

TRANSIENT ANALYSIS OF A HYDROGEN-DESALINATION COGENERATION NUCLEAR POWER PLANT : ACCIDENT SCENARIOS WITHIN THE HYDROGEN PRODUCTION PLANT

**Hyung Gon Jin¹, Hee Cheon NO²
Young Soo Kim³, Ho Sik Kim⁴**

^{1,2,3,4} Department of Nuclear and Quantum Engineering,
Korea Advanced Institute of Science and Technology
373-1 Guseong-dong Yuseong-gu, Daejeon, 305-701, Korea
gonijin@gmail.com, hcno@kaist.ac.kr
ys_kim@kaist.ac.kr , hskim25@kaist.ac.kr

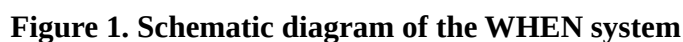
Abstract

The WHEN (Water-Hydrogen-Electricity Nuclear gas-cooled reactor) system is an integrated system based on a nuclear power plant coupled with desalination and hydrogen production. The WHEN system integrates the HELP (High-Economical Low-Pressure) IS (Iodine- Sulfur) cycle for hydrogen production and the CD (Capacitive Desalination) + MED (Multi Effect Distillation) Hybrid system for desalination on top of the HTGR (High-Temperature Gas-cooled Reactor), which generates electricity. The WHEN system can enhance energy utilization by as much as 70%, and it can be flexibly designed according to various user needs. When we operate this type of cogeneration nuclear power plant, the load balance of each system is critical for the continuous operation of the entire system. A set of transient scenarios was simulated using a system analysis code (the GAMMA code), which can take into account the flow path design of hydrogen production coupling, i.e., undercooling and overcooling transients that are initiated in the hydrogen production plant. From the results of a safety analysis, we confirmed that the undercooling and overcooling transients initiated in the IS cycle do not lead any serious safety problems on the WHEN system.

1. Introduction

1.1 WHEN system

As world energy demand is increasing and the shortage of water resources is becoming worse, the need to overcome these issues is also growing. An important requirement for future power plants is the replacement of fossil fuels to reduce green-house gas emissions. The WHEN system meets this requirement through its use of nuclear energy. This system can also produce electricity, water and hydrogen with high efficiency. Because it is based on gas-cooled reactor passive safety features, the WHEN system is free from the typical safety concerns of nuclear power plants. The WHEN system consists of three plants: a high-temperature gas-cooled nuclear power plant (of any type), a hydrogen production plant that uses the IS cycle, and a MED-based water distillation plant. A conceptual diagram is presented in Figure 1.



1.2 HELP (High-Economical Low-Pressure) IS cycle

Among various alternatives, hydrogen is one of the most attractive energy carriers for the clean energy cycle in the future. Thermo-chemical water-splitting cycles, electrolysis, and hybrid processes have been proposed to address hydrogen production on a large scale. Among the many thermo-chemical water-splitting technologies for the mass production of hydrogen, the Iodine-Sulfur (IS) cycle is considered to be one of the most promising processes.

Created in the 1980s by General Atomics in the United States, the IS cycle utilizes high-temperature heat from energy sources such as nuclear reactors. Despite its high viability relative to many other options, numerous technical challenges need to be resolved before it can practically contribute to the mass production of hydrogen.

The HELP IS cycle improves the material and low efficiency issues of the existing IS cycle by operating with the optimized Bunsen reaction at a low pressure. With the optimized Bunsen reaction process to yield an over-azeotropic HI liquid solution, a flowsheet of the IS

The diagram illustrates a chemical looping process for the conversion of sulfur-containing feedstocks. The process involves several interconnected units and streams:

