System Modeling of the HTTR and Economic Dispatch Model of the Secondary System

August | 2021

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517
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ABSTRACT

High Temperature Gas-cooled Reactors (HTGRs) can be used for the generation of electricity and their process heat can be used to improve the efficiency of chemical processes such as hydrogen production. The JAEA-operated High-Temperature engineering Test Reactor (HTTR-GT/H$_2$) is exploring using the reactor for electricity and hydrogen production. A RELAP5-3D model of the HTTR-GT/H$_2$ secondary system has been developed using design information. The various components and heat exchangers in the secondary system were modeled and results were compared to the design conditions. The results for the sole-power generation mode were shown to fit the design conditions very well. The largest temperature difference was on the order of 7 K, and the largest pressure difference was on the order of 0.05 MPa. The results for the hydrogen cogeneration mode did not match the design conditions nearly as well. The largest temperature difference was about 39 K and the largest pressure difference was about 0.27 MPa at the compressor outlet. The larger differences for the hydrogen cogeneration mode are attributed to the various complex components and the flow being split in the secondary loop.

A transient reduction in heat removal capability of the secondary system was investigated. Reactor temperatures are anticipated to rise as a result. The core reactivity response due to this increase in temperature is investigated and is expected to add negative reactivity to the reactor.

An economic dispatch model was developed for a nuclear-driven iodine-sulfur cycle system to determine hydrogen sale prices that would make such a system profitable. The study focuses on the development of the economic model and the role that input data plays on final calculated values. It was found that the input electricity prices, whether using historical data or a host of synthetic time histories, produce significantly different breakeven hydrogen sale prices. As such, great care should be used in these economic dispatch analyses to select reasonable input assumptions.
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<td>Autoregressive Moving Average</td>
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<td>FARMA</td>
<td>Fourier Series ARMA</td>
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<td>HCG</td>
<td>Hydrogen Co-Generation</td>
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<td>HERON</td>
<td>Holistic Energy Resource Optimization Network</td>
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<td>LCOH</td>
<td>Levelized Cost of Hydrogen</td>
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<td>LP</td>
<td>Low Pressure</td>
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<tr>
<td>METI</td>
<td>Ministry of Economy, Trade, and Industry</td>
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<tr>
<td>NPP</td>
<td>Nuclear Power Plant</td>
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<td>NPV</td>
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<td>PDC</td>
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<td>RAVEN</td>
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System Modeling of the HTTR and Economic Dispatch Model of the Secondary System

1. Introduction

Hydrogen is a highly versatile energy carrier. Research in hydrogen production methods, use, and the associated economics has increased in recent years as countries seek to reduce their carbon footprints. Hydrogen as a power source provides flexible electricity generation, potentially generating electricity when the demand is highest. The production of hydrogen could also be used to shift electricity demand to off-peak hours, acting as a large-scale demand response or energy storage medium. Producing hydrogen with nuclear energy (heat and electricity) and using it as a flexible load resource is being investigated by a number of organizations [1–3]. Several nuclear-driven hydrogen production configurations are also being developed.

These nuclear integrated energy systems (IES) could provide economic benefits to nuclear power plants (NPPs) versus producing only electricity. Competing with currently low-cost fossil resources and declining renewable energy costs has left nuclear plants at an economic disadvantage in many regions [4]. Hydrogen production using excess energy from the nuclear plant allows NPPs to diversify revenue streams and has shown to potentially increase nuclear plant profitability [5].

In Japan, the need to import fossil fuels has led to high electricity prices, and investigation into ways to produce electricity affordably and locally [6]. Nuclear power could be advantageous compared to fossil fuel-based energy generation because the uranium fuel used in a nuclear fission system is much more energy dense, requires less frequent imports, and can be stored onsite for future use. Renewable energies do not require any imports after their initial installation, although they are dependent on the fuel source (e.g., wind or solar irradiance) being available when the energy is needed. Finding a mix of nuclear and renewable technologies that also reduces carbon emissions and keeps electricity prices low will be important for the future of Japan’s electricity system. An IES that allows a nuclear plant to sell a secondary commodity such as hydrogen instead of losing money on electricity sales when demand is low or renewable generation is high could help overall system profitability [7].

In addition to cost and security concerns, hydrogen produced via nuclear power could help meet greenhouse gas reduction goals set by Japan’s Ministry of Economy, Trade, and Industry (METI). METI has set cost reduction goals for hydrogen produced with low- or zero-emissions sources [8]. This clean hydrogen could be used to support decarbonization of industry or transport sectors with sufficient infrastructure. Hydrogen in Japan currently has a wholesale price of ~100 JPY/Nm³. METI has set a goal to reduce the hydrogen price to 30 JPY/Nm³ by 2030 and 20 JPY/Nm³ by approximately 2050 [8].

Government and research entities in Japan have also built expertise in high-temperature gas-cooled reactors (HTGR) and their applications. The operating High-Temperature engineering Test Reactor (HTTR) has aided in the development of HTGR experimental and operational experience. The HTTR is a 30 MWt helium-cooled reactor that uses graphite moderated prismatic fuel assemblies. The outlet temperature is 950°C, high enough to integrate different process applications, such as hydrogen production, for testing purposes [9].

The Iodine-Sulfur (IS) cycle for hydrogen production appears to be a good candidate for paring with an HTGR [10]. The IS cycle utilizes a Bunsen reaction to convert water, I₂, and SO₂ into HI and H₂SO₄. HI is then split into its hydrogen and iodine components. A side reaction converts the H₂SO₄ into SO₂, water, and oxygen, completing the cycle. This cycle requires significant heat, meaning coupling with current fleet light water reactors is difficult [11]. The Japan Atomic Energy Agency (JAEA) has placed a focus on
this hydrogen production system [12], going so far as to design the HTTR and IS cycle cogeneration facility known as the HTTR-GT/H$_2$.

The HTTR-GT/H$_2$ is a design for coupling the HTTR with an IS cycle for demonstrating hydrogen and HTGR coupling capabilities. The process, diagramed in Figure 1, adds a secondary heat exchange system to the HTTR to send heat to the IS facility. A turbine for generating electricity using the Brayton cycle is also planned. The demonstration could then choose to dispatch and sell hydrogen or electricity, dependent on regional electricity prices, hydrogen sales agreements, or other economic incentives.

Figure 1. Process diagram for connecting the HTTR with iodine-sulfur hydrogen co-production facility [12].

The INL was given various tasks to investigate the proposed HTTR-GT/H$_2$ plant. The tasks performed and summarized include the following:

- The secondary system was designed to operate in two modes. These modes are the sole power generation mode (in which only electricity is generated) and the hydrogen cogeneration mode (in which a portion of the process heat is used for hydrogen production and the remainder of the heat is used for electricity generation). As a part of this work a transient analysis of a reduction in secondary mass flow rate and the resultant loss of heat removal capability was investigated for the sole power generation mode.

- A primary system input deck was provided to INL from JAEA. This input was originally developed using the RELAP5/MOD3.3 software. This input model was converted to be compatible with RELAP5-3D. This primary system model was then united with the previously developed secondary system model into a single input deck.

- An economic dispatch model was developed to inform reactor operation decisions. The reactor secondary system operation mode is chosen based on hydrogen and electricity
prices that would make the system most profitable.

1.1 Secondary System Modeling

The development of a RELAP5-3D [13] model of the HTTR-GT/H\textsubscript{2} plant secondary system design is based on the data available in [14]. The RELAP5-3D model was developed to reproduce the design data with and to simulate the steady-state conditions and a system transient. The turbomachinery (turbines and compressors) behavior is modeled, and heat exchanger models are developed using control variables with RELAP5-3D input to portray their performance. The methodology used to implement this modeling and their results are described in this document.

1.2 Primary System Input Conversion

A primary system model of the HTTR was developed by JAEA and provided to INL. This model was developed using RELAP5/MOD3.3 which has similar input requirements to RELAP5-3D, but some differences are not compatible with RELAP5-3D. The input model was modified so that it would be compatible with RELAP5-3D. The process of converting the input model to be compatible with RELAP5-3D is described.

In addition, the modified primary input model is combined with the previously developed secondary model into a single input deck. The primary system (which includes the reactor) transfers heat to the secondary system via the intermediate heat exchanger (IHX). With this change, the heat generated in the primary system is transferred to the secondary system through the IHX. The effort of combining the two input decks is described.

1.3 Economic Dispatch Model

The effort to develop a techno-economic model to flexibly dispatch the HTTR-GT/H\textsubscript{2} for electricity and/or hydrogen cogeneration is described. The goal is to investigate the impacts that different input assumptions or real-world conditions might have on the profitability of such a system. This work was undertaken to improve understanding on assumptions that will be necessary for eventually making investment decisions on commercial hydrogen systems.

