C1Or2B-03

Simulation of the cool-down process for the ESS cryogenic moderator system

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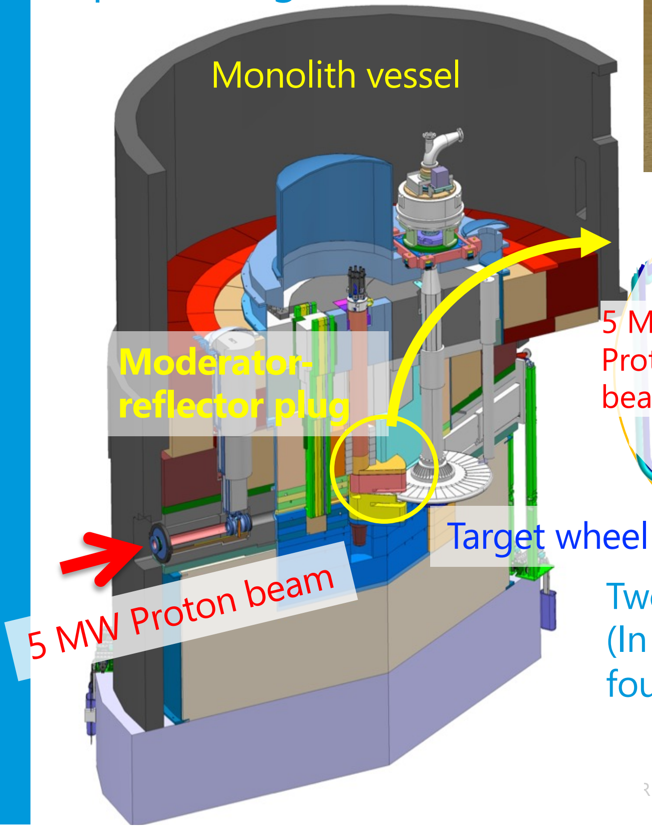
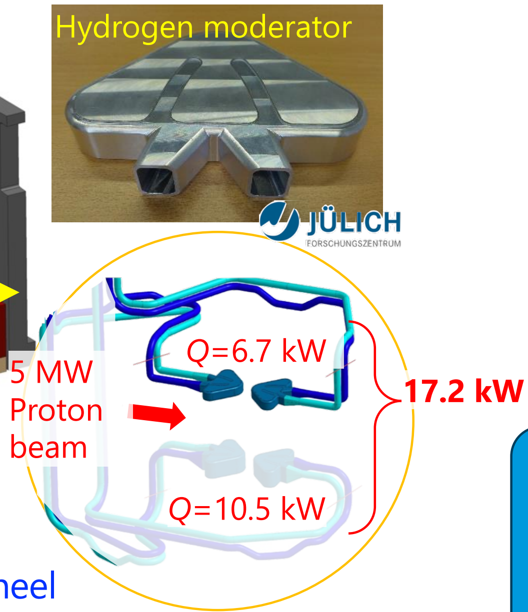
Introduction

ESS Spallation Neutron Source

5 MW proton beam (2.0 GeV proton, 62.5 mA)
- repetition of 14 Hz
- pulse length of 2.86 ms.)





Two hydrogen moderators (In the future, replaced by four moderators.)

- ESS hydrogen moderators

- Optimized to achieve a maximum brightness under the condition of pH_2 fraction of more than 99%.
- Average temperature rise at the moderator caused by the nuclear heating < 3 K.

