Safety Evaluation of VHTR Cogeneration System

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Japan Atomic Energy Agency

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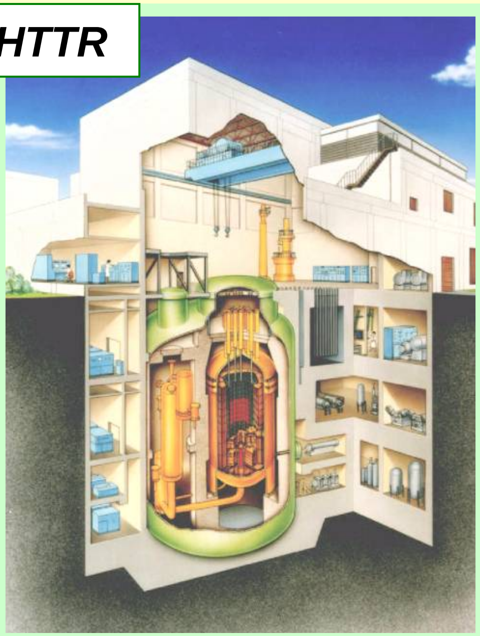
JAEA R&D for the VHTR system

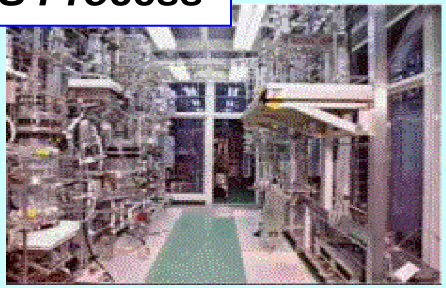
2010 — 2030

HTTR



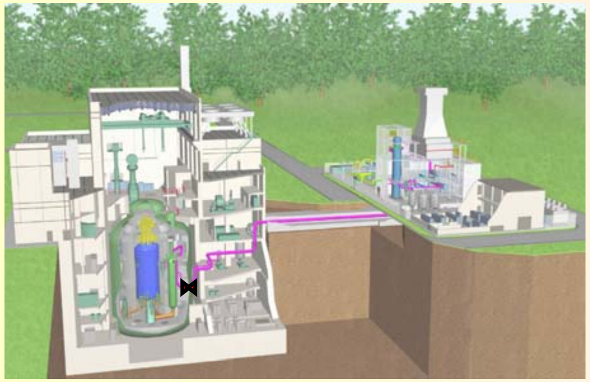
High temperature operation (950℃) : 2004

IS Process



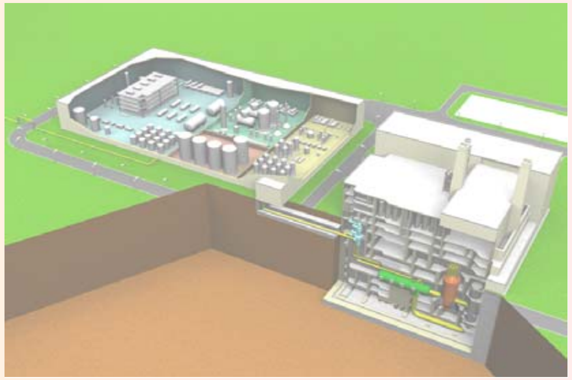
Continuous hydrogen production
30NL/h 175hr : 2005

HTTR-IS system



- *World's first demonstration of hydrogen production utilizing heat from nuclear power*
- *Hydrogen production rate : Around 1000 Nm^3/h*

Commercial VHTR system



- *Hydrogen production for commercial use*
- *Economically competitive*

Japanese Design of VHTR Cogeneration system

GTHTR300C (170MWth for H_2 plant)

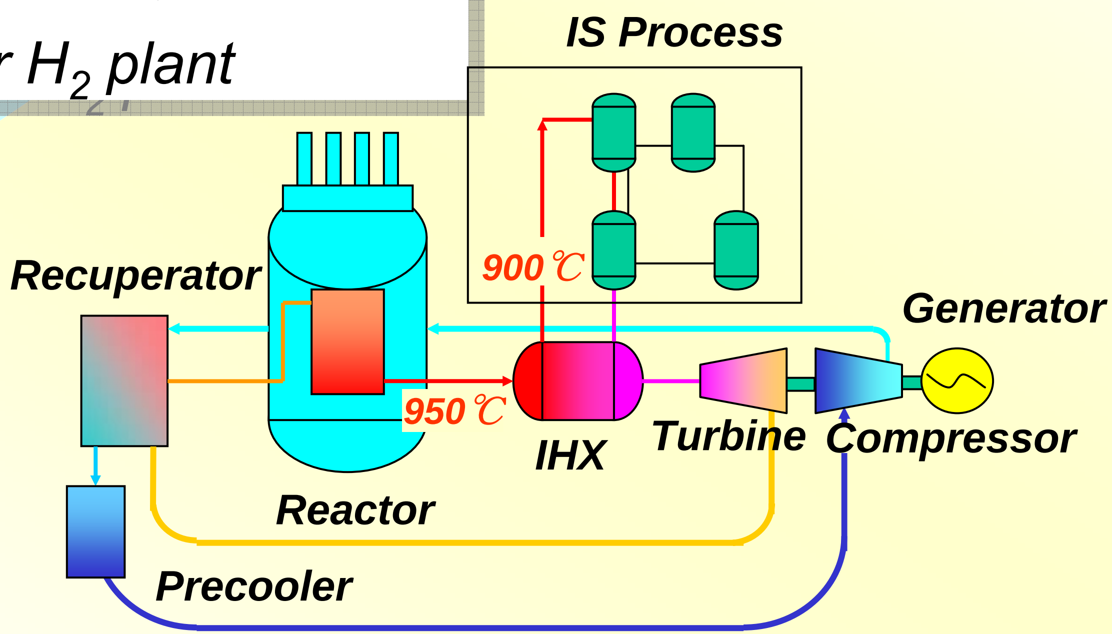
for **C**ogeneration of electricity and hydrogen

- Electricity generation : 202MWe
- Hydrogen production rate : 25,000Nm^3/h

GTHTR300C (370MWth for H_2 plant)

