite as the core structural material allowed the Rankine cycle to be optimized. Besides the unique once-through steam generators (OTSG), the secondary side of the plant was similar to conventional fossil-fired power plants, and it ensured comparable performance. Main steam at 17.32 MPa and 540.5 °C was produced in the SGs and entered the HP stages of the turbine generator. The steam was then routed back to the Nuclear Steam Supply System (NSSS), i.e., it was exhausted to the single stage turbines of the helium circulators where it provided the motive force for rotation of the circulator compressors. Then, the steam was reheated to 540.5 °C in the upper (reheater) section of each SG module, before being directed back to the LP stages of the turbine generator [68]. After being condensed into water, it then flowed to condensate pumps, a demineralizer, a bank of heaters and a deaerating heater, then through the main feed pumps (where it was boosted in pressure to be able to enter the SGs) and finally through another set of heaters before restarting the whole cycle. The use of the reheat cycle ensured overall plant thermal efficiency to about 39% (thermal power output was equal to 842
MW\textsubscript{th} and net electrical power output was equal to 330 MW\textsubscript{e}). The configuration of the FSV energy conversion cycle is shown in Figure 3-6. The main details of the SG system of FSV generating station are listed in Table 3-8.

![Figure 3-6. Fort St. Vrain (FSV) turbine generator plant diagram [69].](image)

**Table 3-8. Technical specifications of the SG system of FSV generating station and the turbine generator throttle conditions.**

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort St. Vrain HTGR [68][69]</td>
<td>1976 - 1989</td>
<td>OTSG</td>
<td>842 MW\textsubscript{th} (330 MW\textsubscript{e})</td>
<td>6 Evaporators, 6 Superheaters</td>
<td>Helium</td>
<td>540.5 °C, 17.32 MPa, 290.4 kg/s</td>
</tr>
</tbody>
</table>

As for the SGs design, the helium flow rate entered from the top, then it proceeded downward around a variety of tubes and surfaces, and passed successively over the reheater, finishing superheater, and discharged from the module above the primary closure. The coolant flow and heat regions vaguely paralleled those found in the OTSG used in PWRs, i.e., FSV SGs were also technically once-through and not recirculating types [70][71]. Feedwater entered each module at the external ring-header via the sub-header leads. The feedwater entered the first helical coil bundle and is heated through the economizer, the evaporator and two superheaters. After driving the HP turbine and the helium circulators, the steam returned and entered the cold reheat connection which was concentric with the hot reheat connection.
3.3.2. Xe-100

X-energy is currently working on the conceptual design of the Xe-100, a 200 MW\textsubscript{th}, multi-pass, pebble-bed HTGR. The standard design deploys four identical units, each consisting of a nuclear island containing the reactor/SG coupled to a conventional island embedding a Rankine energy conversion cycle. This modular design is an evolution of past HTGR technology that uses TRISO-coated particle fuel in the form of billiard ball-sized pebbles. Circulating helium transfers heat to a single SG with dual helical coils designed to produce high-grade, superheated steam at 565 °C and 16.5 MPa. This steam may be used to produce a maximum 80 MW\textsubscript{e} by turbogenerator, high-temperature process heat for industrial markets, or multiple energy products in a cogeneration arrangement. In particular, the output could be electricity, or steam for chemical processing, or some of each [72].

The reactor uses helium as the primary-side heat transport fluid to transfer heat to the power conversion systems. Helium inlet (260 °C) and outlet (750 °C) temperatures provide significant material limit margins for structural graphite and metallic support structures. The helium from the reactor then passes through the helical coil SG via a double-walled cross-vessel. The SG contains two independent tube bundles (independent dual-loop helical coils) using a single-metallic tube material to eliminate the need for bi-metallic welds within the tube bundle. The SG boils secondary water on the inside of the tubes and subsequently eliminates most of the phenomena responsible for SG tube degradation in current LWR U-tube designs, such as pitting corrosion on the shell side. The SG has two helium circulators mounted on the top head to provide the driving force for helium circulation, each rated for 50% of design flow [73][74]. The main details of the SG system of Xe-100 are listed in Table 3-9. For the design of Xe-100, X-energy engineers benefitted from a rich history of design development, testing and operation of Pebble Bed Reactors across the globe. In particular, the collected information about the energy conversion cycle outlined several similarities with FSV in terms of component design and thermodynamic conditions of the generated steam flowrate. Overall, the final arrangement of the system's components is yet to be determined.

Table 3-9. Technical specifications of the SG system of Xe-100 and the turbine generator throttle conditions.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe-100 [73][74]</td>
<td>From 2025</td>
<td>Helical coil OTSG</td>
<td>200 MW\textsubscript{th} (80 MW\textsubscript{e}) 1 Loop</td>
<td>N/A</td>
<td>Helium</td>
<td>565.6 °C 16.5 MPa 76.84 kg/s</td>
</tr>
</tbody>
</table>

