Operational Experiences of J-PARC cryogenic hydrogen system for a spallation neutron source

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ABSTRACT

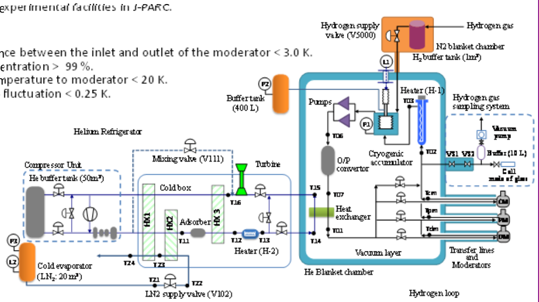
The Japan Proton Accelerator Research Complex (J-PARC) cryogenic hydrogen system was completed in April 2008. The proton beam power was gradually increased to 500 kW. A trial 600-kW proton beam operation was successfully completed in April 2015. We achieved long-lasting operation for more than three months. However, thus far, we encountered several problems such as unstable operation of the helium refrigerator because of some impurities, failure of a welded bellows of an accumulator, and hydrogen pump issues. Furthermore, the Great East Japan Earthquake was experienced during the cryogenic hydrogen system operation in March 2011. In this study, we describe the operation characteristics and our experiences with the J-PARC cryogenic hydrogen system.

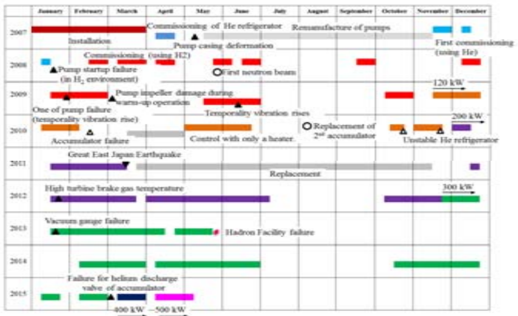
INTRODUCTION

Supercritical cryogenic hydrogen is selected as a moderator material in an intense spallation neutron source (JSNS), which is as one of main experimental facilities in J-PARC.

Design Conditions

- Temperature difference between the inlet and outlet of the moderator < 3.0 K.
- Para-hydrogen concentration > 99 %.
- Supply hydrogen temperature to moderator < 20 K.
- Supply temperature fluctuation < 0.25 K.





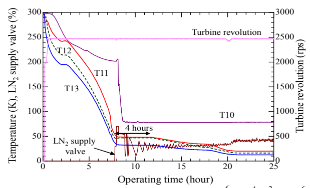
- Cryogenic hydrogen system was installed from August 2006 to March 2007.
  - The first cryogenic test with circulation of supercritical hydrogen was adjourned because of an unexpected issue with the hydrogen pump. However, the cryogenic hydrogen system was successfully cooled down to the rated condition within 19 h for the first time in March 2008.
- Toward the end of May 2008, we succeeded in generating the first cold neutron beam at JSNS.
- Proton power smoothly increased, although the J-PARC facilities were stopped for nine months because of the Great East Japan Earthquake in March 2011.
- Stable 500-kW proton beam operation has been conducted since April 2015. The plan is to increase the proton beam power toward our goal of 1-MW in 2016.

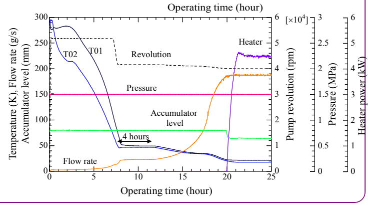
NORMAL OPERATION

- According to the J-PARC accelerator operation plan, we normally conduct cool-down operations thrice annually.
- J-PARC cryogenic hydrogen system can be operated almost automatically using an operational control approach, which comprises cool-down, beam injection, stand-by, warm-up, and quick hydrogen discharge modes.

Cool-down operation

- The hydrogen loop (P = 1.5 MPa) is cooled from ambient temperature to approximately 20 K by a He refrigerator.
- Initial pump speed is 52,000 rpm, and a hydrogen flow of a few g/s circulates approximately at room temperature.
- At 45 K, which is slightly higher than the pseudo-critical temperature, the cool-down operation is temporarily holed for 4 h to supply liquid nitrogen for precooling and to directly adjust the cooling rate using the heater.
- Cool-down operation is completed within 22 h, and the operation mode automatically transitions to the steady-state mode.