- Feedstocks:** SO_2 , O_2 , H_2O and H_2SO_4 , H_2O are the primary inputs.
- Process Flow:**
 - SO_2 , O_2 , and H_2O enter a **Reg. Hx** (Regeneration Heat Exchanger) and then a **Heater**.
 - H_2SO_4 and H_2O enter a **Pump** and then an **L-L Separator** (Liquid-Liquid Separator).
 - The **L-L Separator** outputs H_2SO_4 , HI , I_2 , and H_2O to a **Flash** unit.
 - The **Flash** unit outputs H_2SO_4 to a **R. Hx** (Reaction Heat Exchanger) and HI , H_2O , and I_2 to a **Heater**.
 - The **Heater** outputs HI , H_2O , and I_2 to a **Flash** unit.
 - The **Flash** unit outputs HI to a **R. Hx** and H_2 , I_2 to a **HI decomposer**.
 - The **HI decomposer** outputs H_2 to **Hydrogen storage** and I_2 to a **I₂ & HI absorber**.
 - The **I₂ & HI absorber** outputs I_2 , H_2O , and HI to a **Flash** unit.
 - The **Flash** unit outputs HI to a **R. Hx** and H_2 , I_2 to a **HI decomposer**.
 - The **HI decomposer** outputs H_2 to **Hydrogen storage** and I_2 to a **I₂ & HI absorber**.
 - The **I₂ & HI absorber** outputs I_2 , H_2O , and HI to a **Flash** unit.
 - The **Flash** unit outputs HI to a **R. Hx** and H_2 , I_2 to a **HI decomposer**.
 - The **HI decomposer** outputs H_2 to **Hydrogen storage** and I_2 to a **I₂ & HI absorber**.
- Heat Recovery:** The process includes multiple heat exchangers (**Reg. Hx**, **R. Hx**) and heaters (**Heater**) to optimize energy efficiency. Red dashed lines indicate heat recovery loops.
- Storage and Output:** **Oxygen storage** is used for O_2 storage. **Hydrogen storage** is used for H_2 storage. The final products are SO_2 , O_2 , and H_2O from the **Flash** unit, and H_2 from **Hydrogen storage**.

2. Transient simulation of an IS hydrogen production plant in the WHEN system

2.1 Target reactor and nodalization

(3/12)

Table 1. Major specifications for the GTHTR300+IS+MED core design

Specification	GTHT300	GTHT300+IS+MED
Thermal power	600 MW	600 MW
Reactor inlet coolant temperature	587°C	634°C
Reactor outlet coolant temperature	850°C	851°C
Coolant pressure	7 MPa	6.88 MPa
Mass flow rate	437.4 kg/s	530.6 kg/s
Average core power density	5.4 W/cm ³	5.4 W/cm ³
Heat rate of the hydrogen production plant	N/A	105 MW

Fig. 3 shows the nodalization of the GTHT300 + IS + MED system using the WHEN coupling scheme. One of the most important aspects in IS coupling with the WHEN system is the flow path. For water splitting to occur, the reactor heat should be coupled with the hydrogen production plant using intermediate heat exchangers (IHX) under high-temperature conditions. There are two ways to extract heat from the reactor. The first one is to install an IHX right before the turbine inlet. In this case, possible problem is the increase of the reactor outlet temperature under a steady-state condition due to direct heat extraction from the main stream. For example, to meet the turbine inlet temperature (850°C) of the GTHT300 design specification under an IS coupled situation, the reactor outlet temperature should be surpass 930°C, which is very close to the safety criteria temperature of 1000°C. From a system transient control point of view, the reactor response to an abrupt temperature change at the turbine inlet can be slow because the temperature change can influence the core after the flow goes through the entire system.

On the other hand, with the WHEN system, the heated working fluid is directly divided right after the reactor core outlet (fluid block 20 in the WHEN nodalization shown in Fig. 3). In this case, the turbine inlet temperature (850°C) can be safely achieved without the reactor heating up and the abnormal temperature change in the IS cycle can directly affect the reactor inlet temperature. Hence, the reactor can be stabilized quickly using the reactor control logic.

2.2 Reactor kinetics

In the steady-state analysis, we used the constant thermal power condition, but for the transient analysis, the reactor thermal power was calculated using point kinetics equations with six groups of delayed precursors [4]. The point kinetics equations are solved by the fourth-order Runge-Kutta numerical method. The reactivity of the reactor is the sum of the reactivity contributions by the initial reactivity, core temperature feedback, and fission product poisoning [5]. We do not use control rods to control the reactivity of the reactor.