3.3.3. High-Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM)

In China, the R&D of HTGRs began in the middle of the 1970s. From 1974 to 1985, the Institute of Nuclear and New Energy Technology (INET) of the Tsinghua University carried out
some basic research on HTGR technology. After 1986, these activities were intensified by co-operating with the international HTGR community, especially with German institutions. A second step of HTGR-application started in 2001 when the High-Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) project was launched. Work on the first demonstration power plant began in December 2012, and the first plant started producing electrical power in December 2021 [75]. From 2001 to 2003, the INET cooperated with the East China Electric Power Design Institute (ECEPDI) to carry out pre-conceptual research for HTGR power plants. Three technical solutions, i.e., (1) the conventional indirect steam turbine cycle, (2) the direct helium turbine arrangement, and (3) the indirect helium turbine arrangement, were compared. It was found that the direct helium turbine technology had technical uncertainties, and that the conditions for constructing an industrial demonstration plant of this type were not ready yet. In 2003, it was decided to use a steam turbine cycle for the HTR-PM project after the three abovementioned cycles had been intensively studied and scrutinized. Based on the German AVR design, the HTR-PM is a HTGR pebble-bed Generation IV reactor. It is composed of two modules, each one of 250 MWth, that are coupled with two subcritical SGs which are connected to one super high-pressure condensing bleed steam turbine-generator of 210 MWe (the thermal efficiency of HTR-PM is about 42%). These components exhibit high reliability and economic viability. In each module, the reactor and the SG are installed in two separate pressure vessels, assembled side-by-side, and are connected by a horizontal coaxial hot gas duct. Helium flow rate enters the nuclear reactor at 250 °C, leaves it at 750 °C at a pressure of 7 MPa, and goes to a Helical coil OTSG. Feedwater enters the SG at 205 °C and output steam has a temperature of 566 °C at a pressure of 13.24 MPa. For an exhaustive characterization of the HTR-PM balance of plant, the reader may refer to [76][77]. Each SG consists of 19 separate helical tube assemblies. Each assembly has a central column, five layers of concentric helically coiled tubes and an outer sleeve. This structure is widely used in lots of SGs in recent years for its compact structure, easier manufacture and verification process, and its convenience for service and repair compared with the integral structure. To ensure two-phase flow stability, throttling apertures are installed at the entrance of all helical tubes. The main technical specifications of the HTR-PM energy conversion cycle are reported in Table 3-10.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Operational period</th>
<th>SG design</th>
<th>Installed capacity</th>
<th>Number of modules per loop</th>
<th>Reheating coolant circuit</th>
<th>Turbine generator throttle conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTR-PM</td>
<td>2021 - Present</td>
<td>Helical coil OTSG</td>
<td>500 MWth (210 MW_e)</td>
<td>2 Loop</td>
<td>Helium</td>
<td>566 °C, 13.24 MPa, 187 kg/s</td>
</tr>
</tbody>
</table>

Research activities are currently being performed to replace the subcritical SGs in HTR-PM with supercritical SGs to work with the current reactors and the supercritical steam turbine to improve the thermal efficiency (third technical phase of the HTR-PM program). It is estimated
that the thermal efficiency can reach 45% with supercritical SGs (in which the supercritical pressure fluid flows in the secondary loop) instead of subcritical SGs and a supercritical steam turbine. At a subcritical pressure, in case of a boiling crisis, the heat transfer rate dramatically drops, and the temperature of the tubes increase beyond their limit. However, the density of the supercritical pressure fluid changes substantially and there is no phase change, the heat transfer deterioration is relatively moderate compared with the boiling crisis of the subcritical pressure fluids, which is also good for the SG [77].
4. PAIRING BETWEEN INDUSTRIAL PROCESSES AND ADVANCED REACTOR DESIGNS

In Section 2, four categories of Industrial Processes of interest, i.e., Petroleum refinery, Chemical polymers production, Steel manufacturing, and Calcination for cement production, were selected. For each process, the set of subprocesses was identified, and the corresponding temperature ranges and required heat loads were specified (Table 2-1). In Section 3, the performance of the Rankine energy conversion cycles of representative designs of Advanced Reactors was characterized. For each unit, the thermodynamic conditions of steam at the SG outlet were identified and reported in Table 3-1. In this Section, the possibility of using a portion of the generated steam flow rate to feed the considered Industrial Processes is investigated.

As a first step, we need to determine whether such a coupling is favorable, i.e., we need to assess that the quality of the heat generated within the nuclear reactors is high enough to feed the Industrial Processes. Before presenting the outcomes of this analysis, it’s necessary to outline the assumptions made. We proceeded with the analysis based on the premise that supplying thermal power to the Industrial Process is equally important as producing electrical power for distribution to the grid. To stress the importance of this assumption, let us make a comparison with the configuration of a Combined Cycle Gas Turbine (CCGT) plant. A combined cycle power plant is an assembly of heat engines that work in tandem from the same source of heat, converting it into mechanical energy. In a CCGT plant, the thermodynamic cycle of the basic combined cycle consists of two power plant cycles. One is the Joule or Brayton cycle which is a gas turbine cycle (“topping cycle”), and the other is the Rankine cycle which is a steam turbine cycle and operates at a lower temperature (“bottoming cycle”). Since heat engines can only use part of the energy from their fuel, the remaining heat (i.e., hot exhaust gas) from combustion is meant to be wasted. In CCGT plants, a portion of the low-quality heat rejected by the gas turbine is transferred at constant pressure to feedwater, wet and super-heated steam in a waste heat recovery boiler in the bottoming cycle [78]. The overall effect of this thermal coupling is a significant increase of thermal efficiency (in modern combined cycle plants, the efficiency can exceed 60%). In this work, a different perspective is adopted. Given our assumption that fulfilling the Industrial Process’s heat load is as critical as meeting the electrical power demand of the grid, the Industrial Process is supplied with the highest-quality heat that the nuclear unit can provide (“Turbine generator throttle conditions”). Accordingly, a portion of the steam to be expanded in the HP turbine is then diverted to the Industrial Process (Figure 4-1). We will refer to this configuration as “Direct steam distribution”, since the steam flow rate is directly supplied to the process, without any additional treatment to increase its temperature/pressure conditions.
Figure 4-1. Thermal coupling between an Advanced Nuclear Reactor and an Industrial Process implementing the “Direct steam distribution” configuration [79].