Standby mode

- During short maintenance periods of less than a week, we conduct the operation in the standby mode, whereby the helium refrigerator is operated without liquid nitrogen precooling so as to reduce liquid nitrogen consumption.
- LN_2 consumption: 7 m³ of liquid nitrogen to the cold evaporator thrice a week.

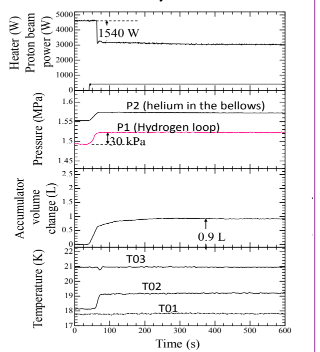
Beam injection mode

- **Accumulator with bellows and a heater to compensate for nuclear heating are used,** when the proton beam is switched off to maintain the pressure fluctuation because of switching on and off of the proton beam within the allowable limit of 0.1 MPa.
- **Heater control (Feedback + Feed-foward)**
  - **Feedback:** Heater exit temperature is always maintained at 20.95 K using a PI control. **Feed-forward:** After the proton beam is switched on, a certain temperature rise appears at the heater inlet (T02), and the heater power corresponding to nuclear heating is quickly reduced.
- Thermal balance at the heat exchanger remains virtually unchanged, and there is no fluctuation in the temperature of the hydrogen supplied to the moderators.

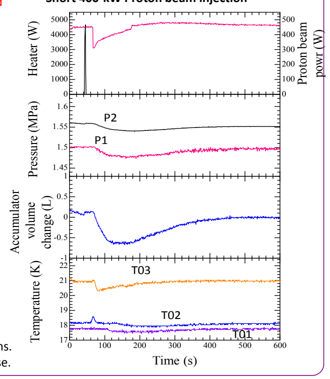
The feed-forward heater control approach is able to mitigate the pressure and temperature fluctuations and maintain a constant supply temperature.

- **When proton beam is injected with a fairly short time,**
- Execution of the feed-forward control when the proton beam is off fails because of lack of temperature reduction at T02.
- The temperature fluctuation propagates over the hydrogen loop and the pressure temporarily decreases to 20 kPa. The pressure fluctuation is continued until the temperature at T03 is adjusted to the set value of 20.95 K by feedback heater control.
- Thus far, in such a case, resumption of the proton beam operation had to wait until the fluctuations disappeared.
- In 2005, we improved the operational program to automatically avoid the stagnating problem.

400-kW Proton beam injection



Short 400-kW Proton beam injection



Warm up mode

- **Normal warm up**

After beam operation for user programs, all hydrogen is discharged through a ventline, whereas nitrogen and helium gas are always purged.

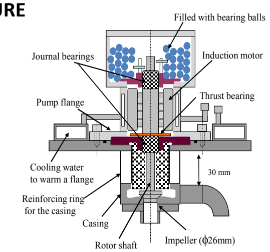
- **Hydrogen discharge mode**

If an off-normal event occurs, we quickly discharge hydrogen for safety reasons. Furthermore, we prepare "quick hydrogen discharge mode" for emergency use.

PROBLEM AND FAILURE

1. *Set-up failure of hydrogen pump*

- **Pumps could not be started in hydrogen environment (in 2007)**
  - because of motor overload, even after we had completed the cryogenic test in helium environment in November.
  - ***Cause:*** Increased static friction at the journal bearing and unstable gas membrane stiffness because of lower density and viscosity.
  - ***Measures:*** Attaching cutting oil on rotor shaft.



- **Unexpected temperature reduction in the pump flange region (in 2008),** during cool-down below 33 K.

The temperature in the flange region, which houses the journal bearings, a thrust bearing and an O-ring seal, was decreased to 250 K.

We were concerned about instability of the gas membrane, and hydrogen leakage because of degradation of the sealing performance.

- ***Cause:*** Unknown
- ***Measures:*** installation of a water channel on the casing flange to warm it using the cooling water for the pump induction motor.

Temperature around the flange could be maintained at approximately 291 K at the maximum adiabatic efficiency, although the heat loads increased by a few hundred watts.

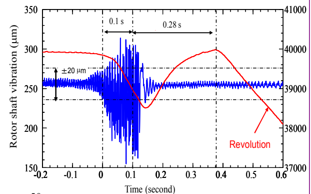
2. *Transient elevation of pump rotor shaft vibration*

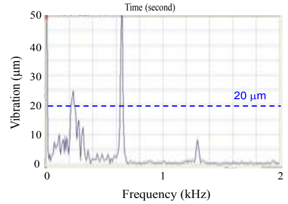
- **Tentative elevation in vibration was often encountered** for more than two weeks after the cool-down operation (in 2009).