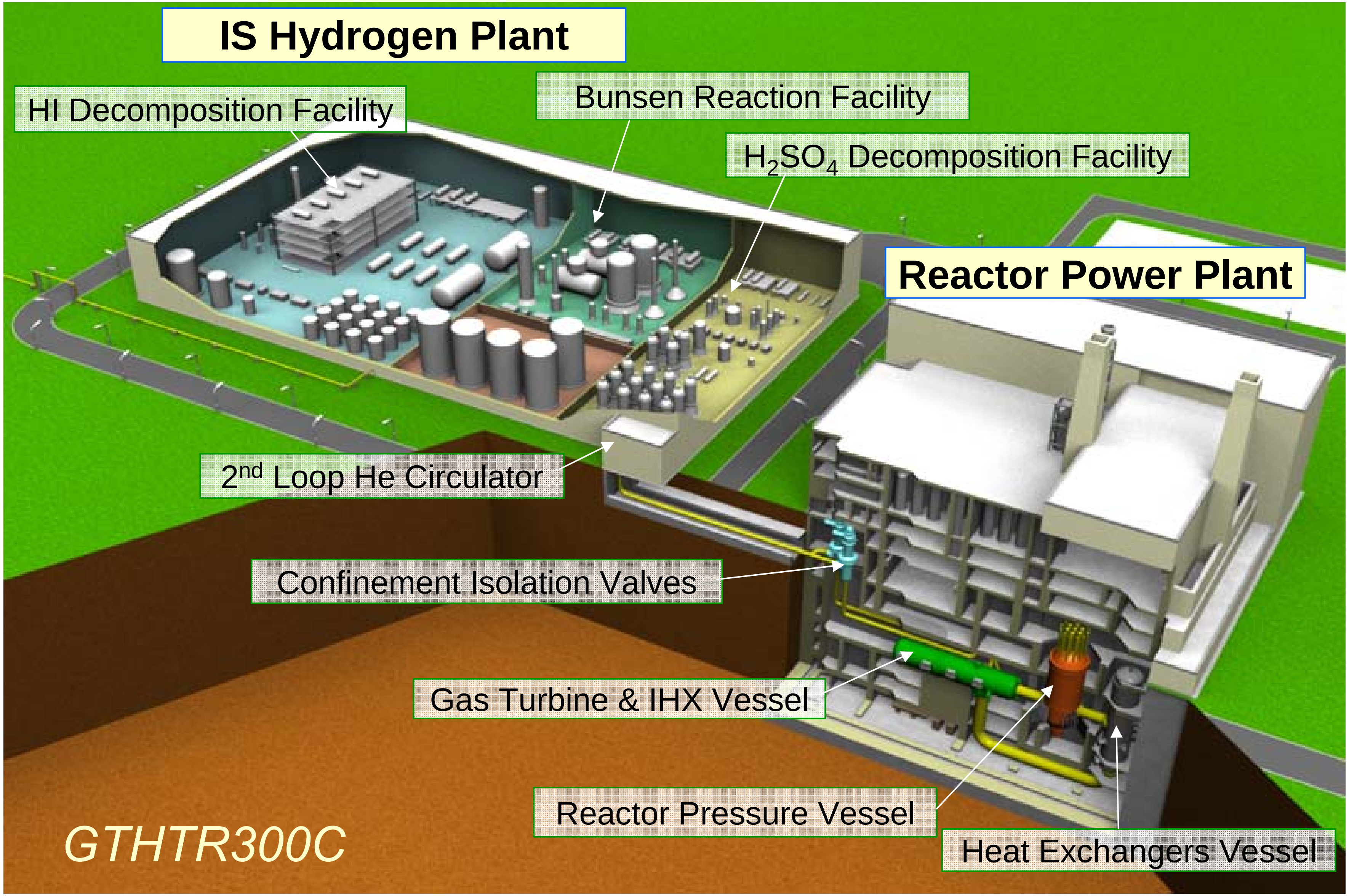
for **H**ydrogen production

- Hydrogen production rate : 52,000Nm^3/h
- Electricity generation for H_2 plant



X. Yan et al., Proc. of 3rd information exchange meeting on nuclear production of hydrogen (2005).

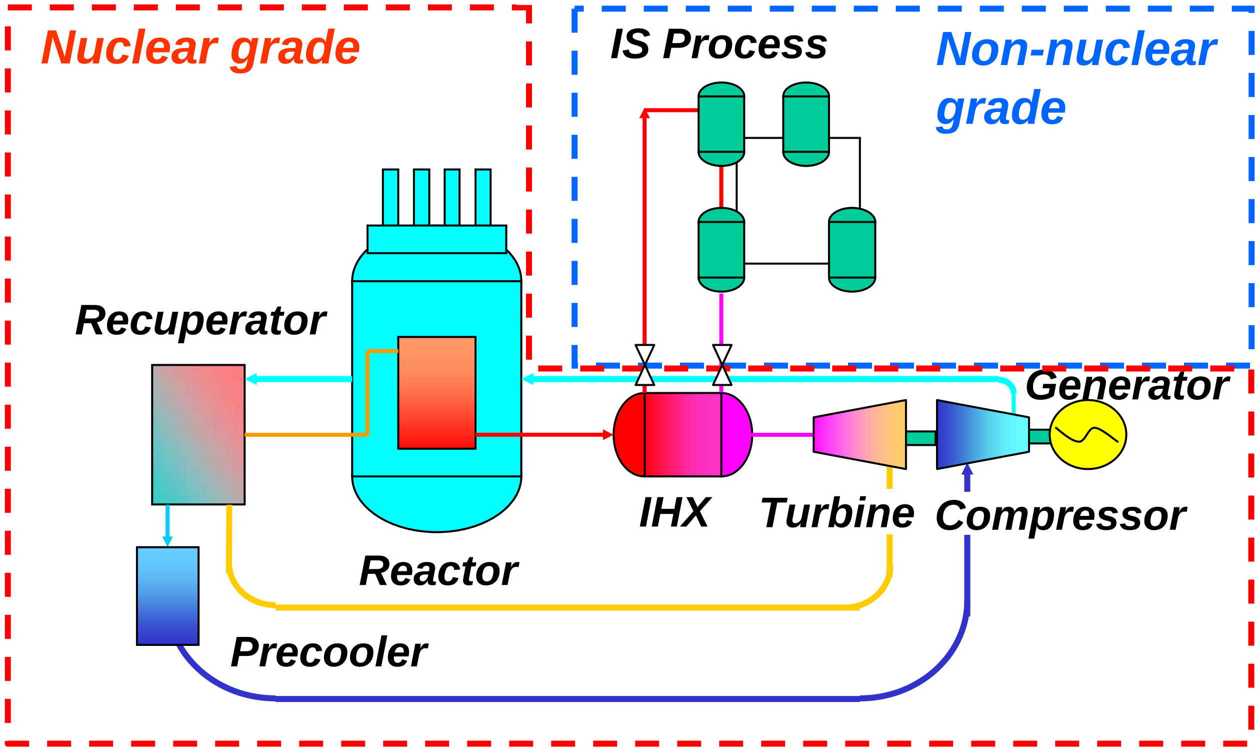
Bird's eye view of GTHTR300C



Basic Design Philosophy of GHTHR300C

Why Non-nuclear grade IS process ?

- *Open the door to non-nuclear industries*
  - *- IS process will be managed by oil and gas companies*
- *Reducing the construction costs of the IS process*
  - *- Apply the chemical plant design standard to the IS process*



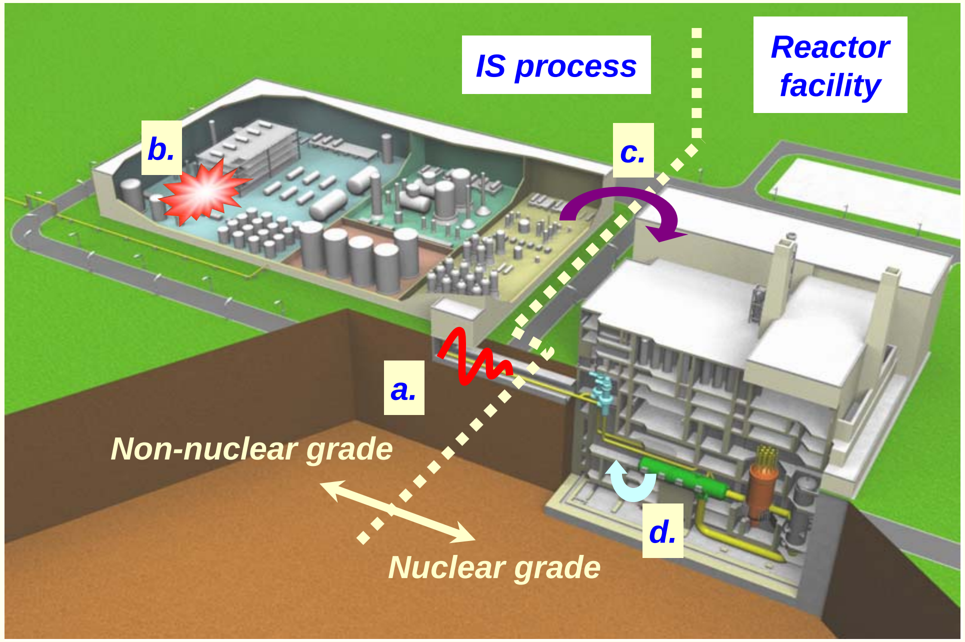
Non-nuclear Design for IS process

Safety philosophy for non-nuclear graded IS process

Exempt the IS process from nuclear safety system

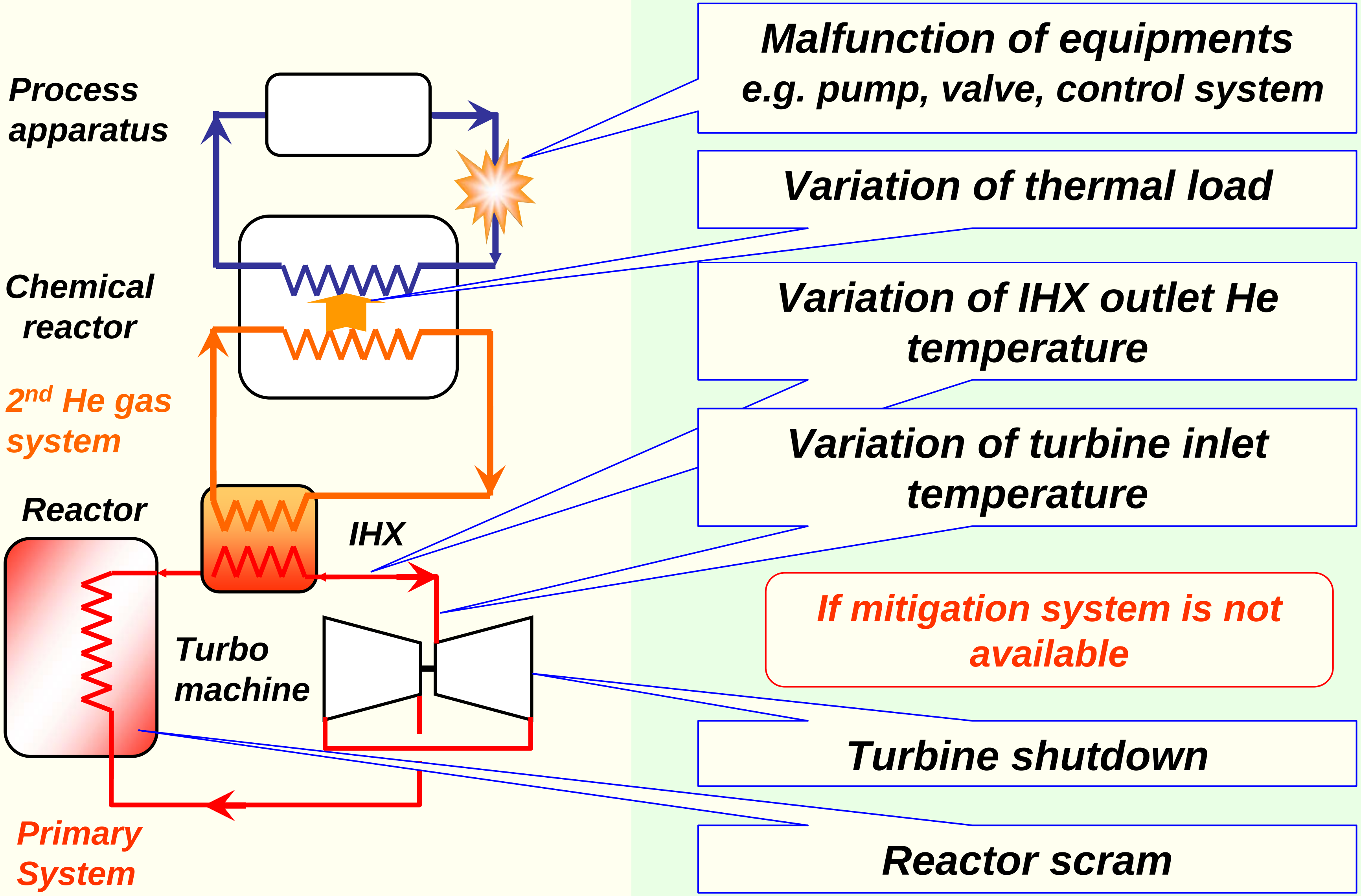
- Operate reactor normally under all conditions of the IS process -

