STUDY ON SUDDEN LOSS OF CRYOGENIC COOLANT ACCIDENT HAPPENED IN THE HYDROGEN ISOTOPE SEPARATION SYSTEM FOR FUSION REACTOR

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Abstract

Sudden loss of cryogenic helium coolant accident (ISS-LOCA) in the cryogenic distillation columns for the hydrogen isotope separation system (ISS) is one of the worst situations because it leads the evaporation of liquid hydrogen in the column. From this background, an intended ISS-LOCA test was conducted with an actual ITER-scale cryogenic distillation column. Sudden increase of internal pressure was not observed and enough time is found to recover the hydrogen isotope into a storage system if vacuum insulation is maintained and reboiler heaters are turned off immediately. In off-normal conditions, the rapid recovery of hydrogen in the column by an empty hydrogen storage bed is a reasonable hydrogen recovery scenario. Validity of the hydrogen recovery scenario was proved by a demonstration test.

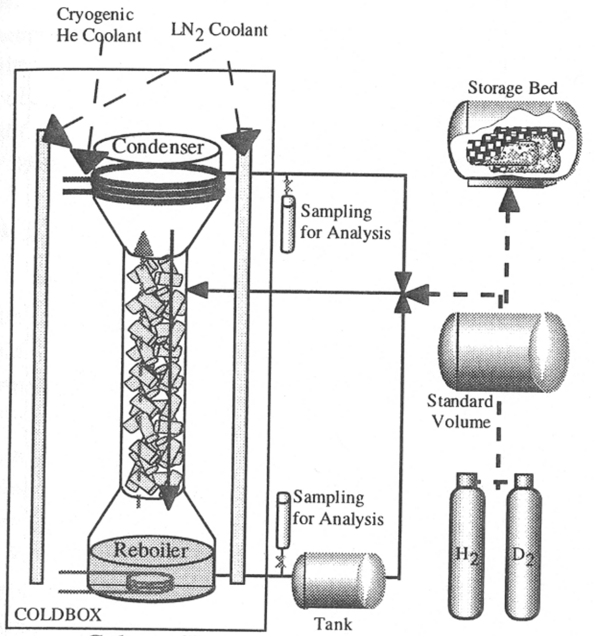
Ⅰ. Introduction

In the fuel cycle system of the ITER[1], a fusion experimental reactor under planning internationally, a large fraction of the tritium inventory is expected in the cryogenic distillation columns for the hydrogen isotope separation system (ISS). Tritium inventory in the ISS is much larger than other sub-systems in the fuel cycle system because hydrogen isotope is held mainly as liquid in it. The tritium inventory in the ISS was reported as 230g in ITER Final Design Report[2]. Therefore the potential hazard is pointed in case off-normal event in operating ISS. Sudden loss of coolant accident (ISS-LOCA) is one of the worst situations. As a matter of course, the ISS has rupture disks and recovery tank as its safety device prescribed in the regulation to the sudden overpressure. The hydrogen isotopes in the ISS can be safely recovered to the recovery tank through rapture disk in case of overpressure. However, there is no systematic data concerning pressure and temperature behavior in case of ISS-LOCA. These systematic data are essential for the design of ISS considering the possibility of accident. From this background, an intended ISS-LOCA test was conducted using an actual ITER scale of cryogenic distillation column at the Tritium Systems Test Assembly (TSTA) in the Los Alamos National Laboratory (LANL) under the US-Japan collaboration on tritium safety engineering. In an off-normal event, rapid recovery of hydrogen during the emergency shutdown has to be considered. The validity of hydrogen recovery by hydrogen storage bed was demonstrated in the ISS-LOCA test.