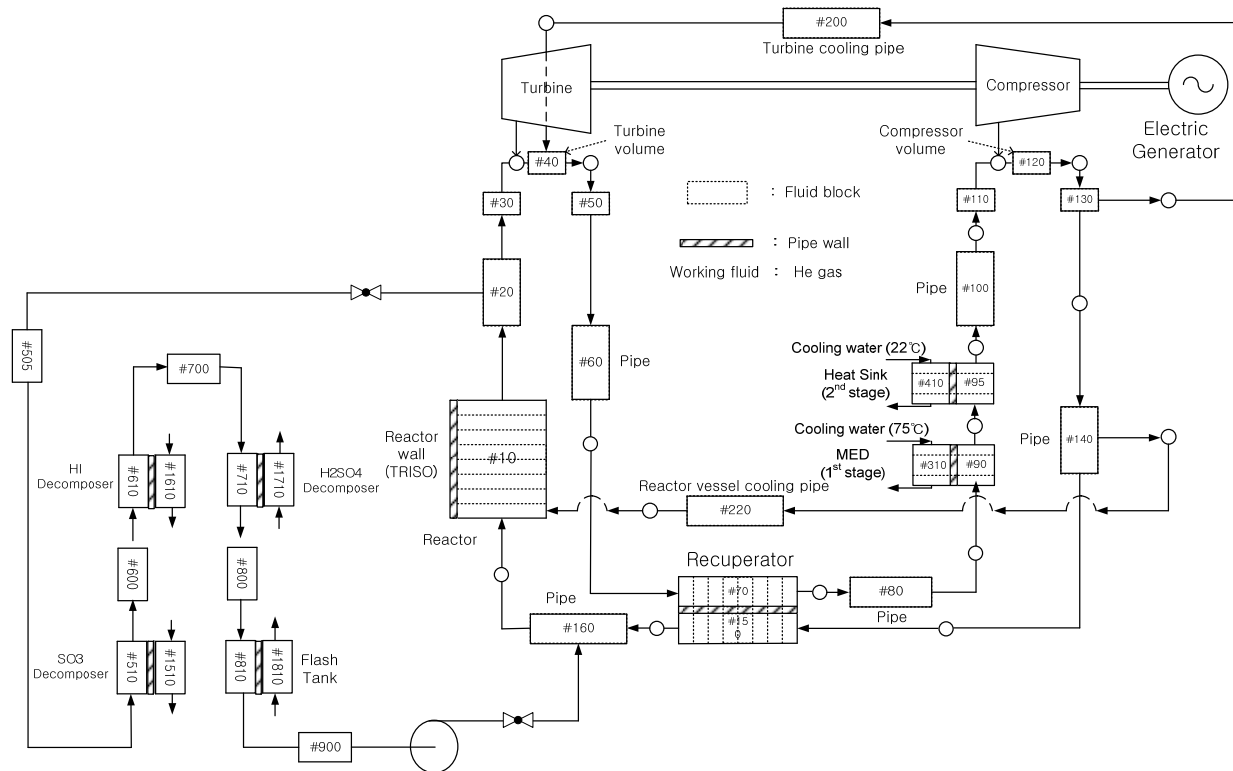


Figure 3. Nodalization diagram of the WHEN system

2.3 Undercooling transient in a hydrogen production plant

Abnormal events in a hydrogen production plant can initiate load changes and induce temperature variations in the reactor core. The first transient scenario we imagined is a loss-of-heat-sink accident, which means an abrupt stop of one or more heat exchangers in hydrogen production system for any reason. An excessive temperature increase in the primary cooling system and the turbine inlet would cause reactor scrams, as temperature increases in those systems are restricted to prevent undue thermal stress from the reactor structures and unnecessary loss of efficiency.

The HELP IS cycle has four IHXs that supply heat to the SO_3 decomposer, the HI decomposer, the H_2SO_4 evaporator and the flash tanks. The heat requirement of each section can be defined by the target hydrogen production rate and the conversion efficiency. This also heavily depends on the properties of the chemical mixture involved. In three decomposers, which are under a high-temperature condition, mixtures behave as ideal gases. However, inside of flash tanks, particularly the properties of the HI mixture are not fully known. In this study, the properties were referenced from OLI Systems© properties, including the phase change of the mixture. The energy requirement of each flow path is given in Table 2. Based on this estimation, the HELP IS cycle in this study is designed to consume 105MW thermal power from a reactor (600MW).