Normal rotor shaft rotates = approximately 4 μm, which is always monitored by a fast Fourier transform (FFT) system.

- ***Cause:*** Unknown (Impurity?)
- ***Measures:*** We definitely clean the shaft several times using pressure swing of purified hydrogen gas before cool-down.

Accordingly, the phenomenon has never occurred since then, although the real cause remains unclear.

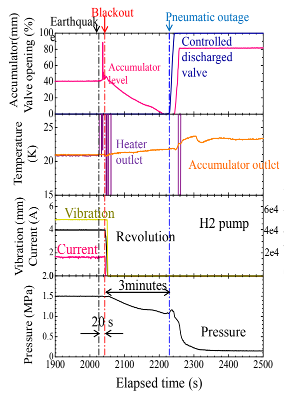


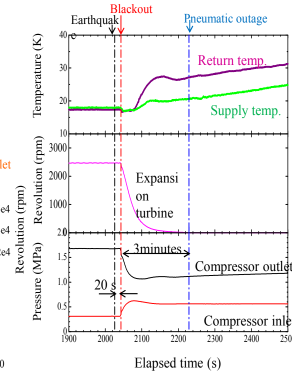


3. *Great East Japan Earthquake*

The Great East Japan Earthquake with a magnitude of 9.0 struck on March 11th, 2011, the cryogenic hydrogen system was operating at the rated condition.

- Blackout occurred after 20 s.
- Instrument air failed after 3 min because the air supply piping buried was broken.
- Facility building sank 1.5 m.
- Liquid nitrogen tank (20 m³)and the helium buffer tank (50 m³) were inclined by 0.84% and 2.14%.
- Part of the external supply piping were also bent because of sinking of the ground. However, there was no hydrogen leakage from the bent part.





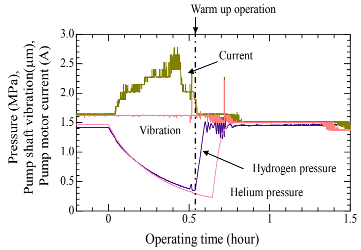
- We confirmed through the huge earthquake that the established interlock system met our performance requirements, although the earthquake caused extreme damage to the external instruments.

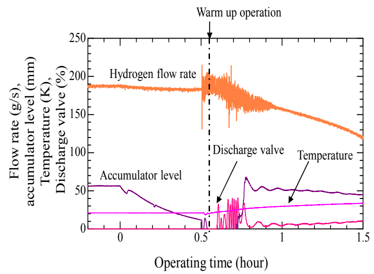
4. *Control valve malfunction*

- **Hydrogen pressure abruptly decreased from 1.5 MPa to 0.4 MPa for 30 min during cryogenic operation (in February 2015).**
  - **No hydrogen discharged through the vent valve,** because the inert gas pressure in the blanket chamber, where the vales and part of the vent line were housed, decreased slightly during the cryogenic hydrogen discharge.
  - **No hydrogen leak** because there was no pressure rises in the inert gas blanket chambers and the vacuum chamber, and there were no alarm signals from the hydrogen gas leak detectors.
  - Vibration and current of the pump increased suddenly at the hydrogen pressure of 0.4 MPa because of two-phase flow.
- **Cause:** Contraction of the bellows contraction because of the discharge of helium gas in them through the helium vent valve, which was installed in 2010 for protecting the bellows of the second accumulator as well as for protection against earthquakes, as mentioned above.
- **Measures:** Instrument air supply was cut off temporarily until the summer outage of 2015, when the electro-pneumatic positioner and the regulator will be exchanged.

It is still unknown why the valve opened abruptly although the opening was less than 0.1% of the total valve opening. The discharge valve has been unnecessary since December 2014 because it was exchanged for the third accumulator with a higher pressure tolerance of 2.0 MPa.

We were able to resume cryogenic operation 4 days after the failure in 2015.





CONCLUSIONS

Until now, we have considerable experiences and gained a lot of knowledge by facing several problems such as unstable operation of helium refrigerator because of impurities, leakage through the welded bellows of an accumulator, hydrogen pump impeller damage, and blackout and instrument air failure due to the Great East Japan Earthquake. We have confirmed through the problems that the cryogenic hydrogen system and its interlock system meet our design requirements.