The HTTR-GT/H\textsubscript{2} system was chosen for this economic model because of its simple design and the availability of process modeling data. The HTTR-GT/H\textsubscript{2} is a relatively small system, both in terms of nuclear plant size and hydrogen production when compared to commercial scale systems. The small size means that electricity price feedback to the operational changes of the HTTR-GT/H\textsubscript{2} would be minimal. The HTTR-GT/H\textsubscript{2} has undergone detailed process modeling and has known operational modes. This makes the economic dispatch simpler to model because the operating conditions are known for electricity sale and hydrogen sale modes. Additionally, the smaller nature of this system helps simplify the problem since the system would participate in fewer electricity markets and have a smaller impact on the electricity and hydrogen market at large. This means that the impact of certain input data (such as electricity price data) will be more readily apparent. These effects and assumptions should be known prior to expanding this modeling methodology to the larger, commercial systems so that a broader study can be conducted.

The HTTR-GT/H\textsubscript{2} dispatch model accepts the prevailing prices in the market. Electricity is sold when regional electricity prices are above HTTR operating costs. Hydrogen is produced when the electricity price is below HTTR-GT/H\textsubscript{2} electricity production costs. The hydrogen is produced by the co-located IS cycle, as detailed in [12].

The goal of the dispatch model is to find the sale price of hydrogen where the system can sell hydrogen to break even economically. This price, also known as the levelized cost of hydrogen (LCOH), is
the point at which sufficient money is made to justify the building of the hydrogen facility and dispatching energy to hydrogen production rather than only selling electricity.

The dispatch model was developed using the Risk Analysis Virtual Environment (RAVEN) model, developed at Idaho National Laboratory (INL) [15]. Two RAVEN plugins, Holistic Energy Resource Optimization Network (HERON) and Tool for Economic Analysis (TEAL), also developed at INL, were used for creating the dispatch algorithm and tracking the economic parameters within the model [16]. The description of the model and its results are documented here.

2. Modeling Methodology

2.1 Secondary System Modeling

A schematic of the secondary system and the helium flow for both sole-power generation (SPG) and hydrogen co-generation (HCG) modes of operation is shown in Figure 2.

In the SPG mode, helium flowing at 9.85 kg/s removes 10 MW from the primary system through the IHX – leaving at 570 °C and proceeds directly to the turbines. Upon exiting the turbines, it flows into an integrated heat exchanger that consists of an offset strip plate/fin recuperator and helical coil precooler to recover turbine exhaust heat. The helium then flows through the compressors to rise in pressure. After it exits the compressors it passes through the high-pressure side of the recuperator for pre-heating before being cooled to the appropriate IHX inlet temperature (374 °C) by Cooler A.
In HCG mode, the flow rate through the IHX is reduced considerably to 2.57 kg/s to increase the helium temperature at its outlet to 900 °C. This high temperature helium transfers heat via a 2nd IHX to the tertiary helium loop and hydrogen plant before merging with a 6.58 kg/s recirculating helium flow and entering the turbines. This combined flow through the turbomachinery and integrated heat exchanger is 9.15 kg/s. After exiting the high-pressure side of the recuperator, 6.58 kg/s is sent back to the turbines, while the remaining 2.57 kg/s is cooled to 150 °C by Cooler B (different from Cooler A due to the lower flow rate and different heat transfer rate) before returning to the IHX.

The RELAP5-3D software was originally developed to model reactor transient behavior for light-water reactor systems [13]. Coding developments have made it possible to model both nuclear and non-nuclear systems and a variety of working fluids and system behavior. In particular, the software has been used to model high temperature gas cooled systems [17-18].

RELAP5-3D models of each system component have been developed in isolation to refine the heat transfer and friction models in each prior to assembly into a continuous, recirculating loop. To do so, each component model is connected to time-dependent volumes upstream and downstream, each with the temperature and pressure fixed at the values specified by the design [14]. When necessary the models or correlations that determine the heat transfer or temperature change in and flow rate through the component are modified to match the design values. The input model and individual components were created in a spreadsheet which ensured that any changes made to a component were propagated through the model. These models are described in the following sections.

### 2.1.1 Turbomachinery

A schematic of the HTTR-GT/H$_2$ plant turbomachinery is shown in Figure 3. The system consists of two single stage radial turbines, and two two-stage centrifugal compressors. Both the high-pressure (HP) and low-pressure (LP) turbines and compressors are geared down to a common shaft, a layout which minimizes shaft vibration. Further details on the turbomachinery design are available in [19-21].

![Figure 3. HTTR-GT/H$_2$ plant turbomachinery [14].](image)

### 2.1.1.1 Compressors

Compressor maps for the HTTR-GT/H$_2$ plant design are shown in Figure 4 (note that the values on these figures are proprietary and are intentionally unclear). These give the efficiency ($\eta$) and pressure coefficient ($\mu$) of the compressors as functions of the flow coefficient $\phi$,

\[ \eta(\phi), \mu(\phi) \]
where \( Q \) is the volumetric flow rate, \( D \) the impeller outer diameter, and \( U \) the blade tip speed. The latter is defined in terms of the rotational speed \( N \),

\[
(2)
\]

The RELAP5-3D compressor model requires compressor maps be input as a series of tables that give the compressor efficiency (\( \eta \)) and pressure ratio (\( \pi_c \)) as functions of the relative corrected speed (\( \alpha \)) and relative corrected flow rate (\( \nu \)), defined (respectively) by

\[
(3)
\]

\[
(4)
\]

here \( T \) and \( P \) are the stagnation temperature and pressure at the compressor inlet. Using the ideal gas law and equations (1)-(2), the flow coefficient can be written in terms of the corrected speed and flow,

\[
(5)
\]

where \( R_s \) is the specific gas constant. This can be solved for the relative corrected flow rate to give

\[
(6)
\]

The pressure ratio is given by [14]:

\[
(7)
\]

where \( Z \) is the compressibility and \( \gamma \) is the specific heat ratio.

The RELAP5-3D input format is a series of tables, one for each relative corrected speed (\( \alpha \)). Entries in each of these tables consist of three values— the relative corrected flow rate (\( \nu \)), and the corresponding pressure ratio (\( \pi_c \)) and efficiency (\( \eta \)). For each table, these are determined for the range of flow coefficients given in Figure 4 using the relations plotted in that figure (to which empirical fits have been made) and equations (6)-(7). These tables are supplied to each of four compressor components in the RELAP model, one representing each compressor stage (there are two, two stage compressors in the system).

Figure 4. Compressor maps [14].

The inlet temperature and pressure used to calculate the high-pressure compressor relative corrected flow rate and the pressure ratio were found to be incorrect initially and were set to design conditions given in [12]. These values are 841.15 K for the inlet temperature and 3.67 MPa for the inlet
pressure of the high-pressure compressor.

2.1.1.2 Turbines

Turbine performance data for the HTTR-GT/H$_2$ plant design are shown in Figure 5 (note that the values on these figures are proprietary and are intentionally unclear). These give the corrected flow rate of each turbine and the efficiency ($\eta$) as a function of the flow coefficient $\phi$.

![Figure 5. HTTR-GT/H$_2$ Turbine performance data: corrected flow rate (a) and efficiency (b) [14].](image)

The turbines are modeled using the “Type 3” turbine model available in RELAP5-3D. This allows the specification of a variable efficiency,

$$\text{(8)}$$

where, as before, $N$ is the turbine speed, $\dot{W}$ is the turbine power, the subscript “$R$” refers to the rated values, and the multiplier “$\text{Mult}$” is set by a control variable. The constants $a_i$ and $b_j$ are specified by the user; here $a_0$ and $b_0$ are set to 1 and the rest equal to zero and control variables are used to model the behavior depicted in Figure 5 via $\text{Mult}$.

To do so, we approximate the relationship illustrated between corrected flow rate and flow coefficient $\phi$ as linear (which it approximately is in the range of flow coefficients shown). This relation is then easily inverted to give the flow coefficient as a function of corrected flow rate, $\phi$. A second (quadratic) empirical relationship can be established between efficiency and flow coefficient from Figure 5. This efficiency is computed with control variables from the flow conditions, $T$, and $P$ using these two fits.

As with the compressors, the second property that must be determined is the pressure ratio. The recommended approach to matching the pressure ratio for a given turbine design in RELAP5-3D is to set the form loss coefficient $K$ to give the proper drop in pressure $P$:

$$\text{(9)}$$

here subscript 1 refers to upstream and 2 downstream conditions, and $v$ is the velocity at the turbine inlet junction. Using control variables, Equation (9) was initially used to calculate the form loss, but the calculation results would minimize the pressure difference across the turbines to reduce the loss factor. This resulted in large flow rates through the system and an excessively small pressure drop across the turbine components that was not physically correct.
To obtain more reasonable results for the pressure drop across the turbine components, the pressure ratio relationship was used. The pressure ratio across the turbine component is defined as:

\[
\text{Pressure ratio} = \frac{P_2}{P_1}
\]

which can be written as .

Equation (10) is substituted into Equation (9) which yields

\[
\text{Form loss} = \frac{\Delta P}{P_1}
\]

Control variables were then used to calculate the form loss given in Equation (11) across both the high- and low-pressure turbines. The pressure ratio across the turbines is defined in [12] and is set to 1.13 for the high-pressure turbine and 1.15 for the low-pressure turbine. Pressure drop results compared favorably to design conditions when Equation (11) was used to calculate the form loss coefficient.