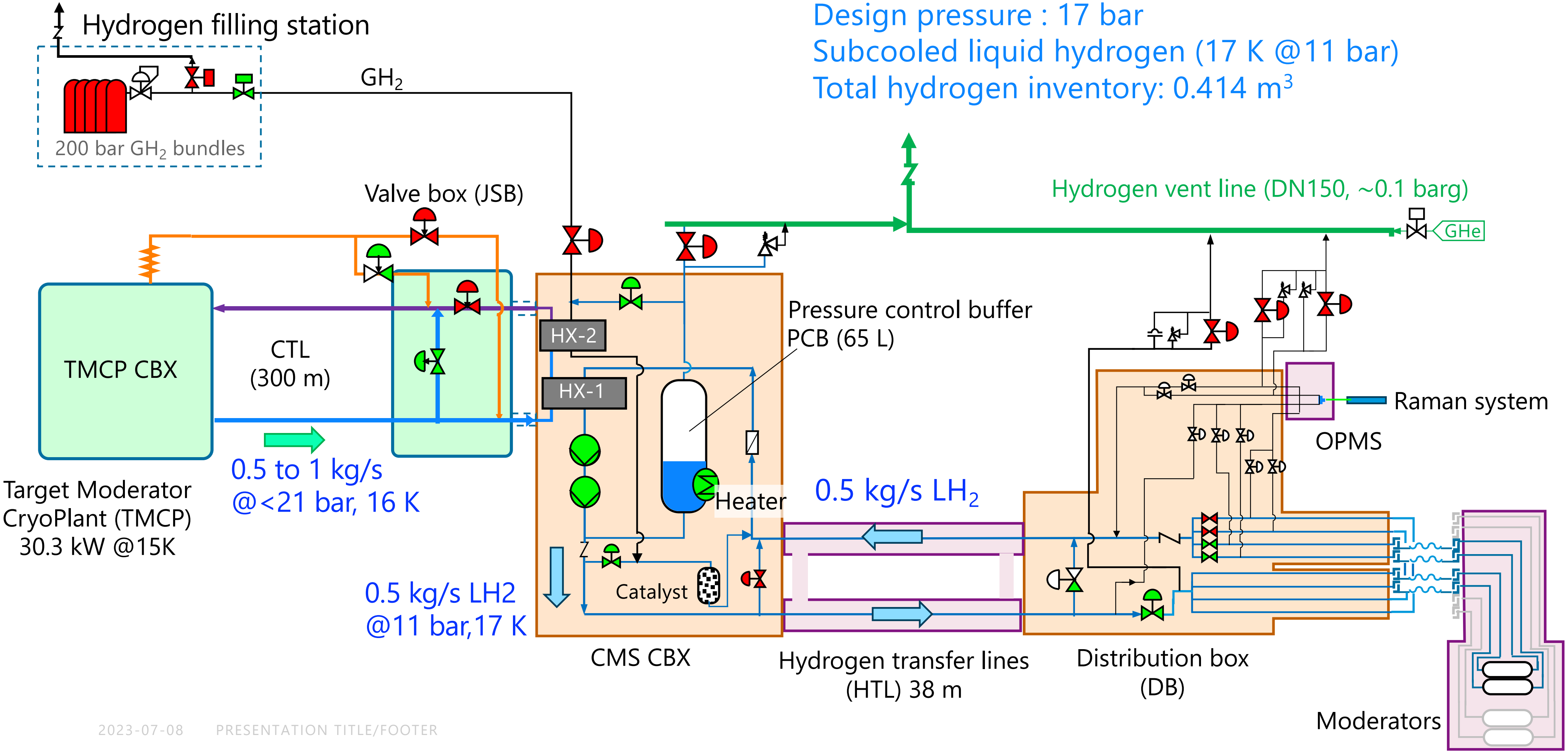
Cryogenic Moderator System (CMS)

- 17 K and 11 bar (Subcooled liquid hydrogen).
- Criculation flow rate of 1 kg/s
- Cooled by a 20 K-helium refrigerator (30.3 kW@15 K)
- Ortho/para hydrogen convertor (catalyst)

ESS Cryogenic Moderator System (CMS)

Overview

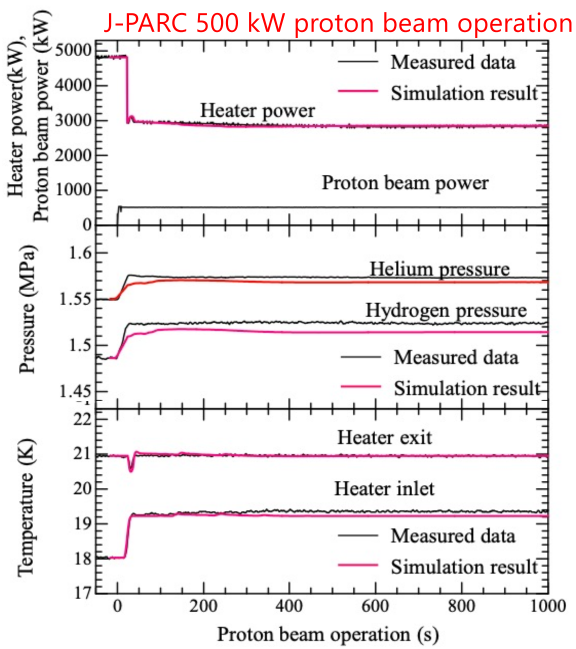
Design pressure : 17 bar
Subcooled liquid hydrogen (17 K @11 bar)
Total hydrogen inventory: 0.414 m^3



