Development of a partitionable accumulator with pressure-tolerance for the cryogenic hydrogen system at J-PARC

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ABSTRACT

A partitionable accumulator with pressure-tolerance has been developed to achieve a stable long-term operation for the J-PARC cryogenic hydrogen system. The accumulator has a bellows structure to spontaneously change the volume according to the pressure fluctuation, which is mainly caused by the proton beam operation. The developed accumulator had been installed in 2014 and uniformly expands and contracts with no hysteresis. It is confirmed through a 300-kW proton beam operation that the pressure rise agrees with the predicted value and becomes lower than that for the previous one. It is confirmed that the performance satisfies the requirements.

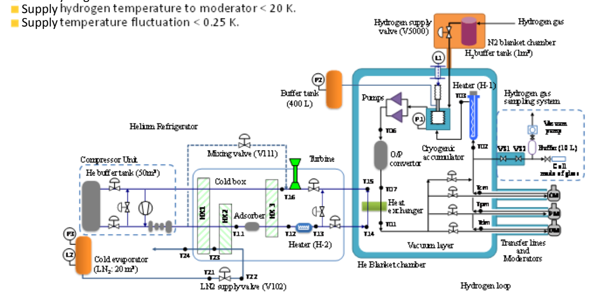
INTRODUCTION

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.

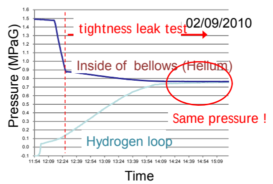
A cryogenic hydrogen system provides supercritical hydrogen with a temperature of below20 K and a pressure of 1.5 MPa to three moderators and absorbs a nuclear heating of 3.75 kW for a 1-MW proton beam operation.

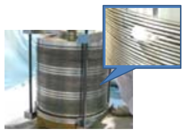
Design Conditions

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

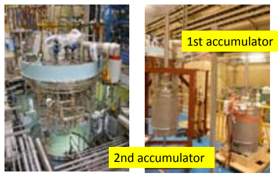


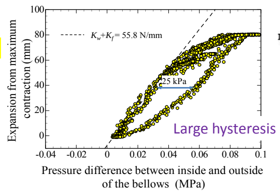
- In February 2010, we had a problem that a leakage between the inside and the outside of the welding bellows.
  - The research revealed that it was caused by a lack of the weld penetration between the bellows plates because the diameter of 520 mm was too large.

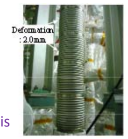




- In August 2010, we replaced the broken accumulator with the 2nd accumulator.
  - A tentative accumulator was designed to resume the proton beam operation.
  - Welding bellows diameter was needed to be decreased from 500 mm down to 330 mm to use the proven welding method, because further R&D was required in order to acquire the internal bellows with high pressure-tolerance and long cycle to fatigue if we use the large size bellows.
  - Design allowable pressure difference between the inside and the outside of the welding was 0.94 MPa, although it was 2.0 MPa for the previous faulty welding bellows.
  - It takes 40 days to replace it.





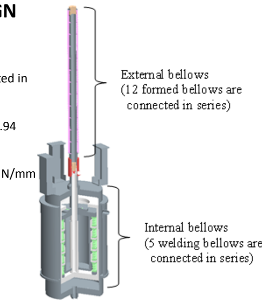


- Large hysteresis behavior.
  - It is concerned that it would bring about the reduction of number of cycles to failure.
- If a rupture disk goes off, the pressure difference of the operation pressure of 1.5 MPa would be applied to the welding bellows albeit briefly.

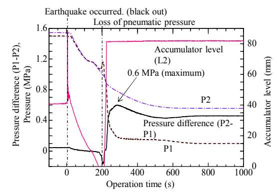
After the summer 2014, the proton beam power will plan to increase toward to our goal of 1-MW.
We have developed the third accumulator with high pressure-tolerance and long fatigue cycle to achieve a long-term stable operation. Further, a splittable structure is also adopted to replace it more easily and shorten the period of its replacement

TENTATIVE ACCUMULATOR DESIGN

- Accumulator has two kinds of bellows made of Stainless steel (SS316L);
  - Internal bellows (Inside :He, Outside: H2)
    - Five welding bellows blocks with the spring constant, k_w, of 200 N/mm are connected in series.
    - Diameter: 330 mm. Unrestricted length: 85 mm. Bellows plate thickness: 0.4 mm.
    - Allowable pressure difference between the inside and the outside of it, ΔP_w, was 0.94 MPa where the bellows cycle to failure is estimated to be 10^5 cycles.
  - External bellows (Inside :He, Outside: Vacuum)
    - It is assembled by twelve formed bellows block with the spring constant, k_f, of 189 N/mm
    - It is installed in the vacuum layer of the cold box.