2.1.2 Heat Exchangers

The HTTR-GT/H₂ plant secondary system design features a wide variety of heat exchanger types, including multiple different helical coil and shell and tube heat exchangers, as well as an offset-strip plate and fin recuperator. While they differ in their details, the primary heat transfer configuration of these heat exchangers (apart from the recuperator) is a tube bundle in cross flow. Early attempts to model one of the heat exchangers did not closely match the heat transfer expected from the design data using the built-in heat transfer correlations of RELAP5-3D—while it includes a correlation for external flow across tube bundles, it is based on a combination of parallel and cross flow. This is appropriate for many heat exchanger designs, though not for all in this system, which are primarily in a configuration closer to pure crossflow. Since RELAP5-3D allows the user to apply a surface heat flux calculated by a control variable rather than using the built-in correlations, the “Delaware method” has been implemented as described in [22] via the control system for most heat exchanger models.

The Delaware method provides correlations for the Fanning friction factor and the Colburn j-factor, given by

\[
\text{Fanning} = \frac{\Delta h}{h}
\]

\[
\text{Colburn} = j = \frac{h}{G}
\]

where \( h \) is the heat transfer coefficient, \( \text{Pr} \) is the Prandtl number, \( C_p \) is the specific heat capacity, \( \phi \) is a viscosity correction factor (not to be confused with the flow coefficient of turbomachinery discussed in previous sections), and \( G \) is the shell side mass flux, given by the mass flow rate divided by the minimum crossflow area. The correlations for an ideal tube bank have the form:
here $P_t$ is the tube pitch and $D_0$ is the outer diameter of the tube, on which the Reynolds number is also based. The constants $a_{i-4}$ and $b_{i-4}$ depend on the Reynolds number and the orientation of the tube bank (triangular, square, or rotated square pitch); tables for each configuration are given in [22]. As noted above, the heat transfer coefficient can be calculated using control variables; in this case the preceding correlations can be implemented exactly, and the heat transfer coefficient is calculated by (rearranging equation (10)):

\[(17)\]

The friction correlations cannot, but these can be closely approximated using the alternate turbulent wall friction model in RELAP5-3D, in which the friction factor is calculated by

\[(18)\]

This has the same form as equation (14) except for the varying dependence on pitch-to-diameter ratio; it can be seen from equation (16), however, that this term approaches a constant at high Reynolds numbers, which are characteristic of the HTTR-GT/H$_2$ plant heat exchangers.

A number of correction factors are applied to the ideal values determined with the correlations above, motivated by a number of bypass flows that might occur in a shell and tube heat exchanger, e.g., around the entire tube bundle, through the gaps where the tubes pass through the baffles, etc. Rather than apply the geometry-based corrections prescribed by the Delaware method, we adjust this factor in what follows to best match design data. Its value should be less than one but not dramatically so (i.e., not less than 0.5 for heat transfer), so a correction factor in this range will be taken as indication that the method describes the heat exchanger in question with reasonable accuracy.

RELAP5-3D models of the heat exchangers whose design details are known are described in detail in the following subsections.

2.1.2.1 IHX

The IHX model was developed and provided previously by JAEA. It has been incorporated into the present model, though it was found that the roughness had to be reduced, and the heat transfer coefficient increased by a factor of 2.2, to match the design values for pressure and temperature drop in SPG mode.

2.1.2.2 2nd IHX

When operating in HCG mode, the component referred to as the 2nd IHX transfers heat from the reactor to a tertiary loop. This transferred energy is used as process heat to improve the efficiency of the Sulfur-Iodine hydrogen generation process. The 2nd IHX is a horizontally oriented shell and helical coil tube heat exchanger. A flow guide directs the helium coolant to flow both over and parallel to the tubes. Thus, this heat exchanger uses a combination of parallel and crossflow to transfer heat. A diagram of the 2nd IHX is shown in Figure 6.
The 2nd IHX component is a shell and tube heat exchanger. The secondary helium flows through the shell side of the helical-coil 2nd IHX component with a diameter of 1.289 m. Tertiary helium flows through the tube side of the 2nd IHX with a coil diameter of 1.139 m. The tube side consists of a bank of 10 0.045 m outer diameter pipes with an effective length of 1.65 m. There is a total of 12.1 m² of heat transfer area between the shell and tube sides.

The RELAP5-3D model of the 2nd IHX uses a pipe component for both the shell and tubes which is divided into 12 axial segments. The tube side heat transfer is calculated using the default heat transfer correlation (Dittus-Boelter). The shell side heat transfer is calculated using the correlation that represents the tube bundle as a vertical bundle with crossflow, which was most appropriate for this component. The form loss coefficients were set to 0.72 to obtain an appropriate pressure drop across the component. A heat transfer multiplying factor of 2.5 was used on the turbulent forced convection heat transfer coefficient to obtain the proper heat transfer.

The model for the 2nd IHX was run independently and transferred the expected 0.7 MW of heat [12]. The other results were representative of design conditions.

2.1.2.3 **Recuperator**

The recuperator component is used to recover turbine exhaust heat and improve the efficiency of the system. The recuperator is an offset strip plate-fin heat exchanger consisting of 4 heat exchange modules with a total flow area of 0.154 m². The component has a total heat transfer area of 891 m² and transfers a total of 19.69 MW of heat.

The RELAP5-3D model of the recuperator was divided into 21 axial volumes for both the primary and secondary sides. The heat transfer coefficient for both sides is calculated using the default heat transfer correlation (Dittus-Boelter). The pressure losses in the component were chosen to obtain the pressure
2.1.2.4 Precooler

After exiting the low-pressure turbine, flow enters an integrated heat exchanger that contains both the recuperator and the precooler. After heat is recovered by the recuperator, the helium is further cooled by the precooler to reduce the compression work in the compressors. The precooler is a helical coil heat exchanger with the secondary helium flowing through the shell side, of diameter of 1.68 m. Water coolant flows through 144 tubes arranged in a 9 × 16 bank. Each tube has an outer diameter \((2r_1)\) of 31.8 mm and is 2.85 mm thick. Radial fins of 0.3 mm thickness \((t)\) extend to 31.8 mm in diameter \((2r_2)\), and their pitch is 1.29 mm. A schematic of the precooler is shown in Figure 7.

The RELAP5-3D model of the precooler divides both the cylindrical shell region and the helical tubes into 12 segments, using a pipe component for each. Tube-side heat transfer is calculated using the built in (Dittus-Boelter) correlations, while the shell-side heat transfer and friction are calculated using the Delaware method as described above. The heat flux is calculated considering the effect of the fins:

\[
(19)
\]

Here \(A_f\) denotes the fin area, \(A_t\) the total area, and \(A_{RELAP}\) the area of identically dimensioned tubes without fins, so designated because it is this area that RELAP determines for a cylindrical heat structure, necessitating the correction \(A_f/A_{RELAP}\). The fin efficiency is given by

\[
(20)
\]
where \( r_i \) and \( r_o \) are the inner and outer fin radii and \( t \) is the fin thickness. The fin parameter \( m \) is given in terms of the heat transfer coefficient \( h \), fin perimeter \( P \), thermal conductivity \( k \), and fin cross sectional area \( A_c \) by

\[
(21)
\]

The modified Bessel functions in equation (20) are recorded in general tables in RELAP for a range of values of \( m \).

To match the design heat transfer rate of 4.784 MW, the calculated heat transfer coefficient must be corrected by a factor 0.87. As discussed above, values somewhat less than one are expected and this indicates good agreement of the model with the design values. To achieve the correct flow rate at the design upstream and downstream pressures, a correction factor of 3.025 must be applied to the calculated friction factor. In this case agreement is not as close.

2.1.2.5 **Cooler A**

In SPG mode, helium exiting the high-pressure side of the recuperator is cooled by Cooler A prior to return to the IHX. Cooler A is best described as a Tubular Exchanger Manufacturers Association (TEMA) type X heat exchanger, a shell-and-tube design in which the shell-side flow makes a single pass of the U-shaped tube bank. The shell-side flow therefore approximates pure crossflow. A schematic of Cooler A is shown in Figure 8.

![Figure 8. Cooler A [14].](image)

The secondary helium flows through the shell side of cooler A, which has a diameter of 1.2 m. Water coolant flows through 185 tubes arranged in a U-shaped bank with seven rows per side. Each tube has an outer diameter of 25.4 mm and is 2.9 mm thick.

The RELAP5-3D model of cooler A uses a pipe component to model the tube bank, divided into 22 segments, 11 per side. There are three segments in the lower baffle regions (one between each lower baffle visible in Figure 8), six in the crossflow region, and two above the top baffle. The shell side heat transfer region is modeled using two volumes, one for each side of the tube bank. Tube-side heat
transfer is calculated using the built-in (Dittus-Boelter) correlations, while the shell-side heat transfer and friction are calculated using the Delaware method as described above.