Ⅱ. Experiments

A. The Preliminary Runs for Grasping the Holdup Distribution in the Column

The grasping of holdup distribution in the column is essential to understand the off-normal behavior in ISS-LOCA. The numerical inventory estimation method has been investigated at the Tritium Engineering Laboratory (TPL) in the Japan Atomic Energy Research Institute (JAERI). Our former investigation made clear that each hydrogen isotope inventory in an ITER-scaled cryogenic distillation column could be estimated by the proposed numerical estimation method with engineering precision[3]. In this study, the advanced method was applied to grasp the hydrogen holdup distribution in the column. Two preliminary runs were carried out to check the validity of the numerical estimation by using about 80 theoretical stages of cryogenic distillation Column H at the TSTA in the LANL. **Figure 1** shows the schematics diagram of the experimental apparatus. The specifications of Column H and related apparatus are listed in **Table 1**. The amount of 157.5NL each of H_2 and D_2 was loaded into the column. The amount and composition of hydrogen isotope was confirmed in the standard volume by a combination of Pressure-Volume-Temperature measurements involving the standard volume and Mass Spectrometry. The gas was then



Column H

Figure 1 Schematics diagram of the experimental apparatus.

Table 1 Specification of Column H and related apparatus

Name			Unit	
Column H	Inner diameter		mm	19.3
	Packed Height		m	4.06
	Volume	Condenser	$m^3 \times 10^{-4}$	17
		Packed Section	$m^3 \times 10^{-4}$	11.34
		Reboiler	$m^3 \times 10^{-4}$	5
	Feed Position from bottom of the column		m	1.25
	Packed material			Heli-Pak(SUS-316) 4.4×4.4×2.3mm
	Reboiler Power			100W@115Volts
Standard Volume	Volume		Liter	265
Ubed	Capacity (UH3)		mol	37.8
	Amount of Uranium (U-238)		g	6000

loaded into the column. The column parameters were set and the column was allowed to reach steady state. All measurable parameters such as column temperature, column pressure, column differential pressure, reboiler heat, helium refrigerator temperature, flowrates of feed and products, liquid level and compositions at all locations were recorded. The runs were repeated for two column conditions to obtain the different hydrogen distribution profiles in the column. **Table 2** shows the summary of loaded amount of hydrogen isotopes, column conditions and observed liquid level at steady state.

B. Intended ISS-LOCA Experiment

After the preliminary runs were finished, the intended ISS-LOCA experiment was conducted. The parameters just before the experiment are as follows. The column temperatures of top and bottom were 21.4K and 23.5K. The column differential pressure was 302.6Pa. The power of reboiler heater was 18.0 watts. The flow rates of feed, top and bottom were 8.04 mol/h, 2.68 mol/h and 5.36 mol/h, respectively. The operating pressure was 108.6 kPa. The liquid level was 41.4mm. The parameters were automatically recorded at six-second intervals into a data logger during this experiment. After making the time, helium refrigerator was turned off and reboiler heater was also turned off to estimate the heat flux into the column. When the pressure reached 214 kPa, the valve to the standard volume was opened and the gas in column was allowed to fill the standard volume for the safety reason. Finally, to confirm the effect of reboiler heater power on the column behavior in off-normal situation, reboiler heater was turned on again (about 45 W).

C. Rapid Dump Test onto a Hydrogen Storage Bed

The data on how rapidly the gas in columns can be recovered to the empty hydrogen storage bed in an off-normal event are also important for ISS safety operation. The rapid dump test onto a hydrogen storage bed was conducted to check the validity of this scenario in off-normal conditions.

After the ISS-LOCA experiment, the gas was transferred to the standard volume. The standard volume in which the known volume of gas was filled was isolated to get the recovery data of this gas onto an empty Uranium bed (Ubed). The valve to the Ubed was opened and the data of pressure of standard volume and temperature of the Ubed were

Table2 List of loaded amount into Colume H and Operation Conditions

	Uint	Run1	Run2
H Holdup	[NL]	157.5	157.5
D Holdup	[NL]	157.5	157.5
Top Flow Rate	[mol/h]	2.68	2.68
Bottom Flow Rate	[mol/h]	2.68	5.36
Pressure inside Column	[torr]	106.9	109.7
Reboiler Output	[W]	10.7	18.0
Liquid Level	[mm]	54.00	41.00
Reflux Ratio	[-]	17.0	29.0

automatically recorded at six-second intervals into data logger during this recovery.