Non-nuclear graded IS process



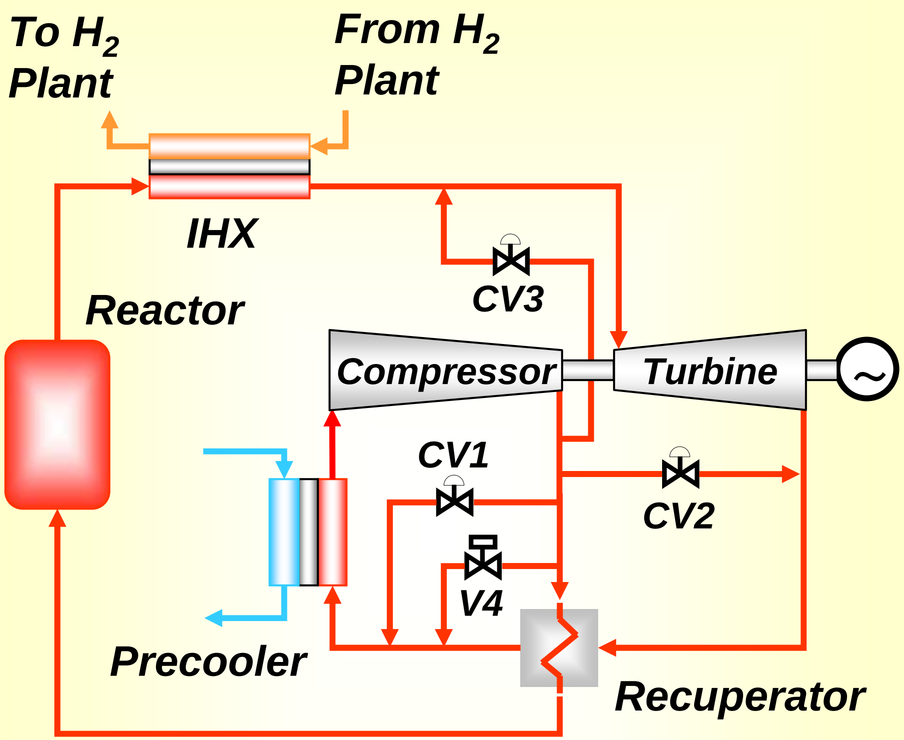
a. *Mitigate thermal load disturbance originated by IS process*
b. *Protect the nuclear safety components from H_2 explosion*
c. *Protect central control room of reactor against toxic gas*
d. *Reduce tritium concentration in 2^{ry} helium loop and the IS process*