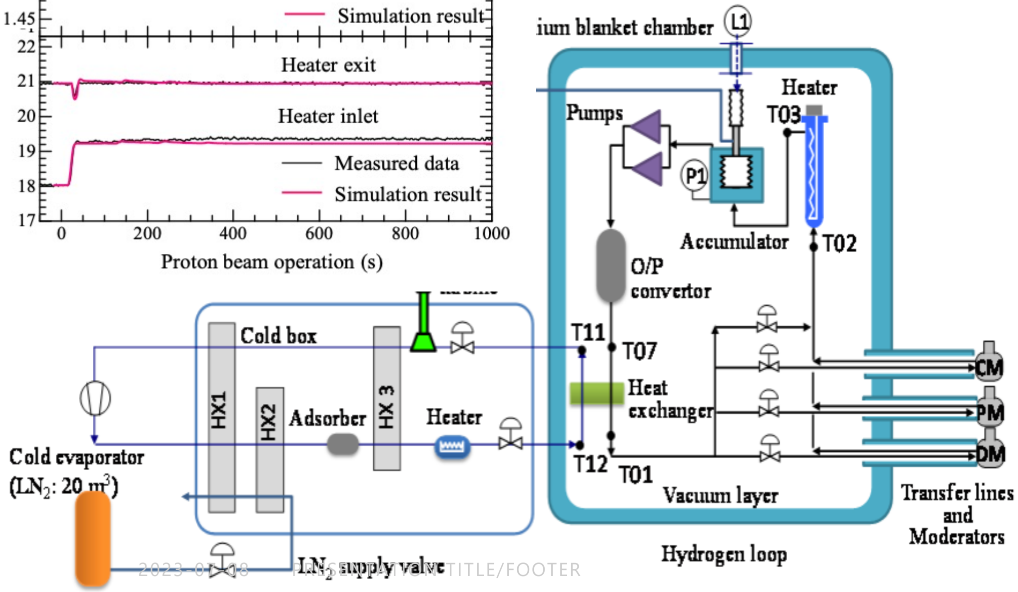
Development of a cooldown simulation code

Based on the simulation code for the J-PARC CMS.

J-PARC 500 kW proton beam operation



- We have already developed an one-dimensional simulation code to predict temperature and pressure behaviors of the J-PARC CMS (2015).
- The sumulation code had been validatated, compared with the CMS behaviors for 500 kW proton beam operation.



- Based on the code of the J-PARC, a simulation code that predicts the cooldown process of the ESS CMS has been developed.
- ESS CMS cool-down processes were analyzed.
  - Phase I: Gaseous state.
  - Phase II: Condensation state
  - Phase III: Liquid state.

Simulation model (1/4)

One-dimensional model

- Only the CMS loop is treated using a one-dimensional pipe (Divided into 903 grids.)
- Two bypass lines for the OP convertor in the CMS CBX and the moderators in the DB are modeled.

  -> Bypass flow rates were given by iteration until ΔP becomes equal.
- Two hydrogen pumps are treated as a combined pump in the model.

Procedure

- Outlet temperature of the Heat Exchanger (TE-01) was applied as a boundary condition.

  - Energy balance in each grid was calculated.

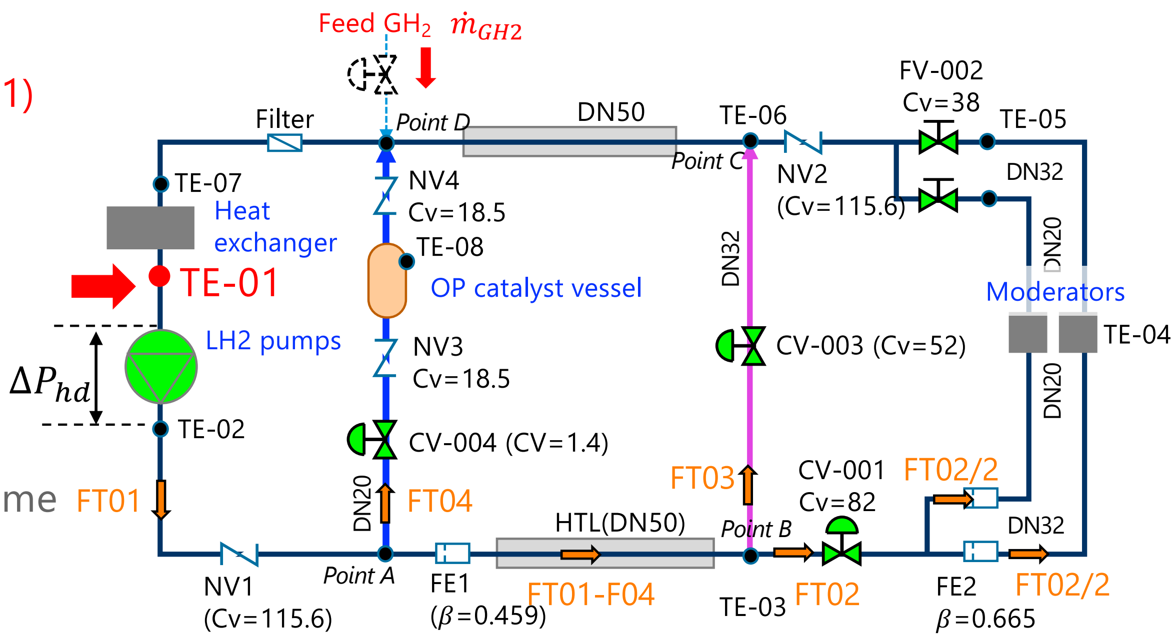
  - Flow rate: iterate approach

    Pump head (ΔP_{hd}) =Pressure drop (ΔP).

- Pressure was maintained at 1.1 MPa.

  Mass difference between previous and current time step means “supplied hydrogen” M-> $\frac{M}{\Delta t} = \dot{m}_{GH2}$

- Time step (Δt)= 5 ms.