To match the design heat transfer rate of 4.43 MW, the calculated heat transfer coefficient must be corrected by a factor 0.935. As with the precooler, this value is near but somewhat less than one, indicating good agreement of the model with the design. The friction factor, however, must be corrected by a factor of 25.67 to give the correct flow rate for the design pressure drop. This value could potentially be improved with a less coarse nodalization of the shell side.

2.1.2.6 **Cooler B**

In HCG mode, helium exiting the high-pressure side of the recuperator is cooled by cooler B prior to return to the IHX. Cooler B is a common TEMA type E heat exchanger, a shell-and-tube design in which the shell-side coolant flows back and forth around a series of baffles, and in this course makes multiple passes of the U-shaped tube bank. In this design, the tube bank does not extend into the baffle window region, and so each pass of the shell-side coolant is approximately pure crossflow. A schematic of cooler B is shown in Figure 9.

![Figure 9. Cooler B [14] and RELAP5-3D nodalization of the shell side (in green).](image)

The secondary helium flows through the shell side of cooler B, which has a diameter of 1 m. Water coolant flows through 153 tubes arranged in a U-shaped bank with six rows per side. Each tube has an outer diameter of 25.4 mm and is 2.9 mm thick.

The RELAP5-3D model of the cooler B uses a pipe component to model the tube bank, which is divided into 28 segments (14 per side), two between each baffle. The shell side heat transfer region is divided into two entrance/exit regions, four baffle window regions, and three bundle crossflow regions.
This nodalization is outlined in Figure 9. The shell side is similarly divided when calculating pressure drops across these disparate regions using the Delaware method [22]. As previously, the tube-side heat transfer and friction are calculated using the built-in correlations.

To match the design heat transfer rate of 4.19 MW, the calculated heat transfer coefficient must be corrected by a factor 1.39, indicating slightly worse agreement than for the previously described components. This is a point for further investigation; the Delaware method was developed specifically to model type E exchangers and might therefore be expected to match best for this component. As with the other heat exchangers, more friction is needed to achieve the correct flow rate at the design pressure drop than is predicted by the model, and a factor of 1.26 must be applied to achieve the design value.

2.1.3 Additional Modeling Changes for HCG Mode

2.1.3.1 Flow splitting for cogeneration mode

A servo valve was added to the model so that the heated helium gas was appropriately split for the HCG mode. In HCG mode a portion of the reactor heat is used for electricity generation and the remainder for hydrogen generation via the sulfur-iodine process.

The servo valve was added to the RELAP5 model to control the helium mass flow rate of 6.58 kg/s for the coolant traveling through the green loop shown in Figure 2 between Cooler B and the 2nd IHX. The mass flow rate through the servo valve was set with a control variable.

2.1.3.2 Boundary conditions modifications for HCG mode

Various boundary conditions were different for the HCG model. The inlet temperature of the tertiary helium loop of the 2nd IHX was changed to a value of 623.15 K per design conditions [14].

The boundary conditions for the reactor primary system are different depending on the operation mode. The reactor primary outlet temperature and the mass flow rate were set to match design conditions. The reactor outlet temperature for the HCG mode is changed to 1223.15 K and the mass flow rate through the primary system is changed to 3.47 kg/s [14].

2.1.4 RELAP5-3D Transient Analysis

When the secondary system operation is switched from SPG to HCG mode the mass flow rate through the secondary side of the IHX is reduced. This change in the mass flow rate reduces the cooling capability of the IHX, which results in an increase in the primary system coolant temperature. The potential reactivity response due to the primary coolant temperature increase is evaluated.

In an actual transient scenario both the reactor inlet and outlet temperatures would change based on a reduced heat load. However, the reactor itself is not a part of this model and the core outlet temperature is set to a constant value. The increase in the reactor outlet temperature due to the reduced heat load is not reflected in the transient. The temperature of the primary system coolant exiting the IHX will increase, and it is assumed that the amount of temperature increase is reflected in the reactor in entirety. No other reactivity changes are considered in this analysis.

The zero-power isothermal temperature coefficients for the HTTR are reported in [23]. These reported values were plotted, and a curve-fit was developed to correlate the reactivity and
temperature. The plotted zero-power isothermal temperature coefficients and the linear fit generated in Excel are shown in Figure 10. This linear fit is used later to determine the potential reactivity response of the reactor.

Figure 10. HTTR zero-power isothermal temperature coefficients as a function of temperature.

2.2 Modeling Changes for the Primary System Input Deck

A nodalization diagram of the primary system input deck is shown in Figure 11. This input deck was initially developed in the RELAP5/MOD3 software. This input deck was modified so that it would be compatible with RELAP5-3D. After the necessary modifications are made, the input model was coupled with the secondary system model. Any reuse in component number, heat structure number, control variable numbers, etc. had to be avoided, because using the same numbering would result in the code deleting the first usage of the number and using only the second instance. This resulted in many of these such numbers being modified to avoid the automatic deletion. Changes that were made are listed in this section.

Figure 11. Primary system nodalization diagram.

In the original input the RELAP5 keywords were entered in upper case. RELAP5-3D did not recognize these keywords in upper case. The keywords were changed to lower case, correcting this issue.

Using helium gas as the working fluid is not an available option in the RELAP5/MOD3 version of the code. However, the helium gas can be modeled as a pure noncondensable gas when water is the working fluid. The helium gas was modeled in this manner. RELAP5-3D however allows the user to model the helium as the working fluid. The input model was changed accordingly to allow this option.

The input deck used system numbers 120 and 121, but these were changed to 127 and 128 in preparation for combining the primary and secondary input decks.

The trips in the primary system input deck were using the 20600000 expanded format but were changed to use the base format to make them compatible with the secondary system input. The two
trips used in the input model were changed from 20600100 to 401 and 20600300 to 403.

The pipe components required the addition of the CCC1201-CCC1299 volume initial conditions cards. These cards were not included in the new primary system input model, so they were added to the input. These cards are required for RELAP5-3D.

The branch components required the addition of the CCC0200 volume initial conditions cards. These cards were not included in the new primary system input model, so they were added to the input. These cards are required for RELAP5-3D.

2.2.1 Component Number Changes

Some component numbers were used in both the primary and secondary system input decks. It was decided to change the component numbers in the primary system model that were repeated to prevent the inadvertent removal of a component. A listing of component numbers that were changed follows.

Single junction component number 904 was changed to 704 because component 904 was already in use.
Branch component number 5 was changed to 505 because component 5 was already in use.
Pipe component number 18 was changed to 118 because component 18 was already in use.
Pipe component number 19 was changed to 119 because component 19 was already in use.
Branch component number 20 was changed to 120 because component 20 was already in use.
Pipe component number 21 was changed to 221 because component 21 was already in use.
Branch component number 22 was changed to 222 because component 22 was already in use.
Branch component number 23 was changed to 223 because component 23 was already in use.
Pipe component number 24 was changed to 224 because component 24 was already in use.
Branch component number 25 was changed to 225 because component 25 was already in use.
Branch component number 26 was changed to 226 because component 26 was already in use.

2.2.2 Changes in Material Property Numbers

Material property 1 was changed to 501 to avoid overwriting a previous material property.
Material property 2 was changed to 502 to avoid overwriting a previous material property.
Material property 3 was changed to 503 to avoid overwriting a previous material property.
Material property 4 was changed to 504 to avoid overwriting a previous material property.
Material property 5 was changed to 505 to avoid overwriting a previous material property.
Material property 6 was changed to 506 to avoid overwriting a previous material property.
Material property 7 was changed to 507 to avoid overwriting a previous material property.
Material property 8 was changed to 508 to avoid overwriting a previous material property.
Material property 9 was changed to 509 to avoid overwriting a previous material property.
Material property 10 was changed to 510 to avoid overwriting a previous material property.
Material property 11 was changed to 511 to avoid overwriting a previous material property.
Material property 12 was changed to 512 to avoid overwriting a previous material property.
Material property 13 was changed to 513 to avoid overwriting a previous material property.
Material property 15 was changed to 515 to avoid overwriting a previous material property.
Material property 17 was changed to 517 to avoid overwriting a previous material property.

2.2.3 Heat Structure Changes

Heat structure 1 was changed from using material property 2 to 502, because of the change in material property numbers.
Heat structure 2 was changed from using material property 1 to 501, because of the change in material property numbers.
Heat structure 3 was changed from using material property 1 to 501, because of the change in material property numbers.
Heat structure 4 was changed from using material property 1 to 501, because of the change in material property numbers.
Heat structure 5 was changed from using material properties 6, 7, and 1 to 506, 507 and 501, because of the change in material property numbers.
Heat structure 6 was changed from using material property 2 to 502, because of the change in material property numbers.
Heat structure 7 was changed from using material property 1 to 501, because of the change in material property numbers.
Heat structure 8 was changed from using material property 1 to 501, because of the change in material property numbers.
Heat structure 9 was changed from using material property 1 to 501, because of the change in material property numbers.
Heat structure 10 was changed from using material properties 6, 7, and 1 to 506, 507 and 501, because of the change in material property numbers.
Heat structure 11 was changed from using material properties 1 and 5 to 501 and 505, because of the change in material property numbers.
Heat structure 12 was changed from using material property 2 to 502, because of the change in material property numbers.
Heat structure 13 was changed from using material property 9 to 509, because of the change in material property numbers.
Heat structure 15 was changed from using material property 1 to 501, because of the change in material property numbers. In addition, the left-hand side of heat structure 15 was previously attached to volume 5 but was changed to 505 with the re-numbering of components.
Heat structure 16 was changed from using material properties 4, 3, 4, and 9 to 504, 503, 504, and 509, because of the change in material property numbers.
Heat structure 19 was changed from using material property 8 to 508, because of the change in material property numbers.