Given this premise, a preliminary pairing was made between (1) the heat load requirements of the selected Processes and (2) the thermodynamic conditions of the steam flow rates generated by the Advanced Reactor designs. The results are shown in Figure 4-2. Different colors are used to label the subprocesses in each category, i.e., Cement production, Steel production, Polymers production and Petroleum refinery. From this plot, the following conclusions can be drawn:

- By using the 490 °C steam from an LMFBR, only a fraction of petroleum refinery processes (ADU, VDU, Hydrotreater, Hydrocracking and Visbreaker) and one polymer production process (Polyethylene Terephthalate) can be supplied.

- By using either the 566 °C steam from a HTGR or the 585 °C steam from an MSR, only two more petroleum refinery processes (Catalytic Reforming and Delayed Coker) and one more polymer production process (Vinyl Chloride monomer) can be supplied.

Overall, these results are encouraging. Despite Advanced Reactor designs are operated at higher temperatures than Light Water Reactors, the temperature/pressure conditions of the produced steam flow rate are not sufficient. Processes like Cement production (limestone/dolomite calcination) and Steel production require inaccessible temperatures (up to 1,700 °C), and radically different engineering solutions will be necessary. At the same time, if the temperature of steam were elevated to 900 °C, most of the processes (i.e., Fluid Catalytic Cracking, Styrene monomer production, Olefins production, steel annealing and the rolling for certain types of steel) could be supplied.
Different solutions are currently being investigated to boost the steam temperature from 490-585 °C to a desired temperature higher than 800 °C. Among the others, heat pumps can potentially expand the flexibility and diversity of applications of nuclear power. They can provide a means for deploying nuclear reactor technology at operating conditions that in the past have been successfully demonstrated on a commercial scale while at the same time providing high-quality heat. Heat pumps rely on a technology similar to that found in a refrigerator or an air conditioner. Once extracted the heat from a source, elevate its temperature and transfer it to where it is needed, usually in the opposite direction of spontaneous heat flow. A typical heat pump circuit consists of a compressor, which moves a refrigerant through a refrigeration cycle, and a heat exchanger, which extracts the heat from the source. Regarding the present application, the presence of the heat source is not strictly necessary. As shown in the numerical example reported in Section 5, the targeted temperature rise in a superheated steam flow can be achieved by appropriately increasing its pressure using a compressor. In Figure 4-3, a modified version of the thermal coupling between an Advanced Nuclear Reactor and Industrial Processes is represented. A portion of the high-quality...
steam flows to the HP turbine, whereas the remaining portion flows through a compressor (“Heat Pump” icon) where its temperature and pressure are increased. When the required thermodynamic conditions are obtained, the steam is delivered to “Industrial Process 1”. As for the steam flow rate exhausted by the HP turbine, its quality has degraded, but it can still be used for industrial applications. For this reason, a second energy distribution is foreseen, i.e., a portion of the flow rate will continue its expansion in the LP turbine, whereas the remaining part will be fed to a second process (“Industrial Process 2”) whose heat loads can be satisfied by low-quality steam. We will refer to this layout as “Boosted-Quality Steam” configuration. Despite the complexity introduced by numerous steam extraction points, this configuration is characterized by a significantly higher thermal efficiency, since the same heat source is used multiple times to meet the requirements of all the connected thermal loads, i.e., the Industrial Processes.

Figure 4-3. Thermal coupling between an Advanced Nuclear Reactor and an Industrial Process implementing the “Boosted-Quality Steam” configuration [79].
5. ANALYSIS OF REFERENCE HEAT PUMP CONFIGURATIONS FOR DELIVERING HIGH-TEMPERATURE HEAT TO AN INDUSTRIAL PROCESS

The results presented in Section 4 pointed out that heat pumps can potentially expand the flexibility and diversity of applications of nuclear power. In this Section, an initial evaluation of the possibility of adopting these components to boost the quality of nuclear reactor-generated steam is described. As an example, the merits of using a heat pump to increase the temperature of the steam produced by a traditional PWR are investigated. There are multiple configurations of components that can render a heat pump driven by the electricity obtained from the thermal power produced in a nuclear reactor. To evaluate the performance from the standpoint of thermal efficiency and achievable temperature rise, we limited the space explored to a few simple cases. A detailed analysis of the corresponding thermodynamic cycles is provided. Here below the main assumptions/requirements are listed:

1. The characteristic conditions of the steam produced in a PWR were adopted, i.e., the temperature equal to 300 °C and the pressure equal to 6.2 MPa.
2. The adoption of Heat Pumps inevitably complicates the layout of the traditional PWR Rankine cycle by requiring the inclusion of additional components. The superior investment needs to be justified by the capability of supplying high-quality heat to the associated industrial process and by superior performance in terms of thermal efficiency. To get a consistent characterization, the Heat Pump-system needs to be addressed as a closed system, i.e., the only input is reactor grade heat. This portion of the unit will be defined as “Secondary System”. This means that the electrical power absorbed by the Compressor increasing the steam pressure must be generated within the closed system, i.e., it needs to be retrieved from the thermal energy provided in the SG. Accordingly, a dedicated Rankine energy conversion cycle powering the Compressor must be envisioned within the “Secondary System”.
3. The industrial process absorbing the high-temperature heat, i.e., the “Industrial Plant”, exhausts either saturated liquid or saturated steam.