Ⅲ. Results and Discussions

A. The Preliminary Runs for Grasping the Holdup Distribution in the Column

The holdup in the column was evaluated by measuring indirect parameters such as temperatures, pressure, flow rates of feed and product streams and compositions of feed and product streams.

The procedures are as follows. First, the hydrogen distribution profile in a column was estimated by the numerical code[4]. The code can describe the isotopic distribution profile in each theoretical stage. First of all, agreement of hydrogen isotopic distribution profile calculated with experimental results was checked. The value of 0.05m for the height equivalent to a theoretical plate (H.E.T.P.) was adopted in this study.

Secondly, the total inventory in a column was estimated to divide it into three sections that are the reboiler section, the packed section, and the condenser section. The equations for the hydrogen holdup evaluation are shown in **Figure 2**. As for the liquid inventory in packed section, the liquid holdup ratio of the packed section (ε_j) can be expressed as follows.

$$\varepsilon_j = \sum_{i=1}^{6} x_{j,i}\,\gamma_{i,s_j} \qquad (1)$$

The liquid holdup ratio of each isotopic species (γ_i) is a function of the superficial velocity (s_j). There is no data for HD, HT, DT and T_2 so that these data are estimated using the data for H_2 and D_2 by the correlation among liquid holdup ratio, Froude number and Reynolds number [5 6].

$$\gamma_{i,s_j} = \alpha_i\,\gamma_{1,s_j} + (1-\alpha_i)\,\gamma_{4,s_j} \qquad (i = 2,3,5,6) \qquad (2)$$

The liquid holdup ratios of the packed section as function of the superficial velocity adopted in this study are shown in **Figure 3**.

Table 3 shows the estimated holdup distribution in column H for Run 2. The amount of H equals the sum of the amount of H_2 and the half amount of HD. The total estimated holdup is consistent with the total amount of hydrogen isotopes loaded in the column. A larger difference between the estimated and loaded values was observed for H in comparison with that for D. Judging from our R&D results concerning the liquid holdup in packed section [3], the liquid holdup ratio for H_2 is dependent on the column geometry. The species with smaller weight density such as H_2 would be lifted more in the packed section by gas stream and the state of liquid dripping in packed section would have a tendency to effect the arrangement of packing.

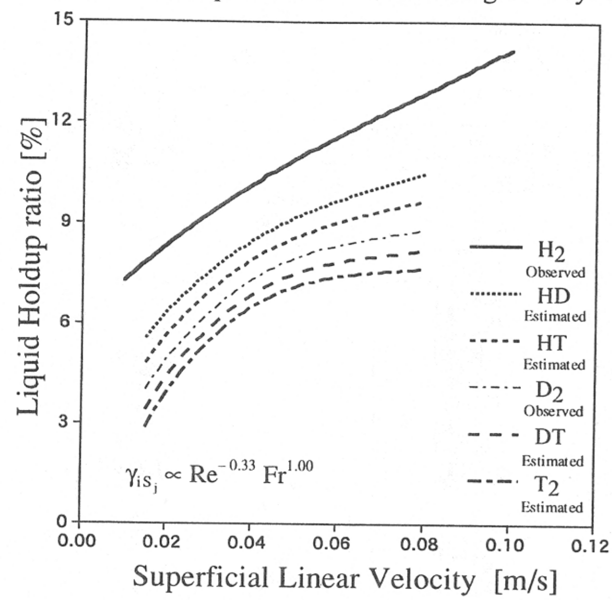


Figure 3 Liquid holdup ratio of the packed section as function of the superficial linear velocity

Table3 Evaluated Hydrogen Holdup in Column H (Run 2)