Simulation model (2/4)

Combined hydrogen pump characteristics

- Ball-bearing type centrifugal pumps are arranged in series.
  - Closed impeller (Diameter, D, of 95.4 mm.)
  - Allowable revolution speed, N,: 1,000 to 14,000 rpm.

- Performance curve can be arranged using dimensionless expressions of a head coefficient, ψ, and a discharge coefficient, ϕ, using a wheel speed, $u_s = \pi N D/60$.

$$\psi = \frac{\Delta P}{\rho {u_S}^2} \qquad \phi = \frac{\dot{m}}{\rho u_S D^2}$$

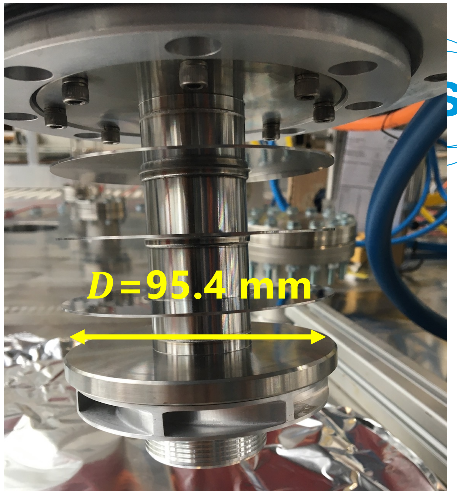
ΔP: Pump head

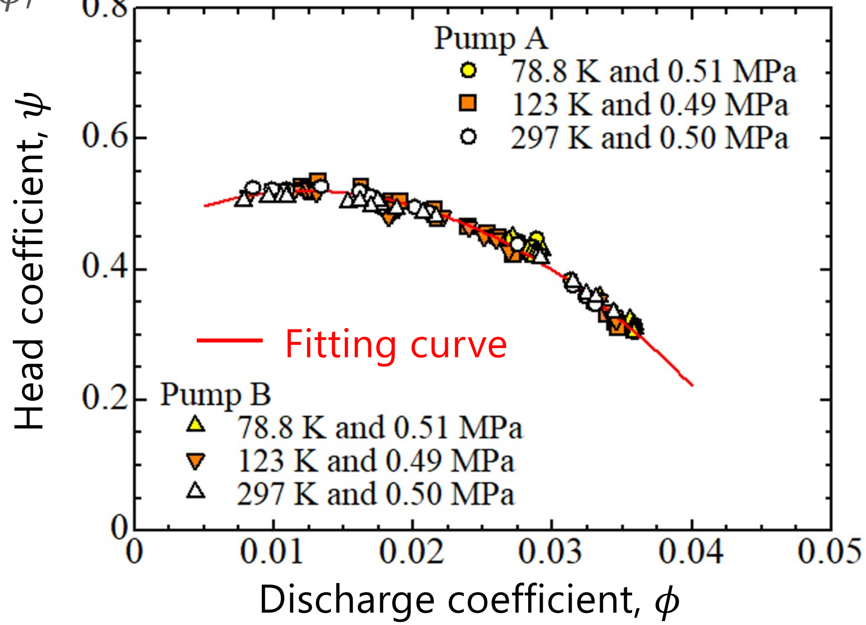
ρ: Density

- Pump performances were measured under the conditions of LN_2 at 78 K and GN_2 at 123 K and 297 K at the CMS CBX commissioning in 2020.

- Heat laod generated by the pump, Q_p, is calculated using an adiabatic efficiency, $\eta = 0.72$.

$$Q_p = \frac{\dot{m}\Delta P}{\rho \eta}$$





Simulation model (3/4)

Correlations (1/2)

- Enthalpy equation: Heat transport through the CMS loop.

$$\frac{\partial(\rho h)}{\partial t} = -\frac{\partial(\rho u h)}{\partial x} + \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + S$$

- Pressure drop calculations:

  (1) Pipe: Colebrook equation $\Delta P = f \frac{L}{d_H} \frac{\rho}{2} u^2$, $\frac{1}{\sqrt{f}} = -2log\left(\frac{\varepsilon}{3.7 d_H} + \frac{2.51}{Re\sqrt{f}}\right)$ Surface roughness, ε, =0.05 mm.

  (2) OP catalyst vessel: Eurgan equation $-\frac{\Delta P}{l} = 150 \frac{\left(1-\varepsilon_p\right)^2}{{\varepsilon_p}^3} \frac{\mu}{{d_p}^2} U + 1.75 \frac{\left(1-\varepsilon_p\right)}{{\varepsilon_p}^3} \frac{\rho}{d_p} U^2$

  (3) Equipment (filter, heat exchanger and moderator) using a CFD results and CMS CBX commissioning results.