Table 2. – Energy Requirement for IS cycle

Sections	Flow paths	Components	WHEN(MW)
H ₂ SO ₄ decomposition section	H ₂ SO ₄ flash	H ₂ SO ₄ (L)	6.4
		H ₂ O(L)	
	H ₂ SO ₄ evaporator	H ₂ S O ₄ (L)	13.3
		H ₂ O(L)	
	SO ₃ decomposer	SO ₃ (V)	35.2
		H ₂ O(V)	
HI decomposition section	HI flash	HI(L)	25.3
		I ₂ (L)	
		H ₂ O(L)	
	HI decomposer	HI(V)	25.1
		I ₂ (V)	
		H ₂ O(V)	

The meaning of an undercooling transient in the HELP IS cycle is related to the continuous operation of the WHEN system. A cogeneration system can be interrupted due to maintenance issues or accidents. This study covers four types of loss-of-heat-sink transient scenarios, as summarized in Table 3 with abbreviations for the legends of the diagrams.

Table 3. Undercooling Scenarios

Undercooling Locations	Heat amount (MW)	Abbreviation
SO ₃ decomposer	35.2	SO3
SO ₃ and HI decomposer	60.3	SO3+HI
SO ₃ , HI decomposer and H ₂ SO ₄ evaporator	73.7	SO3+HI+H ₂ SO ₄
SO ₃ , HI decomposer, H ₂ SO ₄ evaporator and flash tanks	105.3	IS ALL

2.4 Overcooling transient in a hydrogen production plant

Under continuous operation, the HELP IS cycle may sometimes operate under a transient condition, for example, during replacement of the catalyst in decomposers or the load change of a chemical process. For these reasons, the HELP IS cycle includes additional hold-up tanks between the outlet of the Bunsen reactor and each flash tank (Fig. 2). We assume a transient case in which a hold-up tank is accidentally purged to the H₂SO₄ evaporator after which the mass flow rate of the evaporator inlet increases abruptly by 47%. Due to this load increase, additional heating is required at the H₂SO₄ evaporator. Based the OLI Systems© properties, the heat requirements are presented in Table 4.

Table 4. Overcooling Scenarios

Overcooling locations	Required heat amount (MW)	Abbreviation
SO ₃ decomposer	122.1	SO3
SO ₃ and HI decomposer	134.2	SO3+HI
SO ₃ , HI decomposer and H ₂ SO ₄ evaporator	140.5	SO3+HI+H ₂ SO ₄
SO ₃ , HI decomposer, H ₂ SO ₄ evaporator and flash tanks	155.6	IS ALL

3. Transient simulation results

3.1 Undercooling transient

We assume a typical loss-of-heat-sink accident, in which the HELP IS cycle is abruptly stopped. Under this transient scenario, the reactor outlet temperature, turbine power, reactor power and core maximum temperature are presented. The point kinetics is also included to calculate the reactor power.

At 0 seconds, transient simulations initiate from a steady-state condition (with a reactor outlet temperature of 851.35°C). When the accident starts, undercooling leads to a higher outlet temperature of the IS cycle than in a normal steady-state condition, which increases the reactor inlet temperature. Through this feedback, the reactor outlet temperature increases and then enters into another, higher steady state, as shown in Fig. 4. The temperature increase at this point can cause safety issues. However, as the helium temperature the safety criterion at the reactor outlet is 1000°C, the WHEN system is under the safety limit regardless of the occurrence of the loss-of-heat-sink accident.