Variation of H2 Plant Thermal Load



Mitigation system for controlling the turbine inlet temperature is required

Event Sequence of loss of thermal load

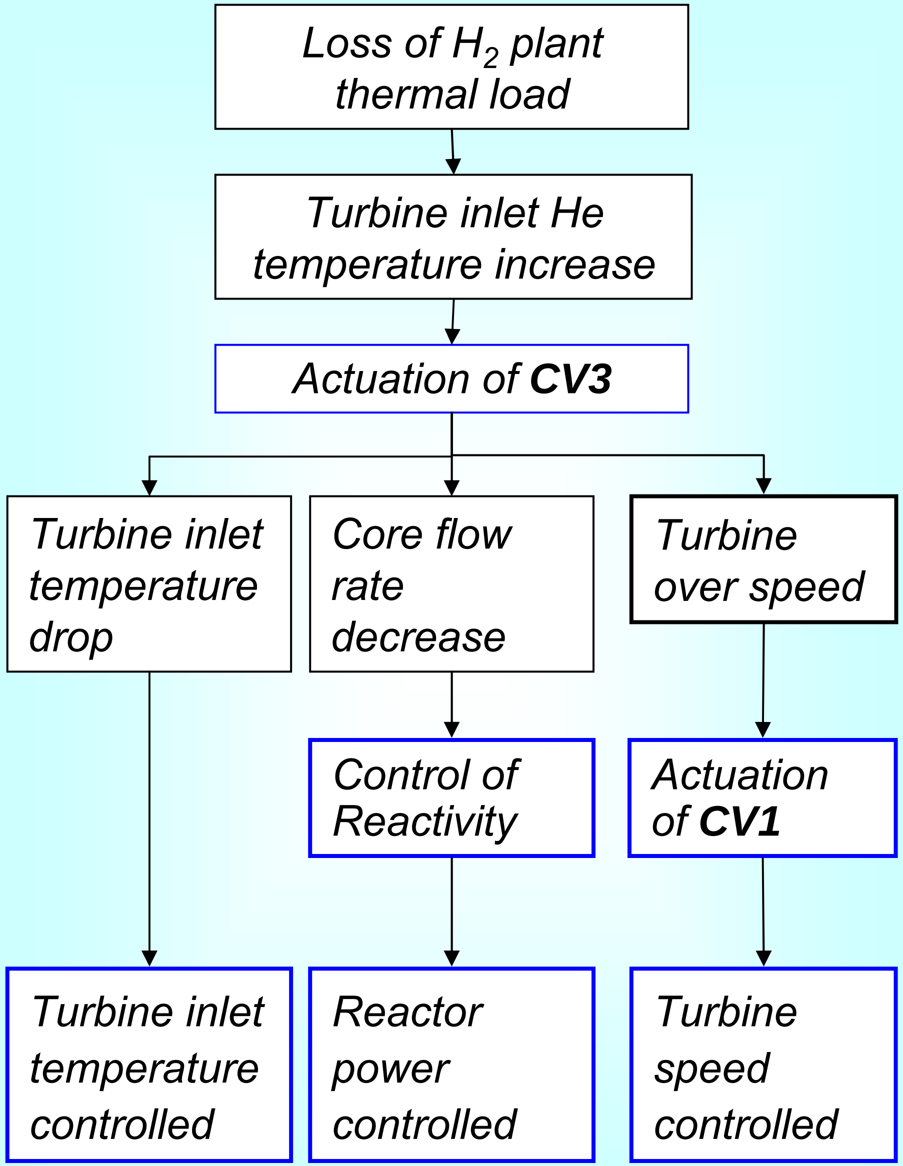


CV1 : Turbine bypass flow control valve

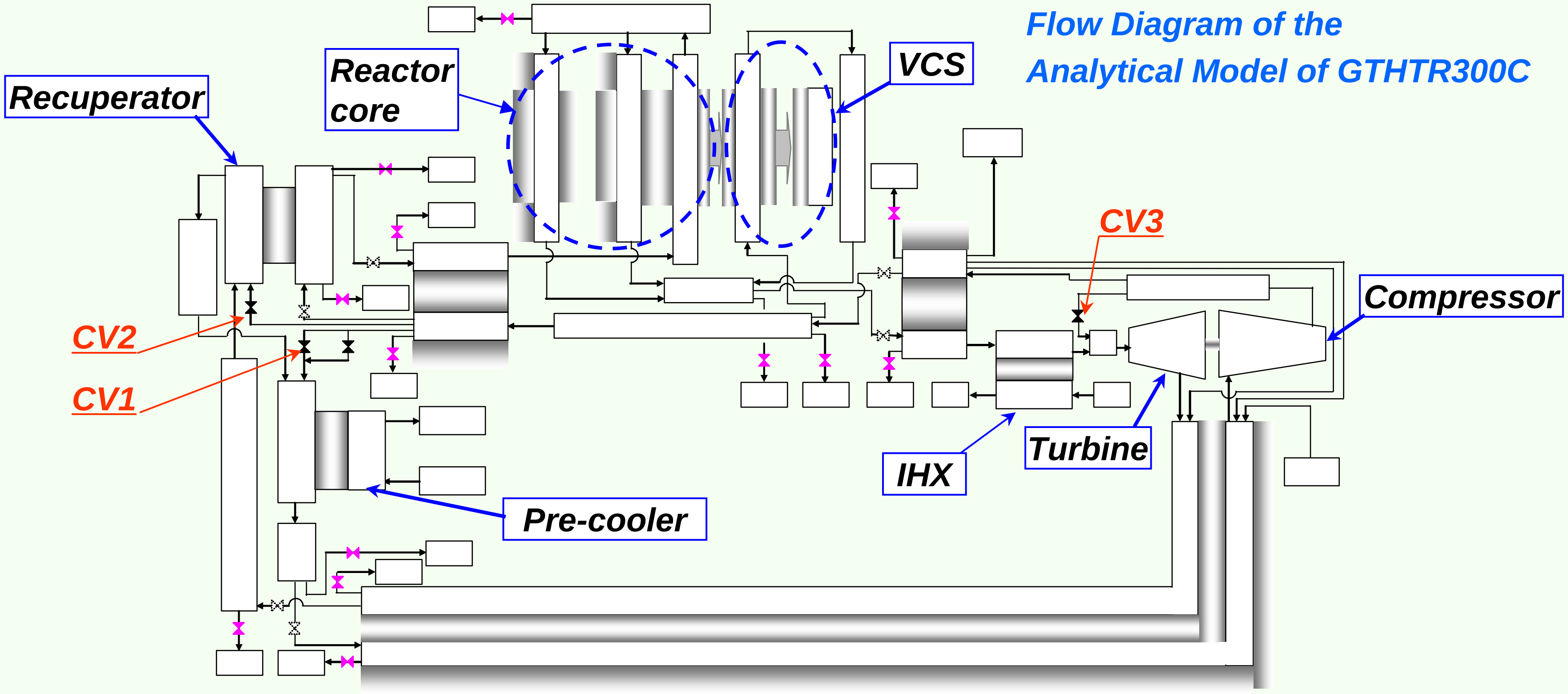
CV2 : Recuperator inlet temperature control valve

CV3 : Turbine inlet temperature control valve

V4 : Turbine bypass valve



Dynamic Simulation Code for GTHTR300C



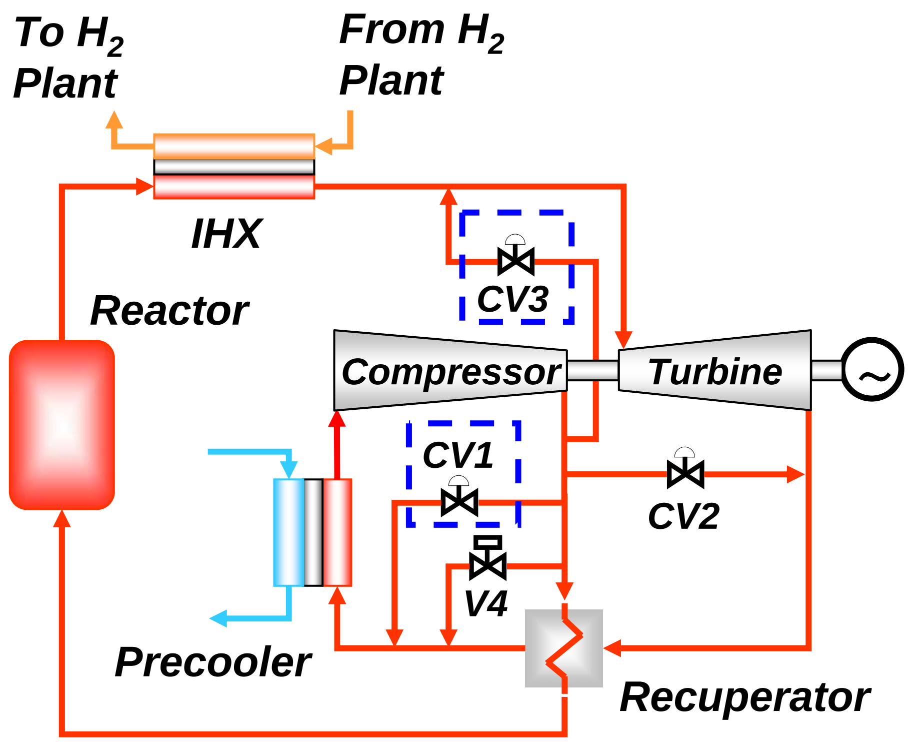
- Thermal-hydraulic model
  - Non-condensable gas model
  - Field equations

    Mass continuity, Momentum conservation, Energy conservation
  - Heat transfer correlation equation

    Experimental equation, Conventional equation
- Component model
  - Gas Turbine
  - Compressor
  - Control system
- Reactor kinetics
  - Point nuclear kinetic equation
  - Reactor kinetics data

Dynamic Calculation (1/2)