  - In turbulent flow region, the pressure drop is proportional to $\dot{m}^2/\ \rho$.

$$\Delta P = F \frac{\dot{m}^2}{\rho}$$

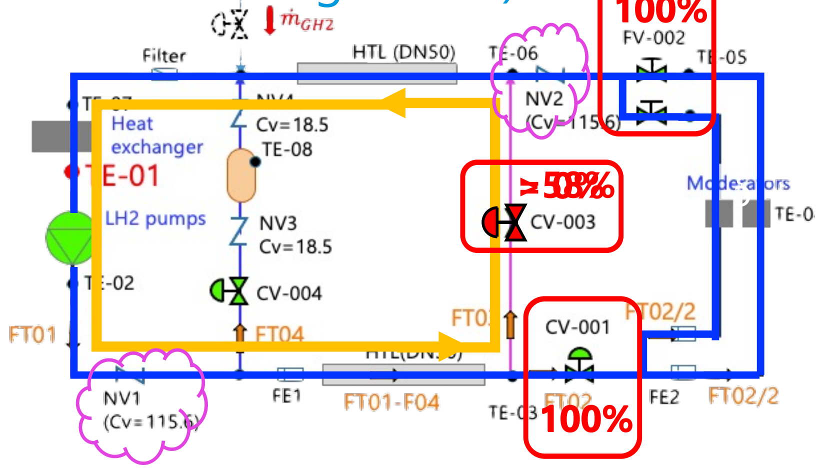
- Forced flow heat transfer: Dittus-Boelter correlation $Nu = 0.023 Re^{0.8} Pr^{0.4}$

Operational conditions

Study of the initial conditions (Pump revolution, Pressure and configuration)

- Maximum pump head at 14,000 rpm and 13 bar ~ 5.4 kPa

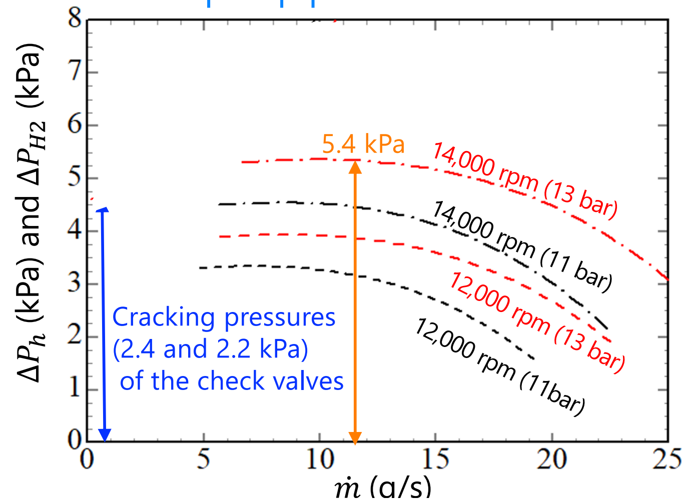
  - Pressure drop over the CMS loop is too high to circulate the hydrogen through the moderators due to the cracking pressure of the two check valves (4.6 kPa)



At the beginning of the cooldown process,

- Hydrogen should be circulated via the DB bypass line. No flow to the moderator due to the cracking pressure of NV2.
- Minimum position of CV-003 is 58% where the pressure drop is slightly lower than the pump head.
- Hydrogen will be able to start to flow into the moderators below 250 K.

Predicted LH2 pump performance curves at 300 K



Simulation results

Phase I (300 to 36 K), Cooling speed = 1.2 K/min

- Initial conditions

  Pump speed=13,000 rpm, CV-001= 60% and CV-003 = 58%

(1) Early stage of Phase I: Flow rate = 9.2 g/s via CV-003.

(2) At TE01=247 K, GH_2 begins to flow to the moderators.

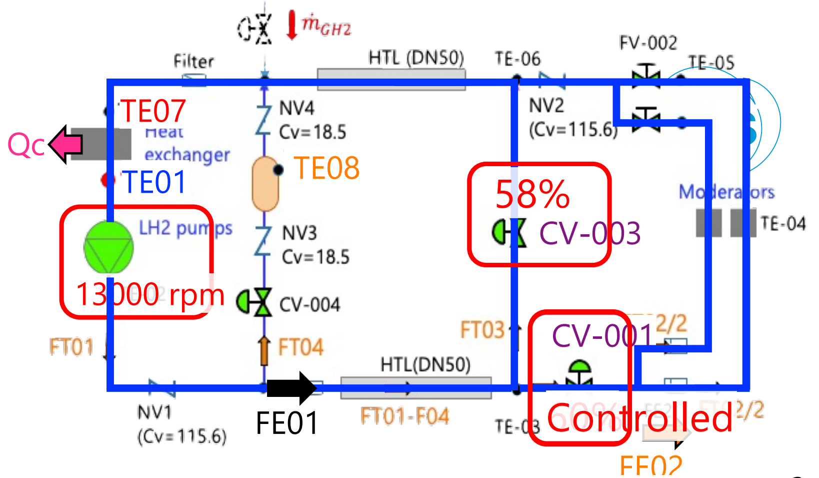
- Precooling process: Flow rate is controlled at 1 g/s by CV-001 (Low limit=4%)