5.1. Definition of two different system configurations providing high-quality heat to the Industrial Plant

Based on the provisions listed above, two potential configurations were identified, i.e., the energy conversion cycle can be either upstream or downstream to the Industrial Plant. They will be presented in Sections 5.1.1 and 5.1.2. In the former configuration (“Case #1”), saturated liquid exits the industrial process. Accordingly, the Rankine cycle is located upstream of this heat load, this being the only location where there is steam of sufficient energy content (Figure 5-1a). In the latter configuration (“Case #2”), the saturated vapor exiting the industrial process is used to drive the Rankine cycle (Figure 5-1b). While variations of these two configurations can be investigated, these examples provide an understanding of the achievable temperatures, pressures, and thermal
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efficiencies. In Section 5.2 and Section 5.3, the stages of the “Secondary System” for “Case #1” are analyzed, the corresponding water conditions are evaluated, and the thermal efficiency is calculated. This analysis was repeated for “Case #2” and the main results were reported in Section 5.4 and Section 5.5. The used symbols, their meanings and the corresponding units are reported below.

\[ m \] Mass flow rate, (kg/s)
\[ T \] Temperature, (°C)
\[ h \] Specific enthalpy, (kJ/kg)
\[ s \] Specific entropy, (kJ/kgK)
\[ x \] Steam quality, (-)
\[ Q \] Provided/absorbed heat per unit of time, (kJ/s)
\[ W \] Provided/absorbed work per unit of time, (kJ/s)
\[ W_{\text{tur,HP}} \] Electrical power output of HP stages of the steam turbine
\[ W_{\text{tur,LP}} \] Electrical power output of LP stages of the steam turbine
\[ W_{\text{pump}} \] power absorbed by the Feedwater (FW) Pump motor
\[ \eta_{t,\text{is}} \] Isentropic efficiency of the Steam Turbine stages, (-)
\[ \eta_{t,m} = 0.98 \] Electromechanical efficiency of the HP and LP stages of the Steam Turbine, (-)
\[ \eta_{c,\text{is}} \] Isentropic efficiency of the Compressor, (-)
\[ \eta_{c,m} = 0.98 \] Electromechanical efficiency of the Compressor, (-)
\[ \eta_{p,m} = 0.98 \] Electromechanical efficiency of the Feedwater Pump, (-)

5.1.1. “Case #1” configuration: Industrial Plant exhausting Saturated Liquid flow rate

In Figure 5-1a, the plant diagram of the system characterized by an industrial process exhausting Saturated Liquid flow rate is shown. The “Secondary System” is outlined in red. Let us denote by \( Q_{\text{in}} \) the reactor grade heat that is provided to the “Secondary System” through the SG. The SG produces a steam flow rate at superheated vapor conditions (point 2) that splits in two, i.e., a portion is supplied to the Compressor upstream to the Industrial Process, and the left amount feeds the Rankine cycle powering the Compressor. Before entering the Industrial Plant, the steam is compressed until it reaches the desired temperature (point 3). Let us denote by \( W_{\text{comp}} \) the power absorbed by the Compressor motor. The Industrial Plant exhausts a saturated liquid flow rate (point 4). Let us denote by \( Q_{\text{IP}} \) the thermal power absorbed by the Industrial Plant. The water is then cooled by a “Heat Sink” until it reaches the SG inlet temperature and pressure conditions. As for the portion of steam flow rate entering the Rankine cycle, it first passes through the “Secondary Steam Turbine” (points 2, 5 and 6). Then, it is condensed (point 7), pre-heated (point 8), and pumped so it can be merged with the main feedwater (FW) flow rate (point 1).

As mentioned before, the electrical power absorbed by the Compressor is derived from the thermal power input (\( Q_{\text{in}} \)). The main task of the “Secondary System” consists of providing the
Industrial Plant with high-quality heat. This entails that the portion of the steam flow rate fed to the Rankine cycle is the minimum amount that is necessary to power both the Compressor and the FW Pump motors. The net electrical power output of the Rankine cycle is then zero (Eq. (16)).

\[ W_{\text{Rankine}} = W_{\text{tur,HP}} \cdot \eta_{t,m} + W_{\text{tur,LP}} \cdot \eta_{t,m} - W_{\text{pump}}/\eta_{p,m} - W_{\text{comp}}/\eta_{c,m} = 0 \]  

(16)

The thermal efficiency of the “Secondary System” (\( \eta_{\text{sys}}^{\text{Case#1}} \)) is evaluated by adopting the approach that is currently used for characterizing the performance of cogeneration (CHP) power plants (Eq. (17)).