- Loss of thermal load of H_2 Plant (170MW) in GTHTR300C -



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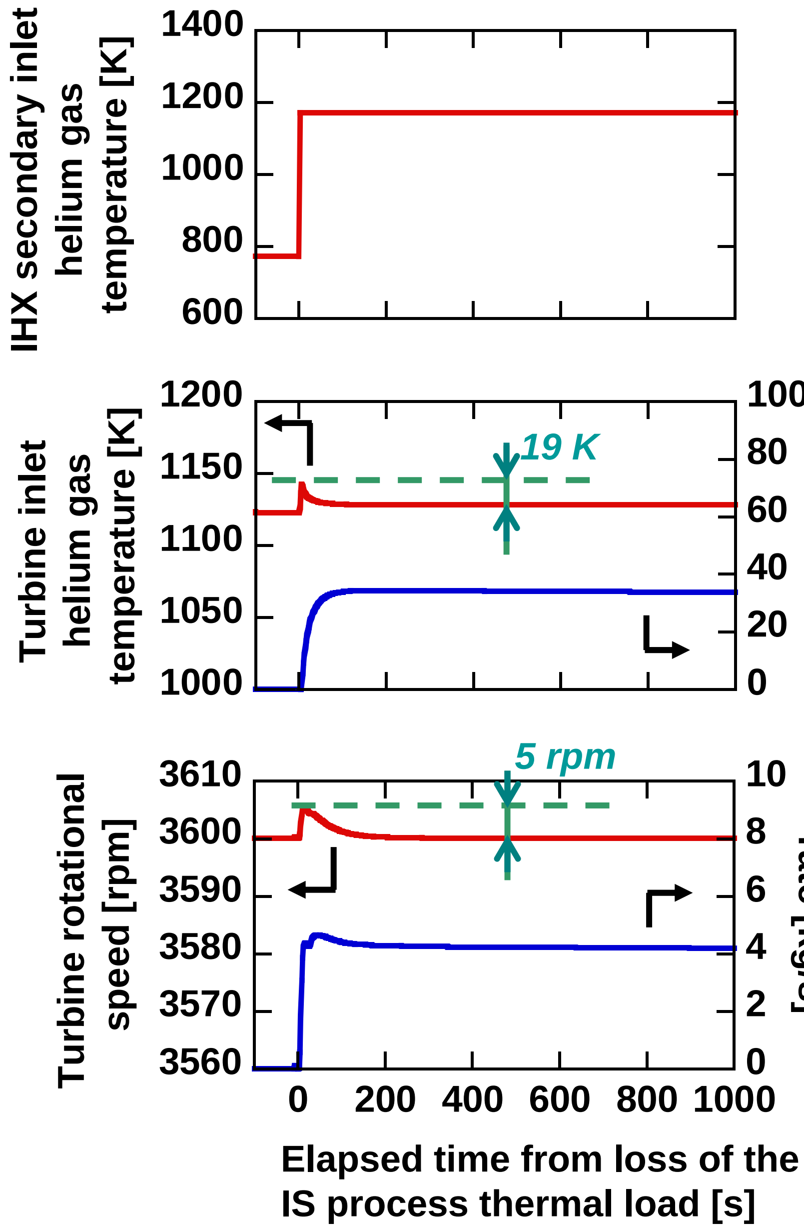
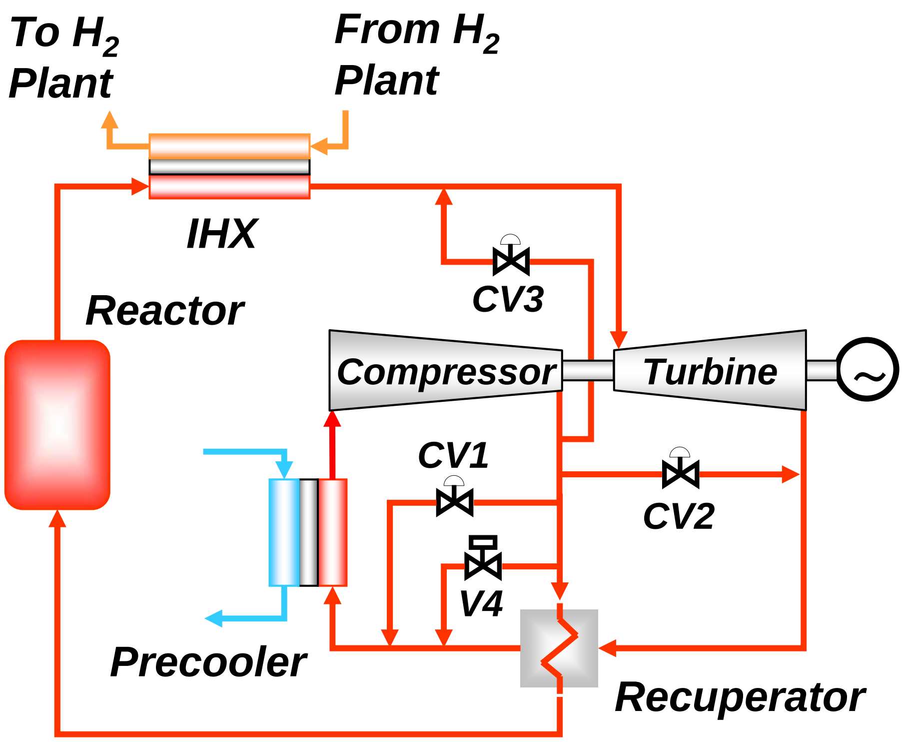
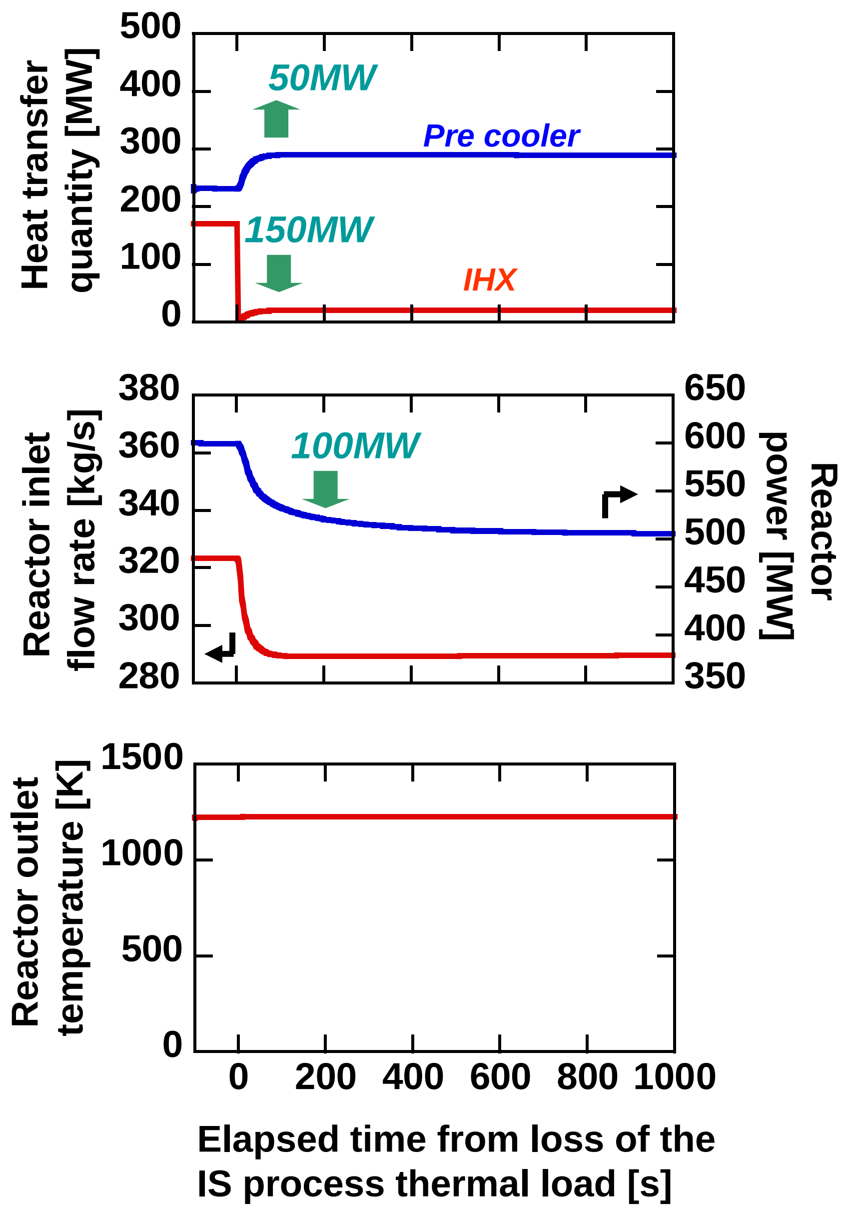


Dynamic Calculation (2/2)

- Loss of Thermal Load of H_2 Plant (170MW) in GTHTR300C -





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Concluding Remarks

- *JAEA started the design study including the safety design of commercial VHTR systems GTHTR300C for cogeneration of hydrogen and electricity*
- *One of the key safety related events is to mitigate the effect of thermal load variation of hydrogen plant on the reactor system*
- *Plant dynamic calculation for loss of the H_2 plant thermal load was performed*
- *Availability of the control system was verified*

Thanks for your attention.

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Back ground information

Control valve data

	Diameter	CV value	Acting time
CV1	500A	4679	5.0 s (Including dead time 2.0s)
CV2	400A	1202	5.0 s (Including dead time 2.0s)
CV3	400A	2070	5.0 s (Including dead time 2.0s)

IHX Heat transfer correlation

(Shell side)

$$Nu = C_1 Re^{0.8} Pr^{0.4} \qquad (800 < Re \leq 7000)$$

$$Nu = C_2 Re^{0.6} Pr^{0.3} \qquad (Re > 7000)$$

(Tube side)

$$Nu = 0.0223 Re^{(5/6)} di \frac{Pr}{Pr^{0.6} - 0.0057} \times \left(1 + \frac{0.0615}{(Re \cdot di^{2.5})^{(1/6)}} \right)$$

C_1, C_2 : *Design Coefficient*

Regenerative heat exchanger heat transfer correlation

$$\alpha_{He} = Nu\lambda / De$$

$$De = 2WH / (W + H)$$

$$j = 0.48 \left(\frac{X}{De} \right)^{0.16} \left(\frac{W}{H} \right)^{0.18} Re^{0.54}$$ ***(Re ≤ 1000)***

$$j = 0.24 \left(\frac{X}{De} \right)^{0.32} \left(\frac{t_F}{De} \right)^{0.09} Re^{0.37}$$ ***(Re ≥ 2000)***

U : Flow velocity

W : Flow path width of fins + fin thickness

H : Flow path height

X: Fin length

t_f : Fin thickness [m]

Pre-cooler Heat transfer correlation

(Helium side)

$$\alpha_{He} = 0.023 Re^{0.8} Pr^{0.4} \lambda / D_{in}$$

(Water side)

$$\alpha_W = J \cdot CpG\, Pr^{-2/3} C_i$$

$$J = 0.292\, Re^k \left(\frac{S}{D}\right)^{1.115} \left(\frac{S}{H}\right)^{0.257} \left(\frac{t_f}{S}\right)^{0.666} \left(\frac{D}{D_0}\right)^{0.473} \left(\frac{D}{t_f}\right)^{0.7717}$$

$$k = -0.415 + 0.0346\, ln\left(\frac{D}{S}\right)$$

Din : Tube inner diameter [m]

Do : Tube outer diameter [m]

Cp : Specific heat [kJ/kg K]

Ci: Correction coefficient

S : Clearance between fins [m]

D : Fin outer diameter [m]

H : Fin height [m]

t_f : Fin thickness [m]

G : Tube outer mass velocity [kg/s m2]

Turbine model

(Rotational speed)

$$\Sigma I_i \frac{d\omega}{dt} = \Sigma \tau_i - \Sigma F_i \omega$$

(Pressure ratio & Turbine Efficiency)

$$\eta_t = f\left(\frac{U}{C_0}\right)$$

$$U = \frac{\pi D_m N}{60}$$

$$C_0 = \sqrt{2g \frac{K}{K-1} R T_i \left(1 - \pi_T^{\frac{1-K}{K}}\right) \Big/ Z}$$

$$\Phi = 0.208 \left(\frac{U}{C_0}\right)^{-1.25}$$

$$\frac{G\sqrt{T_i}}{P_i} = \Phi \frac{N}{\sqrt{T_i}} \frac{\pi D_m}{60} A_m \frac{1}{R}$$