Heat structure 21 was changed from using material property 10 to 510, because of the change in material property numbers.

Some heat structures required the addition of the 1CCCG0401-1CCCG0499 initial temperature data cards. These cards are required for RELAP5-3D.

2.2.4 Radiation Model Changes

The 500000000 card is used for numbering the radiation model cards in the Mod3.3 version, but this value was changed to 60000000 for RELAP5-3D.

Similarly, the radiation model cards are prepended by a value of 50 (MOD3.3 version) compared to 6 (RELAP5-3D version). This was changed to be compatible with RELAP5-3D.

2.2.5 RELAP5-3D Testing

After these changes were made to the input model, it was tested and found to run successfully with RELAP5-3D.

2.2.6 Changes Made to Combine the Input Models

2.2.6.1 Primary System Changes

Time-dependent volume 58 and time-dependent junction 958 were removed from the primary system input model as they represent the IHX secondary system inlet conditions and mass flow rate. These components were no longer needed when the secondary system was combined with the primary system.

Pipe component 50 represents the secondary side of the IHX and consists of 25 volumes. The 25th volume length was reduced from 8.35 to 7.515 m (see the 5003xx cards). This reduction in length was necessary to obtain the correct change in height in the secondary system. RELAP5-3D required this change. No heat transfer occurs in volume 25, so the impact is minimal. The elevation change of the volume was also reduced by the same amount (see the 5007xx cards).

Single junction component 950 and time-dependent volume component 51 were removed in the combined deck as they represent the IHX secondary system outlet conditions. These components were replaced with the corresponding secondary system components when combined with the primary system.

2.2.6.2 Secondary System Changes

The run mode was changed from stdy-st (steady-state) to transnt (transient).

The secondary section of the IHX was represented in both the primary and secondary input decks. The IHX section was very similar in the two input decks so one replaced the other. The IHX section that was in the secondary input deck (Component 62) was replaced by the one in the primary input deck (Component 50). This modification required a change to the connecting junctions. Single junction 301 was modified to connect to Component 50 instead of 62. Single junction 800 was also modified to
connect Component 50 instead of 62. Component 62 was then removed.

The original secondary system input deck represented the IHX portion of the primary system. This input section was removed from the combined input deck and replaced with the new input from the primary input deck. The following components were removed from the original secondary system input for the combined input deck: 18, 19, 20, 21, 22, 23, 24, 25, 26, 78, 79, 390, 391, 392, 393, 394, 900, and 904. In addition, heat structures 40, 41, 42, 43, 44, 45, and 47 were removed from the input deck.

As a result, the containment section of the reactor was removed. This section of the model should be reintegrated. However, no information about the containment was available.

2.3 HTTR dispatch methodology

The HTTR-GT/H₂ dispatch model was developed to generate insights into the optimal dispatch of the nuclear IES and how different factors can affect that dispatch. As such, this model demonstrates how the HTTR-GT/H₂ might best be dispatched in response to fluctuating hourly electricity prices throughout the year. The model also allows for investigation of different input assumptions and their effect on the stochastic optimization of the decision to dispatch hydrogen or electricity.

2.3.1 Modeling Framework

The RAVEN framework is a multi-purpose optimization, data analysis, and uncertainty quantification code. It can be used in conjunction with the HERON plugin to develop economic dispatch models. HERON creates a two-loop dispatch algorithm that incorporates RAVEN’s optimization and synthetic time history generation abilities. The general structure of the stochastic dispatch model is given in Figure 12. The outer loop optimizes some grid parameter(s) (e.g., generator capacity), while the inner loop samples synthetic time histories, performs the economic dispatch, and tracks discounted cash flows via the TEAL plugin.

![Figure 12](image)

**Figure 12.** General schematic of the HERON dispatch model workflow [16].

The HERON plugin was used to build the HTTR-GT/H₂ dispatch model in RAVEN. HERON simplified the creation of this model, which might otherwise prove complicated for typical RAVEN users. HERON enables users to quickly develop inputs based on technology prices, commodities such as electricity or hydrogen, and the hydrogen and electricity markets. HERON then translates these user-friendly inputs
into RAVEN scripts that utilize RAVEN’s sampling, data transfer, and stochastic optimization capabilities to perform the dispatch.

Figure 13 shows the decision process for the HTTR-GT/H₂ dispatch model. This specific dispatch model utilizes an inner loop to perform the hydrogen/electricity (represented by e- in Figure 13) dispatch, and an outer loop to track hydrogen prices.

Figure 13. Algorithm used in the HTTR-GT/H₂ price-taker dispatch model. The model can run a different inner loop for each stochastic time history to generate an expected net present value.

2.3.2 Synthetic Time History Production

For the dispatch model to perform the stochastic optimization, a method of producing synthetic data was required. An autoregressive moving average (ARMA) model coupled with a Fourier series detrending model, known as a FARMA model, was trained and used to produce synthetic electricity-price time histories. RAVEN’s capabilities allow users to train a FARMA on historical, time-dependent data sets, and to then sample that model to create synthetic time histories. The FARMA model takes a time history as input and uses a Fourier fast transform to extract the signals that occur on different time scales. The Fourier detrending equation is given in Equation (22), as taken from [24]:

\[
\begin{align*}
\text{after the Fourier detrending, the ARMA statistically quantifies the noise and allows for stochastic reproduction in future samples. The Fourier detrend pulls out strong, deterministic, time-dependent trends in the data set, leaving the noise. An ARMA algorithm can be used to model that noise. Equation (23) describes the ARMA process:}
\end{align*}
\]

where \( \mathbf{y} \) is the output vector for a given dimension \( n \). The input vectors, \( \mathbf{q} \) and \( \mathbf{f} \), are \( n \) by \( n \) matrices, and \( \mathbf{a} \) is the error term. The variables \( \alpha \) and \( \beta \) are the autoregressive and moving average terms, respectively. When parameter \( \alpha \) is zero, only the moving average is used. When \( \beta \) is zero, the process is exclusively autoregressive.

The dispatch model can then sample the FARMA model and produce large numbers of synthetic time histories for stochastic optimization purposes. As a price-taker model, its dispatch is based on economic decisions dependent on the electricity prices from trained FARMA.

Historical electricity prices for the HTTR operating region (i.e., the Tokyo region of Japan’s electricity system) were used for training the FARMA model. The HTTR-GT/H₂ was assumed ineligible for the non-

2
fossil or baseload markets, due to its status as a small-scale test reactor. Larger commercial reactors could likely participate in the spot and intraday markets, in addition to the baseload and non-fossil markets. The input data were separated into 30-minute increments covering a 1-year period. Prices reflect 2018 historical prices.

RAVEN’s advanced clustering methods were leveraged to improve the accuracy of the synthetic price data [25]. While the Fourier detrending is useful for capturing seasonal effects, the clustering takes it a step further by isolating those segments with major differences.

RAVEN clustered the data set into representative 4-day periods. Each representative 4-day period is known as a cluster, and each cluster was trained as an individual FARMA. By training these individual 4-day clusters—as opposed to a single FARMA—over the year, RAVEN can achieve improved accuracy by further isolating the effects of long-term seasonal trends. Each specific 4-day window, or segment, is then assigned to the cluster that best represents it. The clustering algorithm offers improved accuracy compared to overtraining the FARMA over the entire year.

**Figure 14** shows each cluster and the time at which it occurred in the year. Each panel shows the 4-day periods that are similar to each other and are thus representable by a single FARMA model. Note that the 4-day periods in the shoulder months (usually in the spring and fall) tend to be similar. Additionally, the summer or winter peaks may have only a few 4-day segments in their cluster. This is a feature of the clustering algorithm: by training a different FARMA for each representative window, the peak price events will not impact the production of synthetic data for the more typical shoulder months.

![Figure 14. Four-day segments plotted by cluster, as produced by RAVEN when training the FARMA.](image)

In **Figure 15**, a complete synthetic time history is plotted against the original data. This synthetic history reflects a possible time history of electricity prices that is statistically similar to the original input data. The FARMA can be sampled many times over to produce a broad range of synthetic time histories.
statistically similar to the input price profile.

Figure 15. Historical 2018 Tokyo region electricity prices plotted against the synthetic time history produced by sampling the RAVEN FARMA.