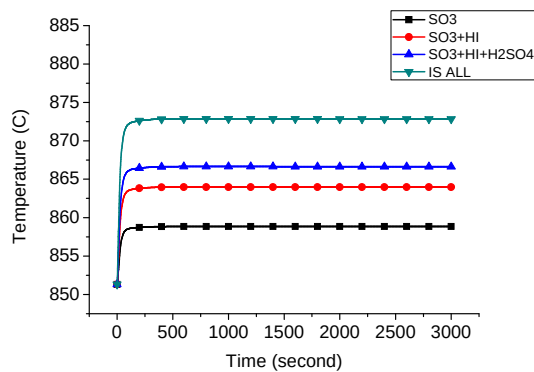


Figure 4. Reactor outlet temperature

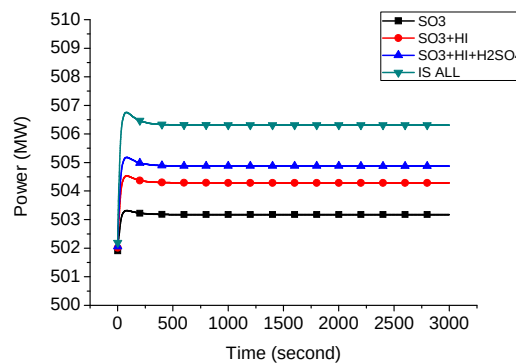


Figure 5. Turbine power

The reactor outlet temperature increase affects turbine power generation as well (Fig. 5). The changes in the turbine inlet condition induce a disproportionate torque balance at the rotational shaft which connects the gas turbine and generator. An increase and decrease of the mass flow rate would result in a power conversion unit (PCU) trip owing to the load ejection in the generator. It would also lead to a reactor scram due to the loss of flow in the primary cooling system. In the loss-of-heat-sink case, the turbine inlet mass flow rate increase is proportional to the reactor outlet temperature, causing the transient scenario 'IS ALL' to generate the highest level of turbine power. On the other hand, reactor power and core maximum temperature get new lower steady state by means of point kinetics.(Fig. 6 and Fig. 7)

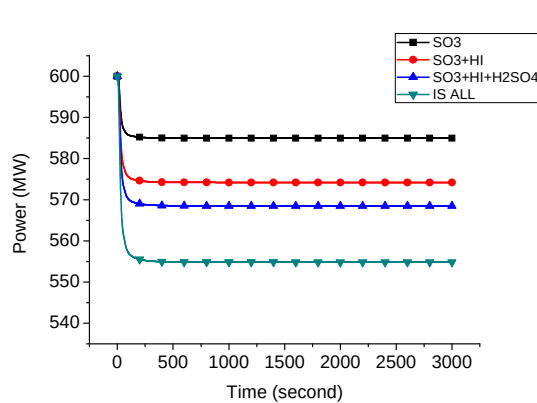


Figure 6. Reactor power

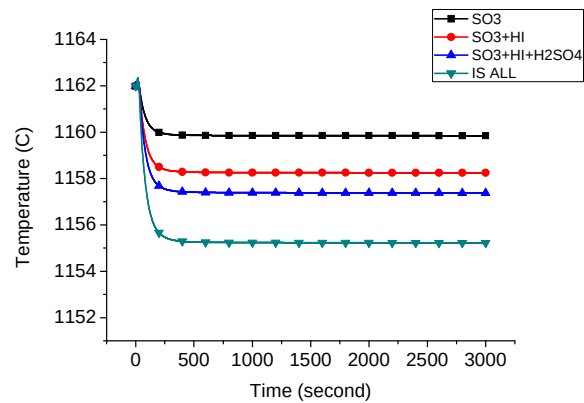


Figure 7. Maximum core temperature

3.2 Overcooling transient

In certain cases, which are not typical accident scenarios, a load-increase transient can take place when the H_2SO_4 mixture in the hold-up tank purges to the H_2SO_4 evaporator. Under this transient scenario, the reactor outlet temperature, turbine power, reactor power and core maximum temperature are presented. The point kinetics is included here as well to calculate the reactor power.

Compared to the undercooling cases, an overcooling transient shows a completely opposite trend. At 0 seconds, transient simulations initiate from a steady-state condition (with the reactor outlet temperature at 851.35°C). When the accident starts, the load increase cools down the outlet temperature of the HELP IS cycle more than it would under normal steady-state conditions, which thus lowers the reactor inlet temperature. As a result of this feedback, the reactor outlet temperature decreases and then enters another, lower steady state, as shown in Fig. 8. The temperature decrease in this case does cause safety issues.