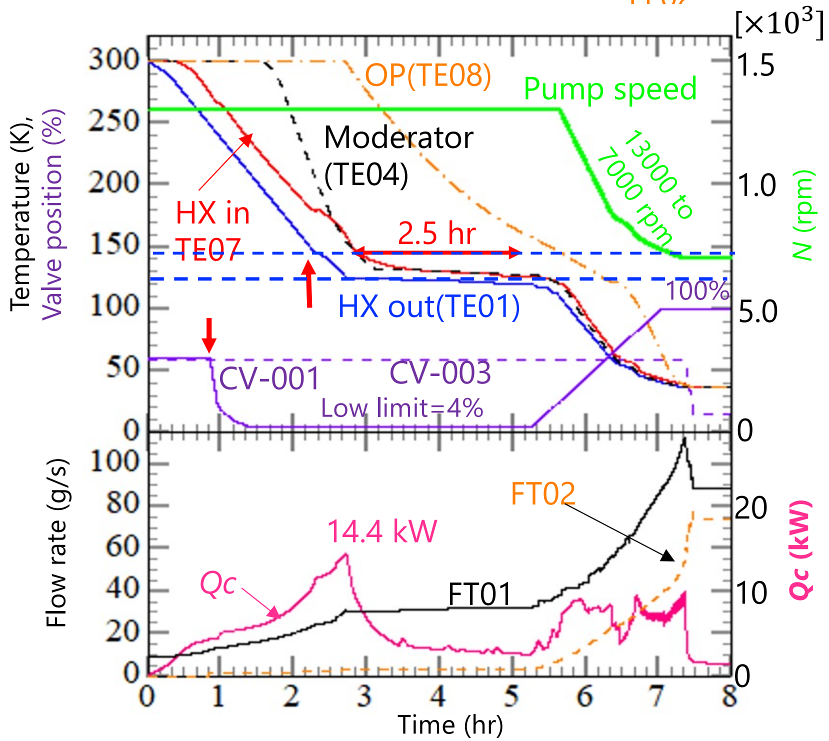
(3) At around TE01 =144 K, a holding function was activated because of ΔT_{HX} >35 K.

(4) At TE01 =125 K, TE01 should be maintained for 2.5 hours to complete the modetator precooling and the catalyst bypass precooling.

Required cooling power (Qc) is 14.4 kW, which is higher than the TMCP cooling power of 8 kW (CEC C3Po1B-05).

➡ *Cooling speed has to be slower.*





Simulation results

Phase I (300 to 36 K), **0.6 K/min**

- ○ Based on the preliminary calculation, the cooling speed was slowed to 0.6 K/min

- HX didn't exceed 35 K.

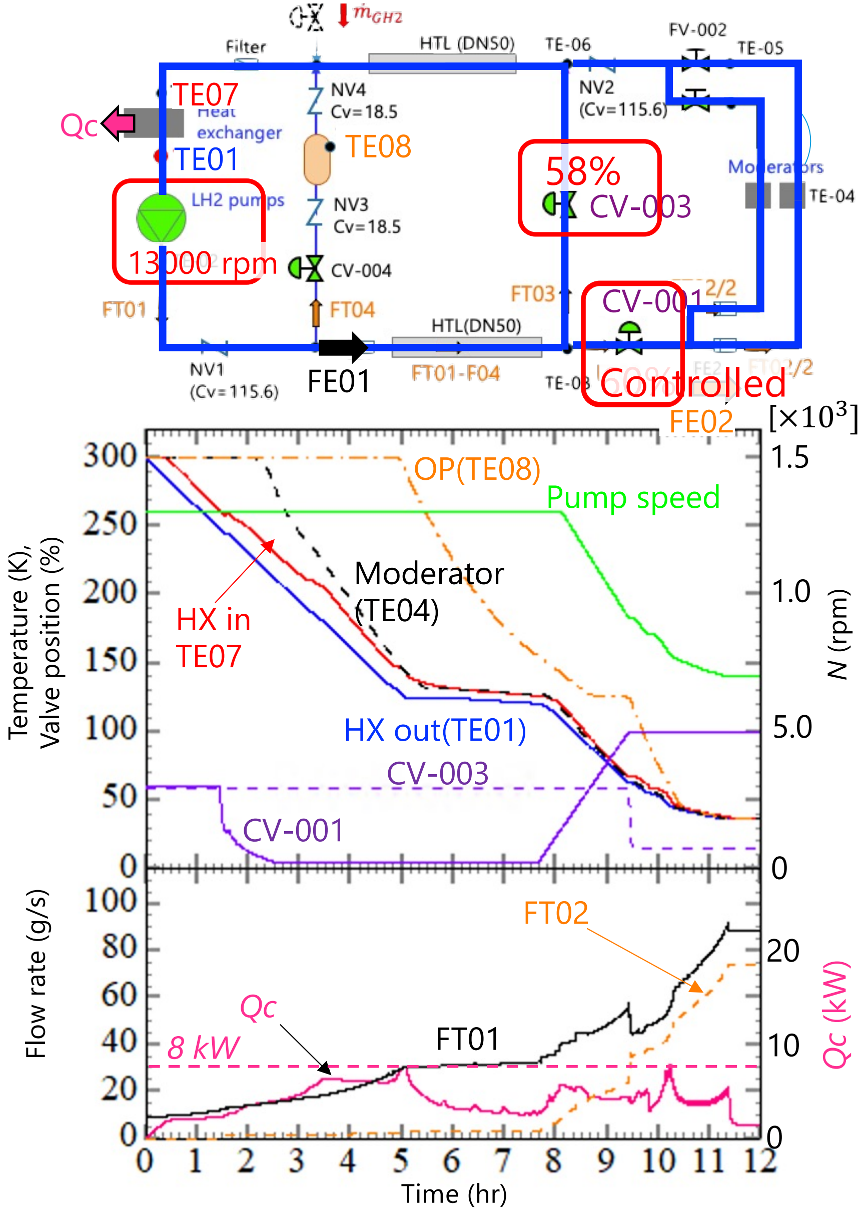
- ○TE01 was held at 125 K for 2.5 hours to complete the modetator precooling.