***I* : Inertia [kg m2]**

***ω* : Rotational speed [rad/s]**

***τ* : Shaft torque [Nm]**

***F* : Friction coefficient (=0)**

***U* : Turbine average circumferential velocity [m/s]**

***D_m* : Turbine average diameter (=2m)**

***C_0* :**

***K* : Adiabatic index (=1.667)**

***T_i* : Turbine inlet temperature [K]**

***π_T* : Pressure ratio**

***Z* : Turbine stage (=6)**

***C_m* : Turbine inlet axial velocity [m/s]**

***G* : Turbine flow rate [kg/s]**

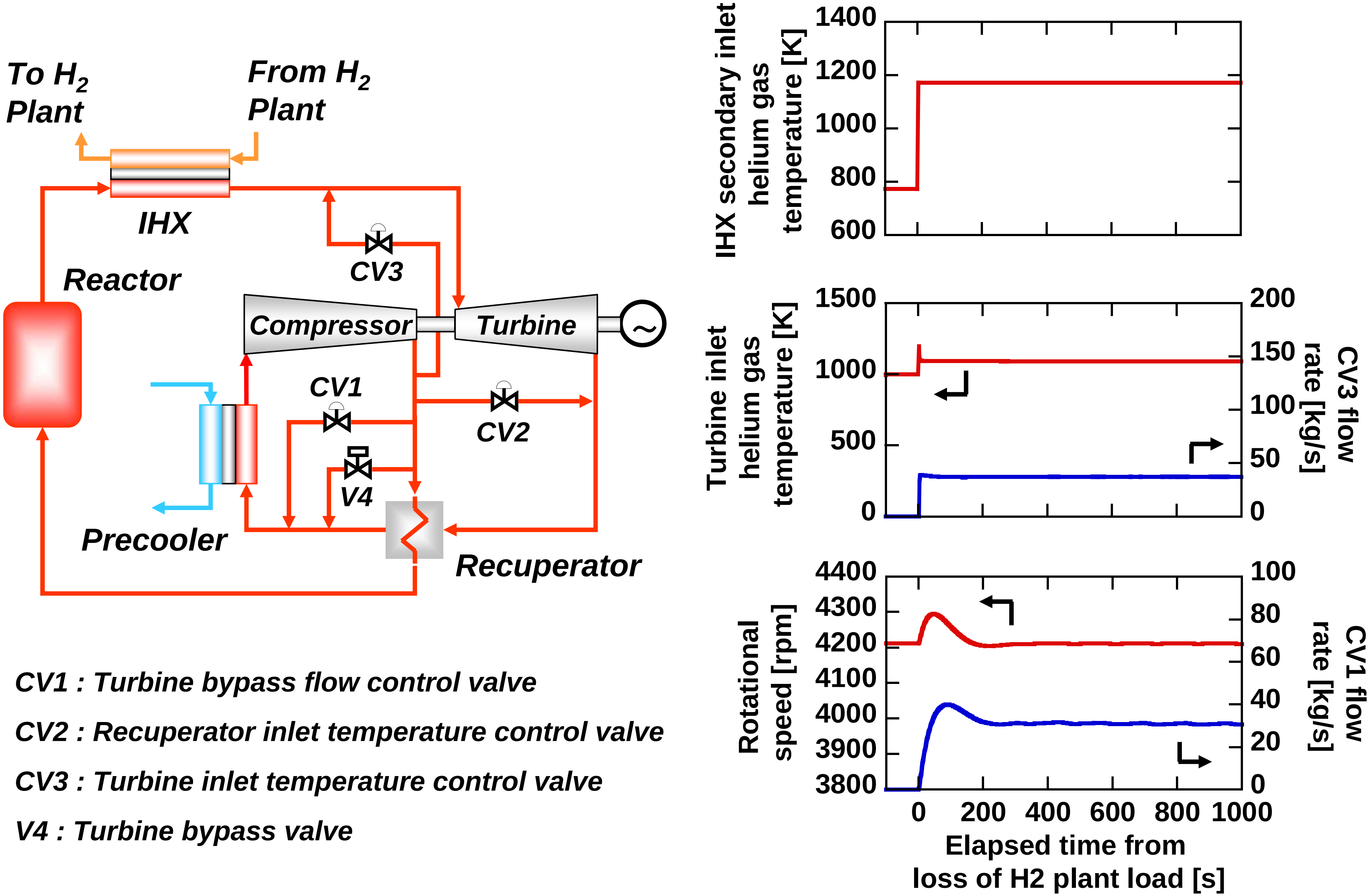
***P_i* : Turbine inlet pressure [MPa]**

***A_m* : Turbine inlet flow area [m2]**

***P_o* : Turbine outlet pressure [MPa]**

Dynamic Calculation (3/4)

- Loss of Thermal Load of H_2 Plant (370MW) in GTHTR300C -



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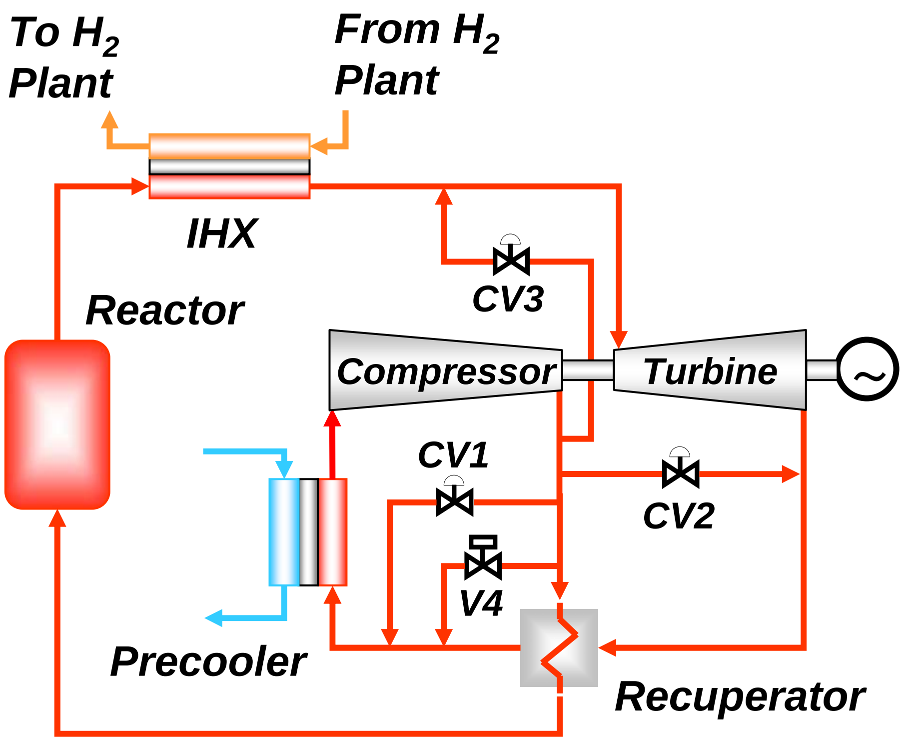
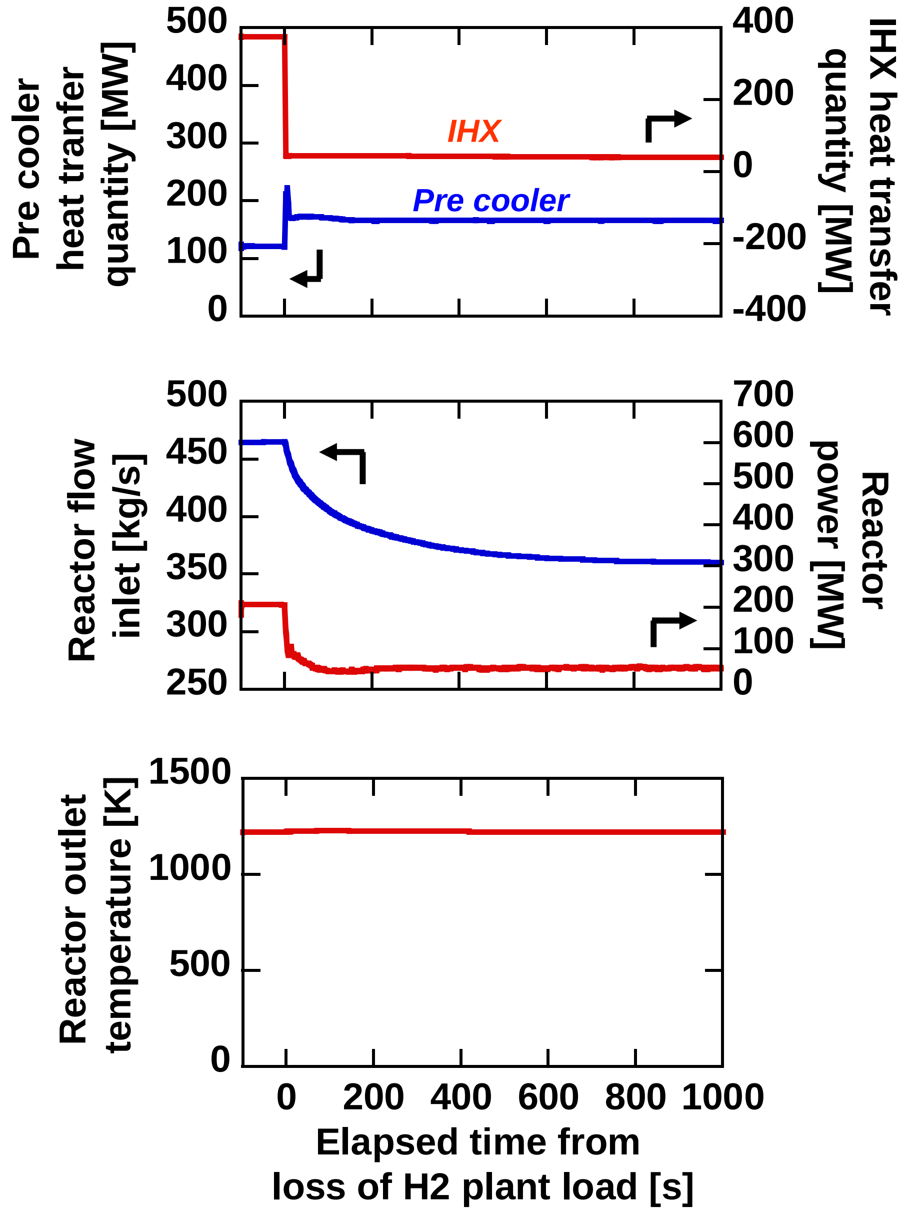
Dynamic Calculation (4/4)