The reactor outlet temperature decrease affects the turbine power generation as well (Fig. 9). In an overcooling transient, the turbine inlet mass flow rate decrease occurs in conjunction with a decrease of the reactor outlet temperature, causing the transient scenario 'IS ALL' to generate the lowest amount of turbine power.

On the other hand, the reactor power and core maximum temperature are our concern in this case. The safety limit, however, has a considerable margin (reactor power: 672MW, core maximum temperature: 1600°C), which implies that a 47% load increase does not activate the trip signal.

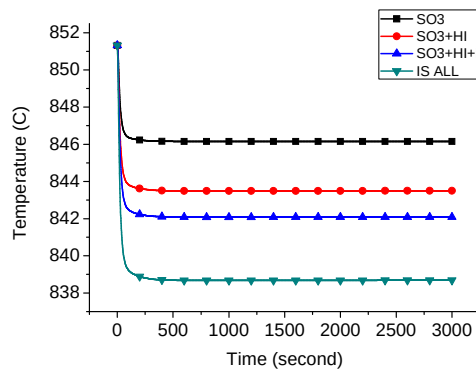


Figure 8. Reactor outlet temperature

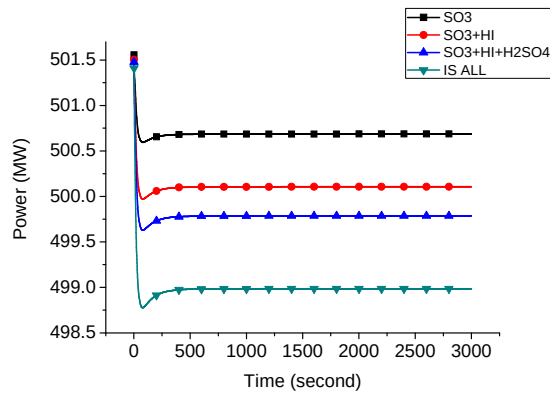


Figure 9. Turbine power

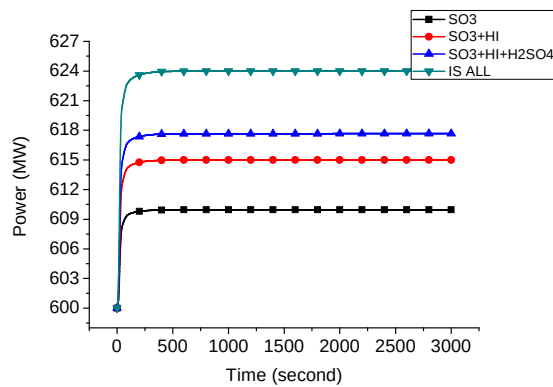


Figure 10. Reactor power

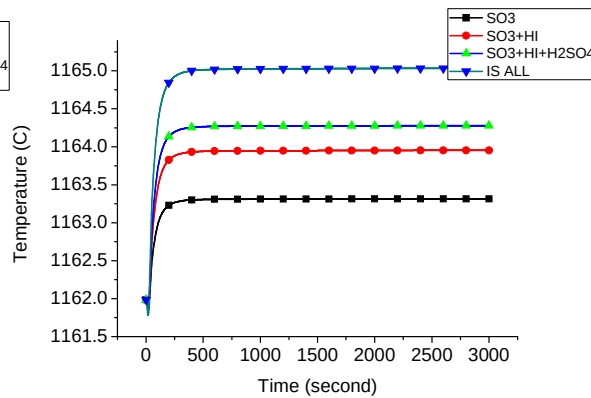


Figure 11. Maximum core temperature

3.3 Overcooling sensitivity

The most severe undercooling situation is very clearly identified: a total loss of all IHXs. For the most severe overcooling case, we select an instantaneous guillotine break of the largest pipe among the outlet pipes of the SO₃ decomposer, which is position 'A' in Fig. 2. When the accident occurs, the SO₂ mixture bursts out into the atmosphere. The pressure ratio is high enough to reach critical flow conditions; therefore, the maximum flow rate can be limited. The operating condition at this point is presented in Table 5, which comes from the HELP system design specifications.