For each model run, the FARMA was sampled 100 times to reduce the modeling uncertainties in the input electricity prices. The price duration curve (PDC) is shown in Figure 16. The historical PDC is largely identical to the average synthetic PDC, except when comparing the 100 or so highest electricity price hours.

Figure 16. PDC comparison between the synthetic and historical data.
This dispatch model will be used to investigate the impact of the PDC discrepancy found in the 100 or so highest electricity price hours. Therefore, the model was run in two modes: one used 100 synthetic price histories and returned the expected breakeven sale price of hydrogen, and the other used the historical PDC to determine the expected breakeven sale price of hydrogen.

2.3.3 HTTR-GT/H₂ Dispatch Dynamics

After sampling the FARMA to produce a synthetic data set, the model dispatches either electricity or hydrogen, depending on the electricity price at each time step. When the electricity price exceeds the cost of producing electricity, electricity is produced and sold. When the electricity price falls below the cost of producing electricity, hydrogen is produced and sold. In this manner, the model chooses the most economically advantageous commodity to produce and sell during each hour.

The dispatch algorithm assumes that the HTTR-GT/H₂ operates in one of two modes, as put forth by Yan et al. [12]. These modes are given as (a) and (b) in Table 1. The dispatch algorithm decides between dispatching electricity in accordance with operational mode (a), or dispatching hydrogen in accordance with mode (b). The system is assumed flexible enough to switch back and forth between modes within the 30-minute time steps allotted. Note that these configurations are based on proposed test designs for the HTTR-GT/H₂, which may not necessarily utilize the HTTR’s entire 30-MWt heat for hydrogen/electricity production.

Table 1. HTTR-GT/H₂ operational modes (reproduced from [12]).

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor outlet temp, °C</td>
<td>850</td>
<td>950</td>
</tr>
<tr>
<td>Reactor power, MWt</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>IHX 2nd side in/out temp, °C</td>
<td>374/570</td>
<td>150/900</td>
</tr>
<tr>
<td>IHX 2nd side flow, kg/s</td>
<td>9.85</td>
<td>2.57</td>
</tr>
<tr>
<td>IHX heat transferred, MWt</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>PPWC heat transferred, MWt</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Turbine inlet temp, °C</td>
<td>568</td>
<td>568</td>
</tr>
<tr>
<td>Turbine inlet pressure, MPa</td>
<td>4.06</td>
<td>4.08</td>
</tr>
<tr>
<td>Turbine flow, kg/s</td>
<td>9.85</td>
<td>9.15</td>
</tr>
<tr>
<td>Compressor pressure ratio</td>
<td>1.38</td>
<td>1.34</td>
</tr>
<tr>
<td>GT system pressure loss, %</td>
<td>7%</td>
<td>2%</td>
</tr>
<tr>
<td>Reactor bypass flow, %</td>
<td>0</td>
<td>72</td>
</tr>
<tr>
<td>HT heat to hydrogen plant, MWt</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>Heating temp to hydrogen plant, °C</td>
<td>-</td>
<td>840</td>
</tr>
<tr>
<td>Power generation, MWe</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Hydrogen production, Nm³/h</td>
<td>0</td>
<td>29.5</td>
</tr>
</tbody>
</table>

The IS cycle design developed by JAEA is sized to provide 29.5 Nm³/hr of hydrogen, as per the design in [12].

The amount of hydrogen delivered during each hour ( is represented in Equation (24). When the price of electricity () falls below the electricity production cost (), the system dispatches hydrogen in accordance with the previously defined operational modes. When electricity price is higher than the cost of producing electricity, hydrogen is not produced; instead, the power is used to make electricity.
2.3.4 Cash Flow Analysis

Once the dispatch is complete, the model collects economic data to produce a system net present value (NPV). These cash flows include the capital cost, operating and maintenance costs of the IS cycle, and an assumed hydrogen storage cost. Revenue comes from the sale of hydrogen and electricity.

The NPVs in this report represent a differential NPV, shown in Equation (25). NPV_{ref} is the NPV of the HTTR-GT/H\textsubscript{2} when only electricity is sold, and no hydrogen process has been built. NPV_{ref} serves as a baseline against which NPV_{cogen} is compared. When ΔNPV is positive, the cogeneration system is more profitable than only selling electricity. When ΔNPV is negative, the system would be more profitable focusing on electricity and not building the IS unit. Thus, when ΔNPV is 0, the profitability of the cogeneration system equals that of only generating electricity. This is the breakeven point, at which the hydrogen price represents the LCOH for this system.

\begin{equation}
\text{(25)}
\end{equation}

Using ΔNPV ensures that only cash flows that differ between reference and cogeneration cases need to be tracked. Expenditures such as fixed HTTR costs and capital investments associated with the nuclear reactor can be disregarded, as they are equivalent in both the reference case and cogeneration cases. The limitation of this method is that ΔNPV only reflects the nuclear-IS profitability relative to the reference case, rather than determining its absolute profitability. More information on the economics of the HTTR-GT/H\textsubscript{2} are required before an analysis of total system profitability can be conducted.

Equation (26) gives the mathematical basis for disregarding equivalent cash flows that appear in both the reference and cogeneration NPVs.

\begin{equation}
\text{(26a)}
\end{equation}

\begin{equation}
\text{(26b)}
\end{equation}

\begin{equation}
\text{(26c)}
\end{equation}

The NPVs are calculated by summing the discounted cash flows associated with each case. Equation (27) details the NPV calculation. For this analysis, the discount rate, \( r \), is 8%.

\begin{equation}
\text{(27)}
\end{equation}

The cash flows accounted for in the cogeneration case are (1) cost of electricity generation from HTTR-GT/H\textsubscript{2}, (2) IS capital and operating cost, (3) hydrogen storage, (4) revenue from electricity sales, and (5) revenue from hydrogen sales. Only the cost of electricity generation and revenue from electricity sale are tabulated in the reference case. The simulation is run for 1 year and used for every year of the project’s 30-year lifetime.
The output for this model is the breakeven cost of hydrogen. Hydrogen prices exceeding the LCOH would make building the nuclear-IS system and strategically dispatching hydrogen more profitable than just selling electricity. Prices below the LCOH mean that the system would lose money relative to only selling electricity. The model allows one to investigate the uncertainty that certain model inputs (e.g., electricity price data) impose on the LCOH.

To find the LCOH, the hydrogen price was varied, and the point at which $\Delta \text{NPV}$ equaled zero was found. This can either be achieved via optimization or by sweeping the solution space on a grid and locating the zero point. For this analysis, the grid sweep was used since the only variable being perturbed was the hydrogen price.

2.3.5 Economic Parameters

The cost of hydrogen production from the nuclear-IS system is given in Figure 17, as estimated by JAEA in [26]. The capital cost is driven by the capacity of the IS cycle. For example, the provided capital cost of 3.4 JPY/m$^3$ was multiplied by the IS cycle capacity of 29.5 Nm$^3$/hr and the 8,760 hours in the year. The loss of chemicals during operation of the IS was treated as a variable operating cost.

![Cost breakdown of hydrogen production by the nuclear-IS system](image)

Figure 17. Cost breakdown of hydrogen production by the nuclear-IS system. Note that, for this analysis, the capital cost is taken on a capacity basis (i.e., Nm$^3$ of capacity). The figure is reproduced from [26].

The dispatch model also assumes a hydrogen storage cost for a tank sized to hold 4 hours of production from the IS cycle. Storage flexing and hydrogen overproduction is not included in this analysis. The storage acts as a simple addition to the capital cost. A price of $600/kg was used [5], equivalent to 5326.5 JPY/Nm$^3$ at an exchange rate of 106 JPY = 1 USD.

3. Results

3.1 RELAP5-3D Steady-State Results

The sole power generation and hydrogen co-generation input decks were both run and results were generated. When the SPG case was first run, the calculated mass flow rates were lower than the design values. The largest pressure drop was observed across the turbine components, so the loss factors across the turbines were reduced slightly to improve mass flow rate results. After this change the mass
flow rates agreed well with design conditions.

The results for the SPG mode are shown in Table 2. The largest difference in temperature results were within about 7 K. The pressures were also in good agreement, with the largest differences on the order of 0.05 MPa. RELAP5-3D underpredicts the pressure at certain points, but the magnitude of the differences were small.