- During the normal operation,
  the pressures in hydrogen loop, P_1, is around 1.5 MPa and the pressure difference, ΔP_w, is maintained below 0.1 MPa.
- When the Great East Japan Earthquake occurred in March 2011,
  the cryogenic hydrogen was automatically discharged due to blackout and loss of pneumatic pressure.
  - Pressure difference temporarily increased up to 0.6 MPa just behind discharging the hydrogen.



- There is a large hysteresis and the maximum ΔP_w is 25 kPa.
  - Although the design spring constant k_w was 200 N/mm, the actual one actually ranges from 256 to 719 N/mm because of its large hysteresis.
  - It was assumed that the second accumulator would not be uniformly in the stroke and the guide ring of the welding bellows would touch the support guide.
  - Further, it was observed that the formed bellows partially became deformed.
  - It was considered that this behavior would affect the decrease of the bellows cycle life and the increase of the spring constant.

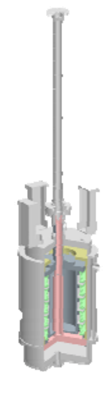
Reliable accumulator with high-pressure proof and long cycles to failure has to be developed to achieve stable long-term operation for the proton beam power of 1 MW.

DESIGN OFRELAIBLE ACCUMULATOR WITH HIGH-PRESSURE PROOF AND LONG CYCLES TO FAILTURE

Basic Design conditions

- The 3rd accumulator basically adopts the same structure and the same size as the 2nd one.
  - Variable volume = 6 L .
    - Variable volume of the bellows for the 1-MW proton beam operation = 2.0 L.
    - Variable margin for each operation status > ±2 L
  - Allowable pressure difference of the welding bellows = 2.0 MPa, which is the same as the design pressure of hydrogen loop.
    - When blackout and loss of pneumatic pressure simultaneously happened, ΔP_w, temporarily increased up to 0.6 MPa in March 2011.
    - If the hydrogen is rapidly discharged caused by a rupture disk going off, ΔP_w is assumed to temporarily increased up to 1.5 MPa.

    Accordingly, maximum pressure tolerance of the welding bellows is determined 2.0 MPa
    - Thickness of the welding bellows plates was increased from 0.4 mm to 0.8 mm.
      It is necessary to think of the effect of the spring constant on the pressure rise in the hydrogen loop.
  - Cycles to failure are :
    (1) > 10,000 cycles at a repetitive pressure variation of 2.0 MPa.
    (2) > 500,000 cycles at a repetitive pressure variation of 1.0 MPa.
  - Allowable pressure rise < 0.1 MPa
    - As measures against hydrogen safety, the hydrogen pressure should be kept below the pressure in helium refrigerator..
    - Pressure rise is also significantly affected by the bellows spring constant.
  - No hysteresis behavior in the stroke.
    - The number of the formed bellows is determined to be 13 blocks to reduce the displacement per block.
    - The number of the welding bellows is 5 blocks, as it is for the 2nd one.



$$mg - S_f\Delta P_f + S_w\Delta P_w = (K_w + K_f)\Delta x$$

m: net mass of the bellows
S: surface area
ΔP_f : differential pressure at the formed bellows
ΔP_w :differential pressure at the welding bellows
K : combined spring constant of the bellows
Δx : bellows displacement from the natural length.

Table 1 indicates the effects of the spring constant on the pressure rise for the 1-MW proton beam operation.

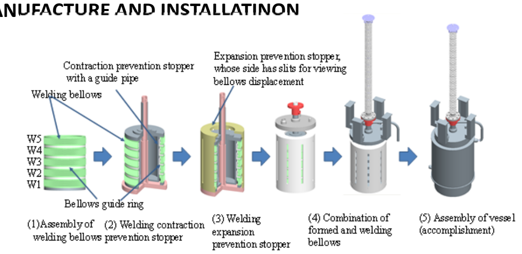
Pressure rise (kPa)	DP_w/DV (Pa/m³)	$K_f + K_w$ (N/mm)	K_f: 13 series (N/mm)	k_f (N/mm)	K_w: 5 series (N/mm)	k_w (N/mm)
100	3.70E+07	270.67	14.54	189	256.13	1280.65
80	2.50E+07	182.88			168.35	841.73
60	1.30E+07	95.10			80.56	402.81
50	8.00E+06	58.52			43.98	219.92

The spring constant of the welding bellows is determined to be less than 402 N/mm so as to mitigate the pressure rise below 60 kPa for the 1-MW proton beam operation.
for example, for the strokes corresponding to the volume changes of 6 and 7 L -> ΔP_w are 78 and 91 kPa, respectively.