Table 5. Operating condition at point A

Property	Amount
Pressure upstream	5 atm
Temperature	900°C
SO ₃ mole fraction	0.06
SO ₂ mole fraction	0.23
H ₂ O mole fraction	0.71

The key parameters of the critical mass flow rate are the cross-sectional area of the broken pipe and the heat capacity ratio of the SO₂ mixture. However, the pipe design of the IS cycle remains unavailable [6]; hence, we chose a general pipe size considering a feasible range (radius: 0.25m ~ 0.45m). The heat capacity ratio depends on the chemical composition and temperature, though practically this can vary from 1.1 to 1.5. According to the mass flow rate estimation (Fig. 12), the maximum value is 10,500 kmole/hour with the largest pipe and the highest heat capacity ratio. Although the massive purge flow at the SO₃ decomposer outlet does not mean that the mass flow rate increases of all sections instantly, to consider the worst case scenario, we assume that an increase of the mass flow rate at one point directly and instantaneously affects the mass flow rate rise of all other sections according to the ratio suggested in the HELP system.

The total heat rejection amounts of all scenarios are presented in Table 6. Transient scenario '3000' is the case in which the mass flow rate at the SO₃ decomposer is 3000 kmole/hour. To meet this decomposition amount, other sections should be increased, making the total required heat 150.5 MW, which is an overcooling condition.

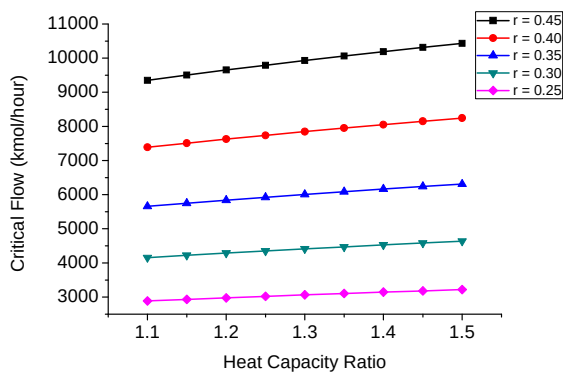


Figure 12. Critical mass flow rate estimation

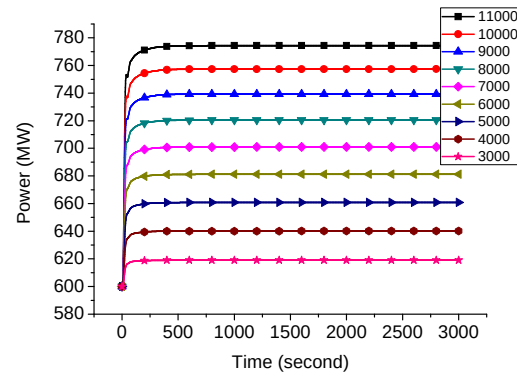


Figure 13. Sensitivity of the total heat rejection

Table 6. Transient Scenarios

	Transient Scenarios								
Sections	3000	4000	5000	6000	7000	8000	9000	10000	11000
HI flash	36.1	48.2	60.2	72.3	84.3	96.4	108.4	120.4	132.5
H ₂ SO ₄ flash	9.2	12.3	15.3	18.4	21.5	24.5	27.6	30.7	33.7
H ₂ SO ₄ evaporator	19.0	25.3	31.6	37.9	44.2	50.5	56.9	63.2	69.5
SO ₃ decomposer	50.4	67.1	84.0	100.7	117.5	134.3	151.9	167.8	184.6
HI decomposer	35.9	47.9	59.8	71.8	83.8	95.8	107.7	119.7	131.7
Total Heat Rejections (MW)	150.5	200.7	251.0	301.1	351.3	401.5	451.6	501.8	552.0

The total required heat linearly increases along with the increase in the mass flow rate in the SO₃ decomposer. Among the monitoring parameters (i.e., the reactor outlet temperature, turbine power, reactor power and core maximum temperature), the reactor power is one of the most

important parameters in terms of safety because other values become lower in a higher overcooling condition. However, the reactor power climbs due to reactivity feedback. If the reactor power exceeds 672MW, the trip signal activates according to the design specifications. In Fig. 13, between scenarios 5000 and 6000 (total heat rejection: 280 MW), a reactor trip occurs.