Table 2. RELAP5-3D predictions of the HTTR-GT/H$_2$ secondary system state points for sole-power generation mode compared to design values.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature [K]</th>
<th>ΔT [K]</th>
<th>Pressure [MPa]</th>
<th>ΔP [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design</td>
<td>RELAP</td>
<td>Design</td>
<td>RELAP</td>
</tr>
<tr>
<td>IHX secondary side outlet</td>
<td>843.15</td>
<td>846.06</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbine inlet</td>
<td>841.35</td>
<td>842.68</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbine outlet</td>
<td>776.65</td>
<td>782.09</td>
<td>-64.7</td>
<td>-60.59</td>
</tr>
<tr>
<td>Recuperator LP side inlet</td>
<td>776.65</td>
<td>782.09</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Recuperator LP side outlet</td>
<td>391.65</td>
<td>394.22</td>
<td>-385</td>
<td>-387.87</td>
</tr>
<tr>
<td>Precooler inlet</td>
<td>391.65</td>
<td>394.22</td>
<td>3.151</td>
<td>3.100</td>
</tr>
<tr>
<td>Precooler outlet</td>
<td>298.15</td>
<td>298.17</td>
<td>-93.5</td>
<td>-96.05</td>
</tr>
<tr>
<td>Compressor inlet</td>
<td>298.15</td>
<td>298.17</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Compressor outlet</td>
<td>348.85</td>
<td>353.87</td>
<td>50.7</td>
<td>55.7</td>
</tr>
<tr>
<td>Recuperator HP side inlet</td>
<td>348.85</td>
<td>353.85</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Recuperator HP side outlet</td>
<td>733.85</td>
<td>740.76</td>
<td>385</td>
<td>386.91</td>
</tr>
<tr>
<td>Cooler A inlet</td>
<td>733.85</td>
<td>740.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cooler A outlet</td>
<td>647.15</td>
<td>652.05</td>
<td>-86.7</td>
<td>-88.65</td>
</tr>
<tr>
<td>IHX secondary side outlet</td>
<td>647.15</td>
<td>652.14</td>
<td>4.26</td>
<td>4.264</td>
</tr>
</tbody>
</table>

The results for the HCG mode are shown in Table 3. The mass flow rates are not reported but fit the case well. The temperature and pressure results did not match design values as well for the HCG case. The largest differences were observed across the turbine component. The largest temperature differences reported by RELAP5-3D occurred at the turbine outlet and near the inlet to Cooler B. These differences were approximately 35-39 K.

The pressure differences were also larger for the HCG mode. The largest pressure drop occurs across the turbine components which could be due to RELAP5-3D calculating a loss factor that is too large. The pressure drop across the turbine is approximately 0.17 MPa. The largest pressure difference (about 0.27 MPa) is observed at the compressor outlet.

The compressors did not increase the pressure of the system as significantly as expected, the implementation of the pressure ratio for this component may need some refinement. The recuperator was also observed to transfer less heat than expected. There may be a need to increase the heat exchange area of this component to improve the results.

The differences in temperature and pressure are primarily attributed to the complexity of the various components and the flow split for the HCG mode in the secondary loop. The largest differences appear in locations where the coolant flow is either split or combined.

Table 3. RELAP5-3D predictions of the HTTR-GT/H$_2$ secondary system state points for hydrogen cogeneration mode compared to design values.
<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature [K]</th>
<th>ΔT [K]</th>
<th>Pressure [MPa]</th>
<th>ΔP [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IHX secondary side outlet</td>
<td>1173.15</td>
<td>-</td>
<td>4.11</td>
<td>-</td>
</tr>
<tr>
<td>2nd IHX secondary side inlet</td>
<td>1160.55</td>
<td>-</td>
<td>4.10317</td>
<td>-</td>
</tr>
<tr>
<td>2nd IHX secondary side outlet</td>
<td>1108.15</td>
<td>-</td>
<td>4.09988</td>
<td>-0.00329</td>
</tr>
<tr>
<td>Turbine inlet</td>
<td>841.35</td>
<td>40.13</td>
<td>3.283</td>
<td>-0.794</td>
</tr>
<tr>
<td>Turbine outlet</td>
<td>779.45</td>
<td>-61.9</td>
<td>3.282</td>
<td>-0.794</td>
</tr>
<tr>
<td>Recuperator LP side inlet</td>
<td>779.45</td>
<td>740.13</td>
<td>3.282</td>
<td>-0.794</td>
</tr>
<tr>
<td>Recuperator LP side outlet</td>
<td>389.65</td>
<td>-389.8</td>
<td>3.275</td>
<td>-0.007</td>
</tr>
<tr>
<td>Precooler inlet</td>
<td>389.65</td>
<td>379.23</td>
<td>3.275</td>
<td>-0.007</td>
</tr>
<tr>
<td>Precooler outlet</td>
<td>298.15</td>
<td>-91.5</td>
<td>3.265</td>
<td>-0.002</td>
</tr>
<tr>
<td>Compressor inlet</td>
<td>298.15</td>
<td>297.23</td>
<td>3.265</td>
<td>-0.002</td>
</tr>
<tr>
<td>Compressor outlet</td>
<td>347.35</td>
<td>341.75</td>
<td>4.402</td>
<td>1.137</td>
</tr>
<tr>
<td>Recuperator HP side inlet</td>
<td>347.35</td>
<td>341.75</td>
<td>4.402</td>
<td>1.137</td>
</tr>
<tr>
<td>Recuperator HP side outlet</td>
<td>737.15</td>
<td>702.02</td>
<td>3.134</td>
<td>-0.004</td>
</tr>
<tr>
<td>Cooler B inlet</td>
<td>737.15</td>
<td>702.06</td>
<td>-</td>
<td>-0.004</td>
</tr>
<tr>
<td>Cooler B outlet</td>
<td>423.15</td>
<td>420.42</td>
<td>-</td>
<td>-0.004</td>
</tr>
<tr>
<td>IHX secondary side inlet</td>
<td>423.15</td>
<td>422.57</td>
<td>4.125</td>
<td>4.12832</td>
</tr>
</tbody>
</table>

### 3.2 RELAP5-3D Transient Results

The transient analysis was performed by reducing the rotational speed of the compressors by approximately 5%. The scenario was run for 2500 s until the primary system temperature stabilized. The secondary system mass flow rate is reduced and nearly levels off at 7.25 kg/s around 1600 s into the transient as shown in Figure 18.

Figure 18. Secondary system mass flow rate.

It should be noted that this transient analysis was performed prior to combining the primary and secondary systems. For this reason, the average core coolant temperature is estimated in this analysis. The core average coolant temperature is calculated by taking the average of the core inlet and outlet temperatures and adding the amount of temperature rise that occurs due to the reduced heat transfer in the IHX. The core average temperature and the associated temperature reactivity response are shown in Figure 19. The reactivity added to the core due to temperature rise is expected to remain negative throughout the transient.

Figure 19. Core average temperature and temperature reactivity coefficient during the transient.

### 3.3 Primary system combined with secondary system

The primary system was successfully united with the secondary system. The input model was run to steady-state conditions.
3.4 Dispatch model results

Two scenarios were run: dispatch using synthetic price histories and dispatch using the historical PDC. For the synthetic case, each dispatch instance was run with 100 synthetically generated electricity price time histories to produce a more stochastic optimization. The historical case used the 2018 historical electricity prices as input. The outer loop varied hydrogen prices from 0 to 120 JPY/Nm$^3$.

A sample 8-hour dispatch window is shown in Figure 20. The amount of revenue that the system would generate during each hour is calculated for hydrogen and electricity sales while operating in hydrogen production mode and electricity production mode, respectively, as shown in Figure 20a. Hydrogen or electricity is then produced, depending on which opportunity cost is greater (see Figure 20b).

![Figure 20](image)

Figure 20. Example of dispatch logic over an 8-hour period. (a) The opportunity cost for producing hydrogen or electricity. (b) Hydrogen or electricity modes dispatched in accordance with the higher opportunity cost. This strategy ensures that electricity is sold only when profitable.
3.4.1 **Stochastic Optimization of LCOH**

The stochastic optimization case performed economic dispatch on 100 different synthetic price time histories generated by sampling the trained electricity-price FARMA. The individual economic parameters were gathered for each of these runs, and the model returned the expected $\Delta$NPV.

*Figure 21* shows the relationship between hydrogen price and $\Delta$NPV. Breakeven LCOH occurs at 67.5 JPY/m$^3$, when the $\Delta$NPV is zero. Hydrogen prices were evaluated in increments of 10 JPY/m$^3$ (from 20 to 120 JPY/m$^3$), with higher resolution around the breakeven price of hydrogen.

![Figure 21. $\Delta$NPV for various hydrogen prices, using the synthetic PDC as input. The red dot represents the breakeven LCOH.](image)

Hydrogen prices above and below the LCOH offer insight into the system dynamics. With the IS cycle dispatched while hydrogen prices are less than the LCOH, too few hydrogen-producing hours exist to recover the capital expenditures incurred by building the IS unit. With hydrogen prices greater than LCOH, hydrogen sale becomes economically advantageous and in ample time, ultimately recovering—even exceeding—the capital cost.

*Figure 22* shows the number of hours per year during which the IS cycle dispatches hydrogen. At 40 JPY/m$^3$ or less, the hydrogen price is so low that the IS unit is never economically advantageous to dispatch. A LCOH of 67.5 JPY/m$^3$ equates to 431 expected hours of hydrogen production per year. Price increases result in boosting the number of hours in which hydrogen production is economically advantageous. At a high enough hydrogen price, the system would choose to dispatch hydrogen exclusively.
Figure 22. Utilization rate of the IS unit, plotted against the hydrogen price in the stochastic optimization scenario. As the hydrogen price rises, hydrogen deployment becomes increasingly more economically advantageous than electricity sale, thus the number of hydrogen production hours increases. The red dot represents the breakeven LCOH.