- Loss of Thermal Load of H_2 Plant (370MW) in GTHTR300C -





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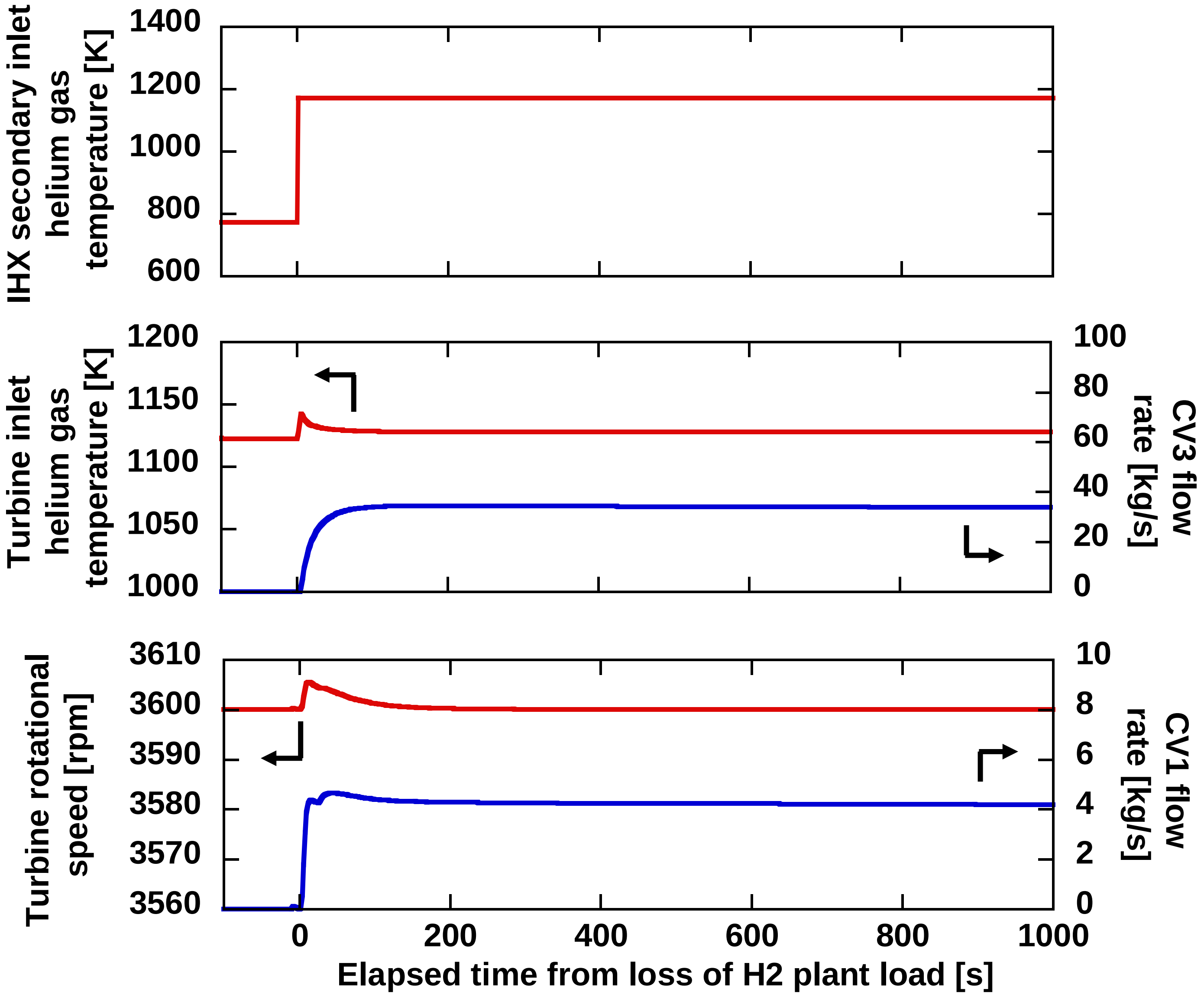


Thermal disturbance

IHX

2nd inlet

: +400 K

Turbine

Inlet

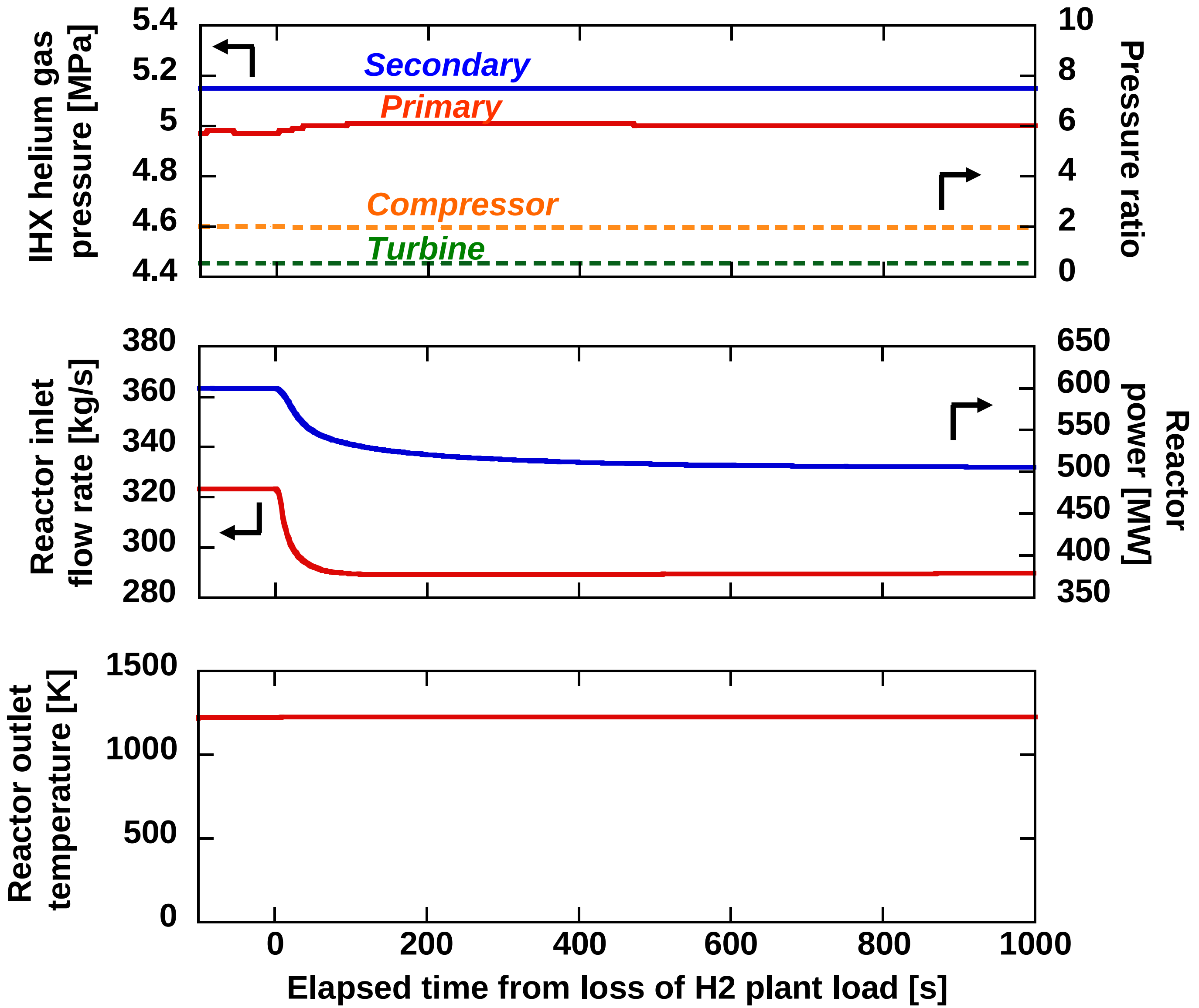
: +19.7 K

Turbine R.P.M. increase

: + 5 r.p.m.