\[ \eta_{\text{sys}}^{\text{Case#1}} = \frac{Q_{\text{IP}} + W_{\text{Rankine}}}{Q_{\text{in}}} = \frac{Q_{\text{IP}}}{Q_{\text{in}}} \]  

(17)

5.1.2. “Case #2” configuration: Industrial Plant exhausting Saturated Vapor flow rate

In Figure 5-1b, the plant diagram of the system identified as “Case #2” is shown. The “Secondary System” is outlined in red. With respect to Case #1, the Industrial Plant exhausts a saturated vapor flow rate. Clearly, the industrial process studied in Case #2 is different from the one studied in Case #1, since it can use of a smaller fraction of the provided high-quality heat. In Case #2 configuration, the whole steam flow rate produced in the SG that is devoted to the Secondary System is processed by the Compressor that increases its temperature until the same value imposed in Case #1 is reached. The saturated vapor flow rate exiting the Industrial Plant is sent to the downstream Rankine cycle producing electrical power (\( W_{\text{Rankine}} \)) that is mostly used to power the Compressor. Once the steam has passed through the two-stage steam turbine (point 5 and 6), it is condensed (point 7), pre-heated (point 8) and then pumped to the SG inlet (point 1). The net electrical power output of the downstream Rankine cycle is obtained by removing from the turbine power output the power absorbed by the FW Pump and the Compressor motors (Eq. (18)).

\[ W_{\text{Rankine}} = W_{\text{tur,HP}} \cdot \eta_{t,m} + W_{\text{tur,LP}} \cdot \eta_{t,m} - W_{\text{pump}}/\eta_{p,m} - W_{\text{comp}}/\eta_{c,m} \]  

(18)

The expression of the thermal efficiency (\( \eta_{\text{sys}}^{\text{Case#2}} \)) is reported in Eq.(19).

\[ \eta_{\text{sys}}^{\text{Case#2}} = \frac{Q_{\text{IP}} + W_{\text{Rankine}}}{Q_{\text{in}}} = \frac{Q_{\text{IP}} + (W_{\text{tur,HP}} \cdot \eta_{t,m} + W_{\text{tur,LP}} \cdot \eta_{t,m} - W_{\text{pump}}/\eta_{p,m} - W_{\text{comp}}/\eta_{c,m})}{Q_{\text{in}}} \]  

(19)
Figure 5-1. Plant diagram of the “Secondary System”, (a) Case #1, (b) Case #2. Black denotes the standard power plant Rankine cycle. Red denotes the closed system heat pump.
5.2. Description of “Case #1” configuration stages

5.2.1. Heat addition at constant pressure in the SG: (1) → (2)

The portion of the FW flow rate supplied to the “Secondary System” \( m_0 \) enters the SG as subcooled conditions (Eq.(20)). It is heated at constant pressure until reaching superheated steam conditions (Eq.(21)). Starting from the enthalpy variation, the thermal power input is calculated (Eq.(22)).

\[
T_1 = 225.0 \, ^\circ C, \quad p_1 = 6.2 \, MPa \quad (20)
\]
\[
T_2 = 300.0 \, ^\circ C, \quad p_2 = 6.2 \, MPa, \quad T_{sat}(p_2) = 277.7 \, ^\circ C, \quad x_2 = 1.06 \quad (21)
\]
\[
Q_{in} = m_0(h_2 - h_1) \quad (22)
\]

5.2.2. Steam compression in the Compressor: (2) → (3)

As mentioned in Section 5.1.1, a portion of the steam flow rate from the SG is supplied to the Compressor, and the left amount enters the Rankine cycle powering the Compressor motor. Let us denote by \( Y_1 \) the fraction supplied to the Compressor. Let us impose that the steam temperature at the Compressor outlet \( T_3 \) is equal to 600 °C. In Eq.(23), the theoretical work \( W_{comp}^{rev} \) that would be required in case of isentropic compression is defined. The actual work \( W_{comp} \) accounting for the entropy production is expressed in Eq.(24).

\[
W_{comp}^{rev} = m_0 Y_1 (h_3' - h_2) \quad (23)
\]
\[
W_{comp} = m_0 Y_1 (h_3 - h_2) \quad (24)
\]

In Eq.(25), the definition of the isentropic efficiency of the compression process \( \eta_{c, is} \) and the adopted value are reported.

\[
\eta_{c, is} = \frac{W_{comp}^{rev}}{W_{comp}} = \frac{(h_3' - h_2)}{(h_3 - h_2)} = 0.86 \quad (25)
\]

To estimate the power absorbed by the Compressor motor, the pressure \( p_3 \) corresponding to the desired outlet temperature \( T_3 \) needs to be evaluated. First, let us define the temperature that would be obtained in case of isentropic compression \( T_3' \) (Eqs.(26)(27)).

\[
s_3' = s_2 = s(T_2, p_2) \quad (26)
\]
\[
T_3' = T(p_3, s_3') = T(p_3, s(T_2, p_2)) \quad (27)
\]