Table 4 summarizes the expected parameters for dispatch at the LCOH.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Value (per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Produced</td>
<td>$1.27 \times 10^5$ m$^3$</td>
</tr>
<tr>
<td>Electricity Produced</td>
<td>5,126.6 MWh</td>
</tr>
<tr>
<td>Hours of Hydrogen Production</td>
<td>431.2 Hours</td>
</tr>
</tbody>
</table>

3.4.2 LCOH with Historical Price Duration Curve

Comparing the stochastically optimized LCOH to one optimized using historical PDC data is useful for understanding the implications of the distribution tails on cost. The stochastic optimization case outputs the expected LCOH under a wide range of possible synthetic PDC. LCOH optimization using the historical data set gives an example of the LCOH found on a PDC that is slightly skewed to higher prices.

As with the stochastic case, Figure 23 shows that hydrogen is not dispatched at low hydrogen prices, and that there is a range in which a small amount of energy is dispatched for hydrogen production despite the inability to recover the IS capital cost. In this case, when hydrogen prices fall below approximately 80 JPY/m$^3$, the system does not dispatch hydrogen. At 80–98 JPY/m$^3$, a small amount of hydrogen is dispatched. At 98.1 JPY/m$^3$, the ΔNPV equals zero, thus representing the LCOH.
Figure 23. ∆NPV for various hydrogen prices, using the historical PDC as input. The red dot represents the breakeven LCOH.

*Figure 24 shows the IS unit’s utilization rate plotted against the hydrogen price. The utilization rate is zero hours when the hydrogen price is low. At an LCOH of 98.1 JPY/m³, the IS unit produces hydrogen for 637 hours. Figure 24 shows the utilization rate of the IS under different hydrogen price conditions.*

![Figure 24: Utilization rate of the IS unit, plotted against the hydrogen price. As the hydrogen price rises, hydrogen deployment becomes increasingly more economically advantageous than electricity sale, so the number of hydrogen production hours increases. The red dot represents the breakeven LCOH.](image)

Table 5 summarizes the dispatch parameters found at an LCOH of 98.1 JPY/m³.

Table 5. Dispatch values for the system at a levelized cost of hydrogen of 98.1 JPY/m³.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Value (per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Produced</td>
<td>1.88 $10^4$ m³</td>
</tr>
<tr>
<td>Electricity Produced</td>
<td>5,064.9 MWh</td>
</tr>
<tr>
<td>Hours of Hydrogen Production</td>
<td>637.0 Hours</td>
</tr>
</tbody>
</table>
3.4.3 Discussion

The reported LCOH values should not be relied on as a basis for making investment decisions. Rather, they help us understand the implications of different inputs, so that when economic competitiveness is evaluated, the correct breadth of input data can be applied.

The effects of price distribution can be viewed by comparing the stochastic optimization case to the historical PDC case. The hydrogen dispatch is driven by two factors: the hours having the lowest electricity prices and the price of hydrogen. By raising the price of hydrogen, selling hydrogen becomes more profitable during more hours. Lower electricity prices and more incidences of low electricity prices also make hydrogen more economically advantageous than electricity.

The lowest-priced hours of the electricity price distribution are what dictate system profitability since the capacity is fixed and the hydrogen price varied. The stochastic optimization case uses synthetic price histories in an attempt to produce the expected LCOH. On average, the synthetic histories showed lower electricity prices at the tail than did the historical price distribution. This led to a lower LCOH than in the historical case.

This lowest-priced hour distribution phenomenon is illustrated in Table 6. The lowest 500 hours of electricity prices from the year are averaged and compared with the LCOHs for several different synthetic histories. The average electricity price over the year is also provided. The LCOH shares a stronger correlation with the bottom-hour average than with the total yearly price average.

Table 6. Impacts of the distribution tail on LCOH.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Electricity Price, Cheapest 500 Hours (JPY/kWh)</th>
<th>Average Yearly Electricity Price (JPY/kWh)</th>
<th>LCOH (JPY/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>2.14</td>
<td>6.91</td>
<td>38.1</td>
</tr>
<tr>
<td>Minus 1 Standard Deviation</td>
<td>3.16</td>
<td>7.73</td>
<td>45.0</td>
</tr>
<tr>
<td>Mean</td>
<td>5.92</td>
<td>10.56</td>
<td>68.2</td>
</tr>
<tr>
<td>Historical(^a)</td>
<td>6.80</td>
<td>11.09</td>
<td>83.2</td>
</tr>
<tr>
<td>Plus 1 Standard Deviation</td>
<td>7.87</td>
<td>13.40</td>
<td>88.0</td>
</tr>
<tr>
<td>Maximum</td>
<td>8.43</td>
<td>14.84</td>
<td>94.0</td>
</tr>
</tbody>
</table>

Synthetic data produced using the ARMA method outputted cheaper bottom-500-hour price averages, as well as overall average prices that were lower than the historical averages. This meant that the distribution of PDCs was slightly more favorable to hydrogen dispatch than the historical PDC. As such, the LCOH was lower in the stochastic case than in the historical case.

This analysis demonstrates that careful consideration should be taken when applying PDCs to this type of economic dispatch problem. The breakeven price of hydrogen highly depends on the PDC input. Stochastic optimization helps reduce uncertainty, but care should still be taken to produce PDCs that are meaningful regarding the chosen timeframe of analysis. For example, using a 2020 PDC to predict the 2030 LCOH would be inappropriate. A projection of 2030 prices would be acceptable, but the best practice would be to use a host of projected possibilities to produce an expected LCOH.

\(^a\) The historical scenario is the only scenario not produced by sampling the ARMA model.
The results from this study also show that lower overall electricity prices and more incidences of low prices would provide greater economic incentives for hydrogen production. This means that NPPs in locations with depressed electricity prices due to factors such as zero- or negative-bid renewable energies, mild climates, or low electricity demand could provide hydrogen at a lower price, yet still breakeven or potentially turn a profit.

Several other pathways exist for reducing the LCOH. Reducing capital expenditures would depress the LCOH. The effects and sizes of potential storage options could be explored in more detail. Additional cashflows generated by the NPPs’ ability to participate in other areas of the electricity market would lower the ∆NPV and thus the LCOH, as well. Before investment decisions are made, each of these sensitivities should be investigated to better understand their feedback.

4. Conclusions

The HTTR-GT/H\textsubscript{2} test plant is being designed to use the heat from an HTGR to generate both electricity and hydrogen based on demand. RELAP5-3D models were developed for both the sole-power and hydrogen cogeneration modes. The RELAP5-3D models were run to completion, and results were compared to design conditions. It was found that the results for the sole-power generation mode compared very favorably to design conditions. The largest temperature and pressure deviations from design conditions are about 7 K and 0.05 MPa, respectively.

Larger differences were observed for the hydrogen cogeneration mode. The largest temperature and pressure deviations from design conditions are about 39 K and about 0.27 MPa, respectively. The larger differences for the HCG mode are primarily attributed to the complexity of the various components and the flow being split in the secondary loop.

The pressure ratio of the compressor component and the heat exchange area of the recuperator are two areas that could potentially improve the calculation.

A transient scenario was investigated in which the heat removal capability of the secondary system was reduced. As a result of this transient the reactor temperatures increased. A core reactivity response calculation showed that this temperature increase will add negative reactivity to the reactor. Future calculations may include a linked primary and secondary system to demonstrate potential effects that off normal conditions in the secondary system may have on the primary system.

The RELAP5/MOD3.3 input model of the primary system was modified so that it would be compatible with RELAP5-3D. This primary system model was linked to the secondary system via heat transfer in the IHX. The combined input was run to completion.

The hydrogen dispatch analysis explored the economics of dispatching a nuclear-IS cogeneration unit. The results demonstrate the economic potential of such a system when compared to only selling electricity. These results highly depend on input assumptions, specifically the magnitude and distribution of electricity prices. The LCOH in this report should not be taken as a final value for the HTTR-GT/H\textsubscript{2}’s profitability, but as an exploration of the impacts of input assumptions on the final answer. Special care should be taken in this type of dispatch analysis to produce a host of meaningful electricity price time histories that represent possibilities for the evaluation years. In this regard, the FARMA approach shows great potential.

This study also serves as another indicator that dispatching hydrogen and electricity could be more economically advantageous than just selling electricity in the right conditions. Much of the nuclear hydrogen production and dispatch work focuses on light water reactors and U.S. electricity markets.
while focusing on hydrogen production technology. This study performs the economic dispatch on a unique reactor, hydrogen production system, and electricity market and shows the breakeven price of hydrogen. Performing these analyses at different locations and with different technologies is important for understanding the economic competitiveness of producing hydrogen from nuclear.

Efforts to further this research could include running a larger stochastic optimization case aimed at optimizing the size of the IS unit coupled to a commercial reactor, or at optimizing different sensitivities (e.g., capital cost).

5. References