- ○ Required cooling power (*Qc*) can be maintained below the measured TMCP cooling power of 8 kW.

- ○ Final stage of the Phase I (36 K holding),

  - OP catalyst can be also cooled down to 36 K.

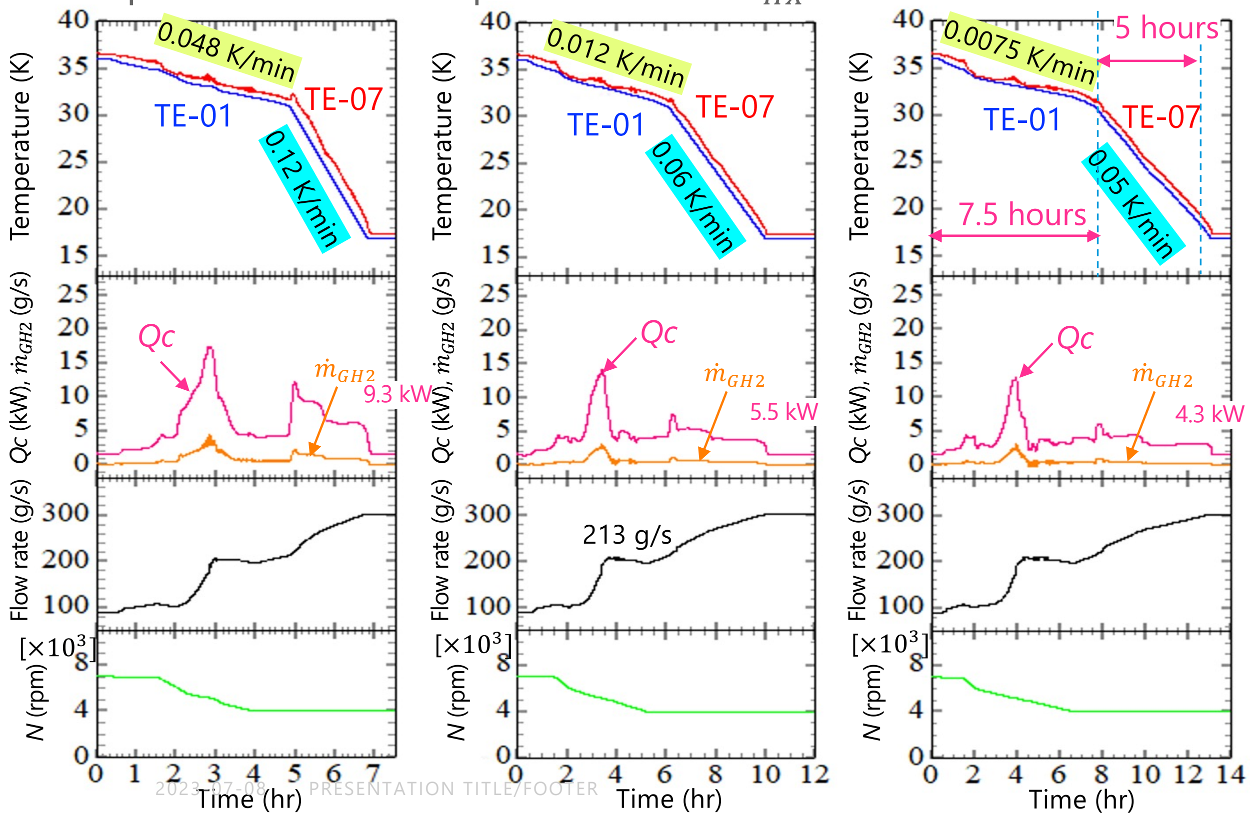
- ○ It takes 12 hours to complete PhaseI cooldown operaetion.