To evaluate the actual enthalpy at the Compressor outlet, Eq.(27) is inserted into the isentropic efficiency equation (Eq.(28)). By numerically solving this equation, the pressure at the Compressor outlet \( p_3 \) can be retrieved (Eq.(29)). Since no heat contribution is foreseen, a significant pressure
increase is necessary, i.e., the Compressor exhausts a supercritical steam flow rate. In Eq.(30), the estimated value of the Compressor Pressure Ratio (CPR) is reported.

\[
\frac{h(T(p_3,s(T_2,p_2)),p_3) - h(T_2,p_2)}{h(T_3,p_3) - h(T_2,p_2)} = 0.86
\]  

\( p_3 = 34.77 \text{ MPa} \)  

\( \text{CPR} = \frac{p_3}{p_2} \cong 5.61 \)  

5.2.3. *Heat absorbed by the Industrial Plant: (3) \( \rightarrow \) (4)*

The Industrial Plant exhausts saturated liquid flow rate (Eq.(31)). The absorbed thermal power is expressed in Eq.(32).

\[
p_4 = 20 \text{ MPa}, \quad T_4 = T_{\text{sat}}(p_4) = 365.7 ^\circ\text{C}, x_4 = 0.0
\]  

\[
Q_{iP} = m_0 Y_1(h_3 - h_4)
\]  

5.2.4. *Heat rejection to the Heat sink: (4) \( \rightarrow \) (1)*

Downstream to the Industrial Plant, a “Heat Sink” is foreseen. Its task consists of cooling the saturated liquid exhaust until it reaches the SG inlet conditions. In Eq.(33), the rejected heat is expressed.

\[
Q_{\text{out}} = m_0 Y_1(h_4 - h_1)
\]  

5.2.5. *Steam expansion in the HP stage of the steam turbine: (2) \( \rightarrow \) (5)*

As mentioned in Section 5.1.1, the portion of the steam flow rate directed to the Rankine cycle is carefully evaluated so that the net electrical power output of the “Secondary System” is zero. First, the various stages of the energy conversion cycle need to be identified. As for the steam expansion in the HP stage of the steam turbine, let us evaluate the theoretical work \( W_{\text{tur,HP}}^{rev} \) that would be obtained in case of isentropic expansion (Eqs.(34)(35)). In Eq.(36), the expression of the actual work \( W_{\text{tur,HP}} \) is reported. Starting from the definition of isentropic efficiency (Eq.(37)), the enthalpy at the outlet of the HP stage \( (h_5) \) can be calculated, and so the electrical power output.

\[
s'_{5} = s_2 = s(T_2,p_2)
\]  

\[
W_{\text{tur,HP}}^{rev} = m_0(1 - Y_1)(h_2 - h'_{5})
\]  

\[
W_{\text{tur,HP}} = m_0(1 - Y_1)(h_2 - h_5)
\]  

\[
\eta_{t,\text{is}} = \frac{W_{\text{tur,HP}}}{W_{\text{tur,HP}}^{rev}} = \frac{(h_2 - h_5)}{(h_2 - h'_{5})} = 0.90
\]
5.2.6. Regeneration: (5) \rightarrow (8) & (7) \rightarrow (8)

To improve the efficiency of the system, the temperature of the FW flow rate at the Condenser outlet is increased in a dedicated heat exchanger, i.e., the pre-heater. To this aim, the saturated liquid is heated by a fraction of the steam extracted from the HP stage of the turbine. After throttling, the condensed steam merges with the FW flow rate. Here below the adopted modeling assumptions are listed.

- The pre-heater exhausts saturated liquid flow rate at the same pressure \((p_8)\) as the extracted steam \((p_5)\), as shown in Eq.(38). As shown in Figure 5-2b, the water temperature at the FW Pump outlet is equal to the temperature at the SG inlet \((T_1 = 225.0 \degree C)\). The water temperature at the FW Pump inlet needs to be lower than that value (Eq.(39)). Since the water at the pre-heater outlet is at saturated liquid conditions, its temperature also determines the pressure at the outlet of the HP stage (Eq. (40)).

\[
h_8 = h(p_5, x = 0.0) \tag{38}
\]
\[
T_8 = 220.0 \degree C \tag{39}
\]
\[
p_8 = p_{sat}(T_8) = 2.32 \text{ MPa} \tag{40}
\]

- The power absorbed by the extraction pump is negligible.

Let us denote by \(Y_2\) the fraction of steam flow rate that is diverted from the LP stage for heating the FW flow rate. Its value can be obtained by solving an energy balance over the portion of the system bounded by the dash line in Figure 5-2a (“Secondary FW system”), as reported in Eq.(41).

\[
m_0(1 - Y_1)Y_2 h_5 + m_0(1 - Y_1)(1 - Y_2)h_7 = m_0(1 - Y_1)h_8 \tag{41}
\]

5.2.7. Steam expansion in the LP stage of the steam turbine: (5) \rightarrow (6)

Once defined the operating pressure of the Condenser (Eq.(42)), the power obtained from the steam expansion in the LP stage can be evaluated (Eq.(43)). The value of the isentropic efficiency adopted for the HP stage was used for the LP stage as well (Eq.(44)).

\[
p_6 = 0.005 \text{ MPa}, T_6 = T_{sat}(p_6) = 32.9 \degree C \tag{42}
\]
\[
W_{tur,LP} = m_0(1 - Y_1)(1 - Y_2)(h_5 - h_6) \tag{43}
\]
\[
\eta_{t, is} = \frac{W_{tur,LP}}{W_{tur,LP}^{rev}} = \frac{(h_5 - h_6)}{(h_5 - h_6')} = 0.90 \tag{44}
\]