		H [NL]	D [NL]
Phase	Measured Total	157.50	157.50
Liquid	Condenser	19.23	0.14
	Packed Section	100.49	77.22
	Reboiler	17.36	34.32
Gas	Condenser	26.21	0.12
	Packed Section	28.34	22.51
	Reboiler	4.99	7.87
	Piping, etc.	4.60	8.81
	Estimated Total	201.23	151.00
	Difference [%]	27.76	-4.13

Table 4 summarizes the comparison of the total estimated holdup with the loaded amount of hydrogen isotopes. As seen in this table, it can be concluded that both estimated amounts of D_2 for Run 1 and Run 2 agreed well with the loaded amount under different column conditions. As for the H, some extent of disagreement was observed again. This disagreement was mainly caused by the same reasons discussed above. The tendency that the liquid holdup ratio for H_2 is more influential in column geometry than that for D_2

$$H_{te} = H_{VC} + H_{VP} + H_{VR} + H_{LC} + H_{LP} + H_{LR}$$

Condenser

Gas Phase (H_{VC})

$$H_{VC} = \sum_{i=1}^{6} \frac{P_1 V_1 (1-\varepsilon_1)}{R T_1} y_{1,i}$$

Liquid Phase (H_{LC})

$$H_{LC} = \frac{V_1 \varepsilon_1}{\sum_{i=1}^{6} x_{1,i}\, v_{1,i}}$$

Packed Section

Gas Phase (H_{VP})

$$H_{VP} = \sum_{j=2}^{N-1}\sum_{i=1}^{6} \frac{P_j V (1-\varepsilon_j-\varepsilon)}{R T_j} y_{j,i}$$

Liquid Phase (H_{LP})

$$H_{LP} = \sum_{j=2}^{N-1} \frac{V \varepsilon_j}{\sum_{i=1}^{6} x_{j,i}\, v_{j,i}}$$

Reboiler

Gas Phase (H_{VR})

$$H_{VR} = \sum_{i=1}^{6} \frac{P_N (V_N - V_{LN})}{R T_N} y_{N,i}$$

Liquid Phase (H_{LR})

$$H_{LR} = \frac{V_{LN}}{\sum_{i=1}^{6} x_{N,i}\, v_{N,i}}$$

Figure 2 Equations for hydrogen holdup evaluation was observed by the experiment. The important facts are 1) the precision of this estimation method is almost independent of the composition profile in a column, and 2) the estimated amounts of D_2 of Run1 and Run2 by using the liquid holdup ratio shown in Figure 3 agree well with the loaded amount.

B. Intended ISS-LOCA Experiment

Figure 4 shows the Column-H pressures during the ISS-LOCA experiment. It is worth notice from the view point of ISS safety that we had no less than 90 minutes until pressure of Column-H rose from 107 kPa to 214 kPa (upper limit for safety reasons). Sudden increases of internal pressure were not observed and enough time was found to recover the hydrogen isotope into the storage system under the conditions that vacuum insulation was maintained and reboiler heaters were turned off immediately, simulating a sudden loss of cryogenic coolant accident. In an ISS-LOCA, heat was estimated to be mainly input from the copper section of the condenser where the helium coolant line is contacted, so that a sudden increase of temperature in the upper section was observed as seen in **Figure 5**. Heat flux into the condenser led to the gradual drop of liquid in the condenser and packed section to the reboiler, and the heat transfer through column surfaces and packing produced gradual rising of pressure and temperature and the gradual evaporation of liquid. Just after the gas in column was allowed to fill the standard volume, a sudden drop of temperature was observed because of abiabatic expansion. However, by connecting the column with a standard volume, other trespasses of heat such as conduction from feed piping quickened