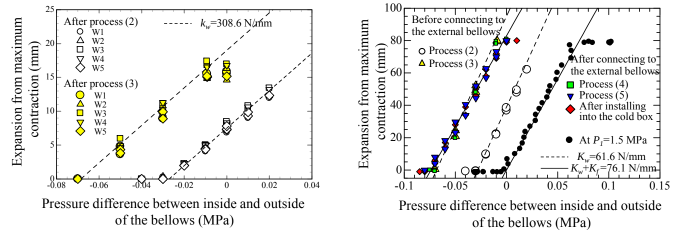
Structure

- When we replace the failure previous accumulator with the second one, we hoisted the top flange of the cold box of the hydrogen loop, because the accumulator size was too big to pass through the maintenance hatch of the cold box.
  - It took six weeks to finish the replacement and the restoration.
    - A partitionable structure between the external and the internal bellows is adopted to the 3rd accumulator using a reliable flange and a helicoflex seal in order to shorten the replacement period because there is not hydrogen but helium gas in the external bellows.

MANUFACTURE AND INSTALLATINON



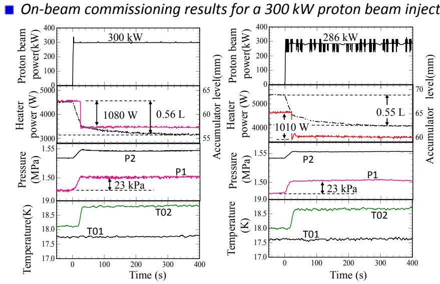
- The levelness accuracy of the assembly was kept within 1 degree to avoid the effect of the welding distortion and excessive contact with the guide ring and the guide pipe.



- All welding bellows have the same spring constant between the processes (2) and (3).
- It is confirmed that the welding bellows can expand and contract uniformly and smoothly in the stroke of 80 mm, which corresponds to the variable volume of 6.85 L, and the spring constant k_w is almost 308.7 N/mm, which can be reduced below the design value of 402.8 N/mm.

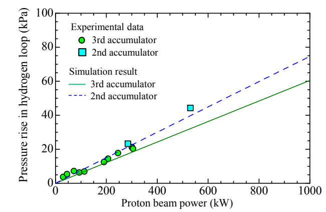
PERFORMANCE TEST RESULTS

- *On-beam commissioning results for a 300 kW proton beam injection*



- After the proton beam injection, the accumulator spontaneously contracts with increase in the pressure.
- There are no changes of the temperature and the pressure fluctuations after the onset of the heater control.
- The pressure rise is exactly similar to that for the 2nd accumulator for the beam power of 286 kW, although the spring constant for the 3rd accumulator is higher than that for the 2nd one.
  - This is because the actual spring constant for the 2nd accumulator was larger than the design value in the operating ranges due to the large hysteresis.

- *Effect of the proton beam power on the pressure rise*
  - The pressure rise increases in proportional to the proton beam power and agrees well with that predicted by the analytical model.
  - It appears that the pressure rise can be reduced by being exchanged for the 3rd accumulator and would be 60 kPa for the 1MW proton beam operation just as designed.
  - It is confirmed through the commissioning that the developed accumulator satisfied the requirement.



CONCLUSIONS

A partitionable accumulator with high pressure tolerance and long cycle to failure has been developed to achieve long-term stable operation with the proton beam power of 1-MW.

- The spring constant of the welding bellows increased to 308.7 N/mm by increasing the thickness of the bellows plates from 0.4 to 0.8 mm.
- The smooth expansion and the contraction of the accumulator can be achieved without hysteresis to keep the levelness of the assembly below 1-dgree.
- It was confirmed through on-beam commissioning with the beam power of 300 kW that the pressure rise agreed with the design value and became lower than that for the second accumulator.
- It is confirmed that the developed accumulator satisfies the requirements.