5.2.8. Heat rejection at constant pressure in the Condenser: (6) \rightarrow (7)

The water conditions at the Condenser outlet are reported in Eq.(45). The disposed heat is expressed in Eq.(46).
\[ p_7 = p_6, \ h_7 = h(p_7, x = 0.0) \]  
\[ Q_{\text{cond}} = m_0 (1 - Y_1)(1 - Y_2)(h_6 - h_7) \]  

5.2.9. **Water compression in the FW Pump: (8) \rightarrow (1)**

The actual work performed by the FW Pump is expressed in Eq.(47).

\[ W_{\text{pump}} = m_0(1 - Y_1)(h_1 - h_8) \]  

5.3. **Evaluation of thermal efficiency for “Case #1” configuration**

As mentioned in Section 5.1.1, the purpose of the Rankine cycle upstream to the Industrial Plant consists of powering the FW Pump and the Compressor motors. This means that the net electrical power output is zero (Eq.(48)).

\[ W_{\text{Rankine}} = W_{\text{tur,HP}} \cdot \eta_{t,m} + W_{\text{tur,LP}} \cdot \eta_{t,m} - W_{\text{pump}} / \eta_{p,m} - W_{\text{comp}} / \eta_{c,m} = \\
= m_0(1 - Y_1)(h_2 - h_5)\eta_{t,m} + m_0(1 - Y_1)(1 - Y_2)(h_5 - h_6)\eta_{t,m} + \\
- m_0(1 - Y_1)(h_1 - h_8) / \eta_{p,m} - m_0 Y_1(h_3 - h_2) / \eta_{c,m} = 0 \]  

By simultaneously solving Eq.(48) and the energy balance expressed in Eq.(41), the values of \( Y_1 \) and \( Y_2 \) can be retrieved (Eq.(49)). In Eq.(50), the calculated value of the thermal efficiency of the “Secondary System” for Case #1 configuration (\( \eta_{\text{sys} \ Case#1} \)) is reported. In Figure 5-2, the plant diagram of the thermodynamic cycle provided with the water conditions at each stage along with the T-s diagram is represented.

\[ Y_1 = 0.552, \ Y_2 = 0.314 \]  
\[ \eta_{\text{sys} \ Case#1} = \frac{Q_{IP}}{Q_{in}} = Y_1 \frac{(h_3 - h_4)}{(h_2 - h_1)} \cong 45.55\% \]
Figure 5-2. Representation of the “Secondary System” (Case #1), (a) plant diagram of the thermodynamic cycle provided with the water conditions at each stage, (b) T-s diagram.
5.4. **Description of “Case #2” configuration stages**

5.4.1. **Heat addition at constant pressure in the SG: (1) → (2)**

The water conditions at the SG inlet and outlet are identical to the ones adopted in “Case #1” configuration (Eqs. (20)(21)), and so is the heat input (Eq.(51)).

\[ Q_{in} = m_0 (h_2 - h_1) \]  \hspace{1cm} (51)

5.4.2. **Steam compression in the Compressor: (2) → (3)**

The operating conditions at the Compressor inlet and outlet are the same that were evaluated for “Case #1” configuration (Eqs. (21)(29)). The only difference is that the entire steam flow rate from the SG is processed (Eq.(52)).

\[ W_{comp} = m_0 (h_3 - h_2) \]  \hspace{1cm} (52)

5.4.3. **Heat absorbed by the Industrial Plant: (3) → (4)**

In “Case #2” configuration, the Industrial Plant exhausts saturated vapor (Eq.(53)). The absorbed heat is expressed in Eq.(54).

\[ p_4 = 20 \text{ MPa}, \ T_4 = T_{sat}(p_4) = 365.7 \text{ °C}, x_4 = 1.0 \]  \hspace{1cm} (53)

\[ Q_{IP} = m_0 (h_3 - h_4) \]  \hspace{1cm} (54)

5.4.4. **Steam expansion in the HP stage of the steam turbine: (4) → (5)**

The steam flow rate exiting the Industrial Plant is directed to the downstream Rankine cycle. The same approach used to characterize “Case #1” configuration is followed. The major difference is that the entire steam flow rate processed by the industrial process is flowing through the stages of the Steam Turbine. As for the steam expansion in the HP stage, the theoretical work that would be obtained in case of isentropic expansion \( W_{tur,HP}^{rev} \) is first evaluated (Eqs.(55)(56)). In Eq.(57), the expression of the actual work is reported. By solving the isentropic efficiency equation (Eq.(58)), the enthalpy at the outlet of the HP stage \( h_5 \) can be calculated, and so the electrical power output.

\[ s_5' = s_4 = s(p_4, x = 1.0) \]  \hspace{1cm} (55)

\[ W_{tur,HP}^{rev} = m_0 (h_4 - h'_5) \]  \hspace{1cm} (56)

\[ W_{tur,HP} = m_0 (h_4 - h_5) \]  \hspace{1cm} (57)

\[ \eta_{t,is} = \frac{W_{tur,HP}}{W_{tur,HP}^{rev}} = \frac{(h_4 - h_5)}{(h_4 - h'_5)} = 0.90 \]  \hspace{1cm} (58)