Each case shows the power rising rapidly as soon as a transient starts. It enters into another steady state within 10 minutes. In other words, if the total heat requirement is 150.5MW, the peak reactor power is 620MW, or a heat requirement of 200MW requires 640MW of peak power. In this manner, Fig. 13 can be summed up with Fig. 14.

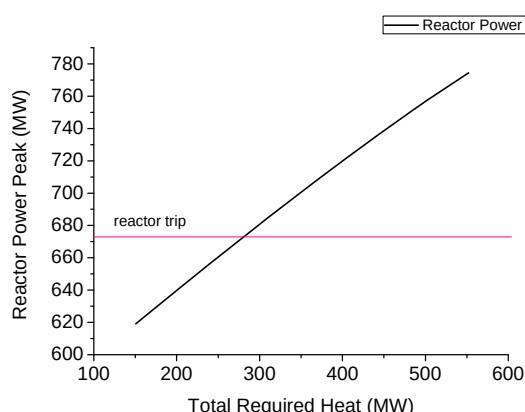


Figure 14. Reactor trip and overcooling transient

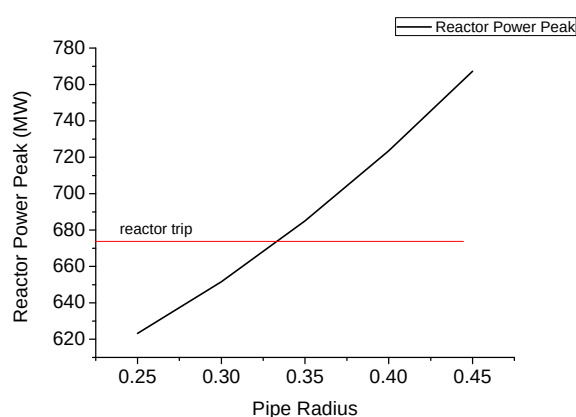


Figure 15. Pipe radius vs. reactor power peak

The total rejected heat and reactor power peak value have a linear relationship. The horizontal red line represents the reactor trip level. It can be confirmed that overcooling at less than 280MW does not trigger a trip signal. In terms of the pipe sizing, a pipe with a radius of 0.33m is the upper limit to avoid a reactor trip when a rupture occurs (Fig. 15). Fig. 16 shows the result when we plot the reactor power peak overcooling and undercooling together. The slope of the line is determined by the core temperature coefficient of the point kinetics model.

4. Conclusion

To enable the continuous operation of a cogeneration power plant during abnormal load change events that initiate in the IS cycle, a set of load change scenarios was simulated using a system analysis code (the GAMMA code), which can take into account the flow path design of hydrogen production coupling. From the safety analysis results, we found that a failure of the IS cycle does not lead to any catastrophic safety problems on the WHEN system. Only a reactor trip can be observed when overcooling exceeds 280MW.

Further studies should be done to assess the full range of transient scenarios assumed in an IS hydrogen production plant. Verification and validation studies of the system analysis code can be also conducted in a next step in an effort to ensure the credibility of the evaluation methods and chemical mixture properties. Future experimental data obtained from process engineering tests would contribute to the validation.

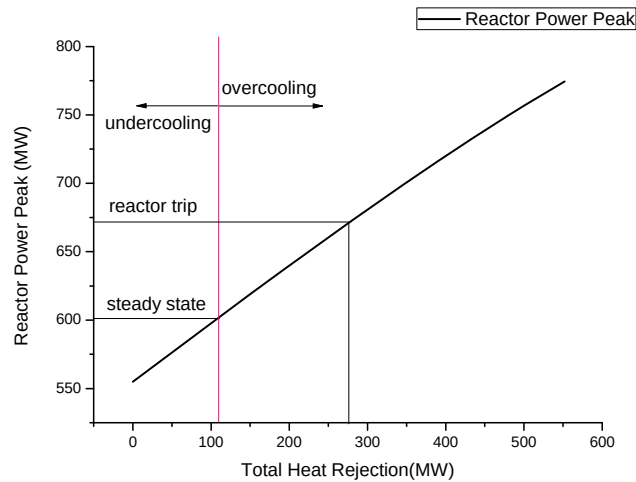


Figure 16. Total heat rejection vs. reactor power peak

5. Acknowledgments

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