Simulation Results

Phase II (36 to 31K) & III (31 to 17 K)

- Discharge pressure of the hydrogen pump was temporarily increased to 1.35 MPa, which was higher than Pc (=1.29 MPa) to avoid forming two-phase flow in the pumps.
- Set point of TE-01 was paused while ΔT_{HX} > 0.7 K in Phase II and ΔT_{HX} > 4.0 K in Phase III.

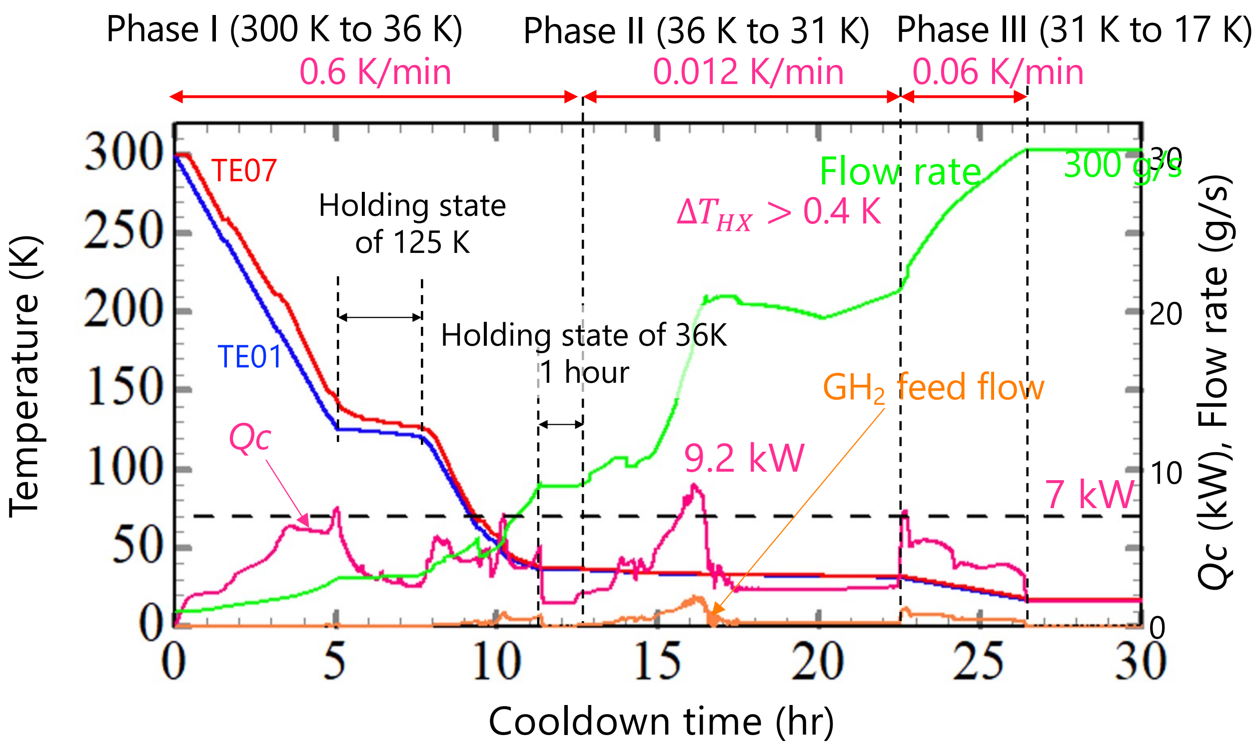


PHASE II	48 mK/min	12 mK/min	7.5 mK/min
Qc (kW) <17 kW	17.5	14.0	13.0
$\dot{m}_{GH2}$ (g/s) < 4.0	4.5	3.0	2.5
Time (hr)	4.8	6.2	7.5

PHASE III	0.12K/min	0.06 K/min	0.05 K/min
Qc (kW) < 17 kW	9.0 (12.5)	5.0 (7.0)	4.0 (6.0)
$\dot{m}_{GH2}$ (g/s) <4.0	2.5	1.0	0.5
Time (hr)	2.0	3.8	5

Simulation results

Optimized cooldown simulation results in Phase I to III.



- Filling the PCB tank up with 20 liter (=1.51 kg) of LH_2.

→ 63 minutes.

As a result of the simulation,

CMS can be cooled down to the nominal condition within 27 hours, which did not include the filling-up time for the PCB tank (1 hour).

Conclusions

- A one-dimensional cooldown process simulation code has been developed.
- Cooldown procedures and its optimum parameters have been studied.
- CMS cooldown process was divided into three phases (I: vapor state, II: condensation state and III: liquid state).
- At the beginning, the cooldown had no choice but to be implemented without the parallel moderator lines because the cracking pressure at the return line from the moderators was relatively larger than the pump head at around 300 K.
- The valves positions, pump speeds and cooldown speeds were optimized based on the simulation. It was verified that the CMS would be able to be cooled down to the nominal condition within 27 hours (28 hours).

Thank you.