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5.4.5. **Regeneration: (5) → (8) & (7) → (8)**

“Case #2” configuration foresees a regeneration stage as well. The same assumptions adopted for “Case #1” configuration were used. Let us denote by $Y$ the fraction of extracted steam flow rate that is diverted from the LP stage for heating the FW flow rate. The value of $Y$ can be obtained by solving an energy balance over the portion of the system bounded by the dash line in Figure 5-3a (“Secondary FW system”). The energy balance and its solution are reported in Eqs.(59)(60).

$$m_0 Y h_5 + m_0 (1 - Y) h_7 = m_0 h_8$$  \hspace{1cm} (59)

$$Y = \frac{h_8 - h_7}{h_5 - h_7} \approx 0.398$$  \hspace{1cm} (60)

5.4.6. **Steam expansion in the LP stage of the steam turbine: (5) → (6)**

Once defined the operating pressure of the Condenser (Eq.(61)), the power obtained from the steam expansion in the LP stage can be evaluated (Eq.(62)). The isentropic efficiency value adopted for the HP stage was used for the LP stage as well (Eq.(63)).

$$p_6 = 0.005 \text{ MPa}, \quad T_6 = T_{sat}(p_6) = 32.9 \text{ °C}$$  \hspace{1cm} (61)

$$W_{\text{tur,LP}} = m_0 (1 - Y) (h_5 - h_6)$$  \hspace{1cm} (62)

$$\eta_{t, is} = \frac{W_{\text{tur,LP}}}{W_{\text{tur,LP}}^{rev}} = \frac{(h_5 - h_6)}{(h_5 - h_6')} = 0.90$$  \hspace{1cm} (63)

5.4.7. **Heat rejection at constant pressure in the Condenser: (6) → (7)**

The heat disposed to the Condenser is expressed in Eq.(64).

$$Q_{\text{cond}} = m_0 (1 - Y) (h_6 - h_7)$$  \hspace{1cm} (64)

5.4.8. **Water compression in the FW Pump: (8) → (1)**

The actual work performed by the FW Pump is expressed in Eq.(65).

$$W_{\text{pump}} = m_0 (h_1 - h_8)$$  \hspace{1cm} (65)

5.5. **Evaluation of thermal efficiency for “Case #2” configuration**

In Eq.(66), the calculated value of the net electrical power output of the downstream Rankine cycle is reported.

$$W_{\text{Rankine}} = W_{\text{tur,HP}} \cdot \eta_{t,m} + W_{\text{tur,LP}} \cdot \eta_{t,m} - W_{\text{pump}} / \eta_{p,m} - W_{\text{comp}} / \eta_{c,m} =$$

$$= m_0 [(h_4 - h_5) \eta_{t,m} + (1 - Y)(h_5 - h_6) \eta_{t,m} - (h_1 - h_8) / \eta_{p,m} - (h_3 - h_2) / \eta_{c,m}] =$$

$$= m_0 \cdot 27.0 \text{ kJ/kg}$$

54
Most of the electrical power generated by the “Secondary Turbine” is spent to power the FW Pump and the Compressor motors. In Eq.(67), the thermal efficiency of the “Secondary System” ($\eta_{sys}^{Case\#2}$) is reported. In Figure 5-3, the plant diagram of the thermodynamic cycle provided with the water conditions at each stage along with the T-s diagram is represented.

$$
\eta_{sys}^{Case\#2} = \frac{Q_{IP} + W_{Rankine}}{Q_{in}} \equiv \frac{Q_{IP}}{Q_{in}} = \frac{(h_3 - h_4)}{(h_2 - h_1)} \equiv 53.26\% \tag{67}
$$
Figure 5-3. Representation of the “Secondary System” (Case #2), (a) plant diagram of the thermodynamic cycle provided with the water conditions at each stage, (b) T-s diagram.
6. CONCLUSIONS

In this report, the possibility of using Advanced Nuclear Reactors to supply the required thermal power input to Industrial Processes of interest is investigated. The analyzed processes include Petroleum refinery, Polymers production, Steel Manufacturing, and calcination for Cement production. The required temperatures and heat loads for the analyzed industrial processes were listed. In addition, the technical specifications of the energy conversion cycles of representative Advanced Reactor designs were collected, with particular attention to the thermodynamic conditions of the generated steam. The comparison between the requirements of the industrial processes and the capabilities of the candidate reactors showed that currently available heat from nuclear units can meet the thermal requirements of only a few processes. At the same time, the collected values outlined the need of exploring engineering and economically feasible solutions to boost the temperature of the generated steam flow rate to 900 °C. From this standpoint, the adoption of heat pumps could expand the flexibility and diversity of applications of nuclear power. A simple numerical example illustrating the viability of this method is provided. Specifically, the energy conversion cycle of a conventional PWR was altered to incorporate a compressor, which enhances the quality of the steam produced. Two reference configurations were considered, i.e., the industrial process coupled with the nuclear power plant exhausts either saturated liquid or saturated steam. To obtain a consistent basis for comparing the efficiencies, the heat pumps are set up as closed systems, i.e., the thermal and electrical power absorbed by the heat pump was solely obtained from thermal energy of the steam provided by the steam generator.
REFERENCE

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