Dynamic calculation (2/4)

- Loss of thermal load of H_2 Plant (170MW) in GTHTR300C -



IHX pressure difference

MAX

: +0.19 MPa

Reactor inlet flow rate variation

: -34.0 kg/s

Reactor power variation

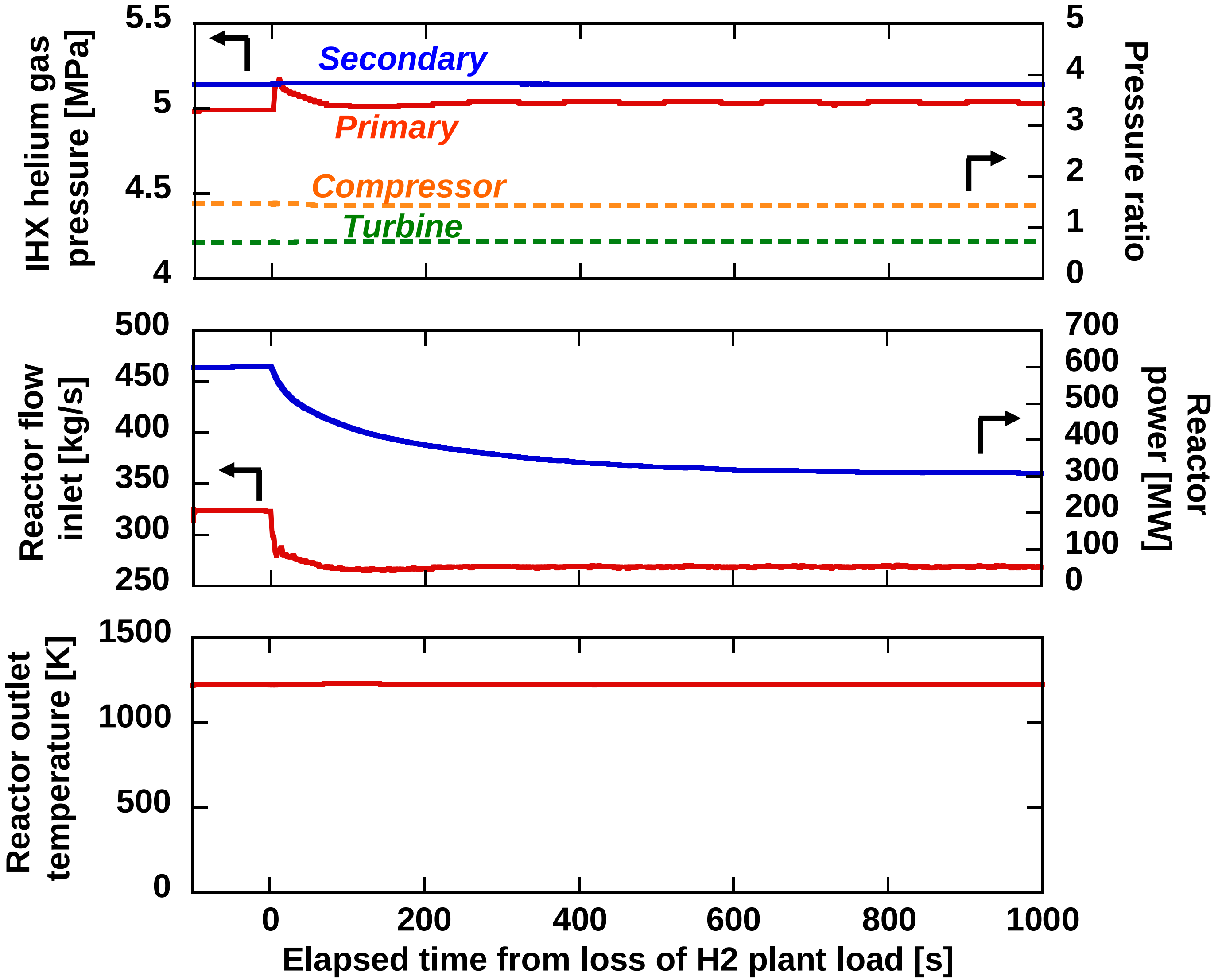
: -93.5 MW

Reactor outlet temperature

: Constant

Dynamic calculation (4/4)

- Loss of thermal load of H_2 Plant (370MW) in GTHTR300C -



IHX pressure difference

MAX

: +0.16 MPa

Reactor inlet flow rate variation

: -59.7 kg/s

Reactor power variation

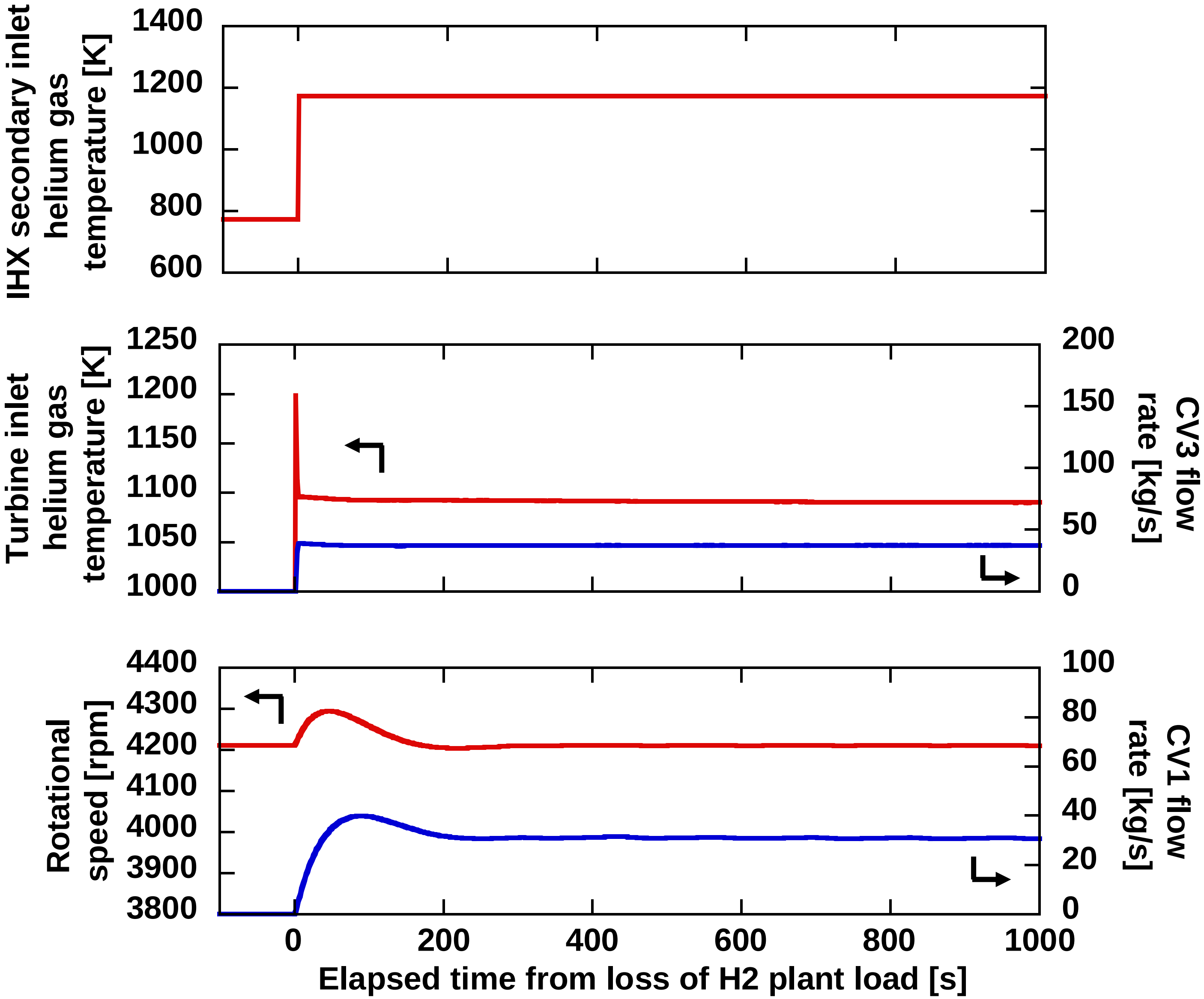
: -293 MW

Reactor outlet temperature

: Constant

Dynamic calculation (3/4)

- Loss of thermal load of H_2 Plant (370MW) in GTHTR300C -



Thermal disturbance

IHX

2nd inlet

: +400 K

Turbine

Inlet

: +201 K

Turbine R.P.M. increase

: + 90 r.p.m.