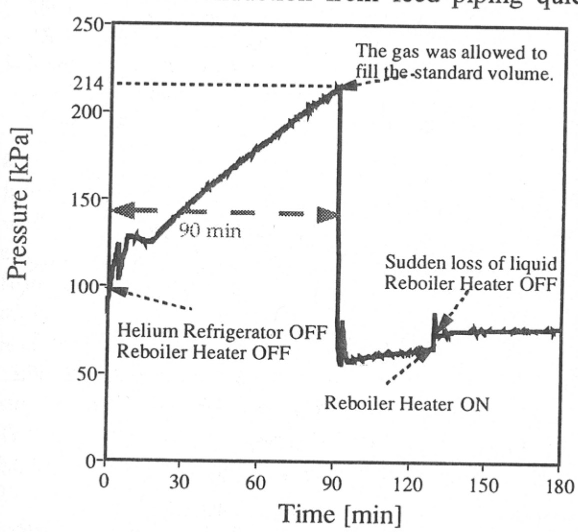


Figure 4 Column-H pressures during LOCA experiment.

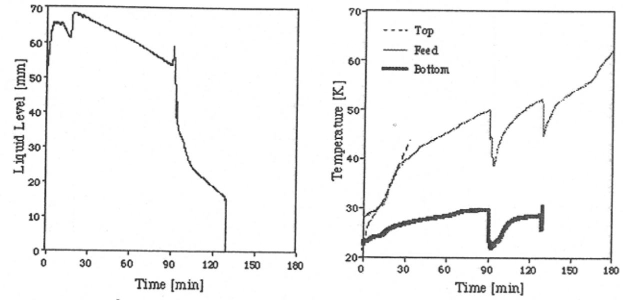


Figure 5 Behavior of liquid level in reboiler and temperature during LOCA experiment

the evaporation of liquid in the reboiler and they caused the sudden increase of temperature. Sudden loss of liquid in the reboiler was observed just after the reboiler was turned on again. This led to the sudden increase of the pressure in the system. An interlock system for automatic shutdown of heaters in case of off-normal conditions has to be provided in the ISS to avoid the rapid increase of internal pressure. Finally, negligible pressure increases were observed after 5 hours following the time that the refrigerator was turned off.

C. Rapid Dump Test onto a Hydrogen Storage Bed

The exhaust rate as a function of pressure is shown in **Figure 6**. The value of about 4 NL/s is achieved against the pressure of 101kPa. Judging from this result, a storage bed which capacity is a few tens of moles has enough capacity for the recovery of loaded hydrogen in an ITER-scaled cryogenic distillation column in case the ISS-LOCA event happens. The surface temperature of the Ubed and estimated calorific value as function of elapsed time are shown in **Figure 7**. The rising temperature in a bed leads to remarkable deterioration of exhausted capacity. The estimated calorific value calculated by heat for hydrogenated formation of uranium is large, however this heat is effectively removed by air convection. It is found that the all loaded gas can be smoothly recovered onto an empty bed without the remarkable deterioration of exhausted capacity from increasing temperature.

IV. Conclusions

From the viewpoint of safety of a fusion reactor, it is important to grasp the off-normal behavior of ISS-LOCA. From this background, a simulated ISS-LOCA test was conducted by turning off the helium refrigerator manually using an actual ITER scale of cryogenic distillation column for the hydrogen isotope

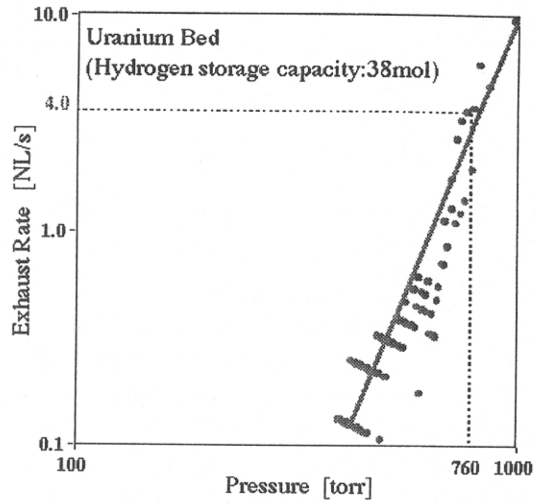


Figure 6 Exhaust rate as function of pressure

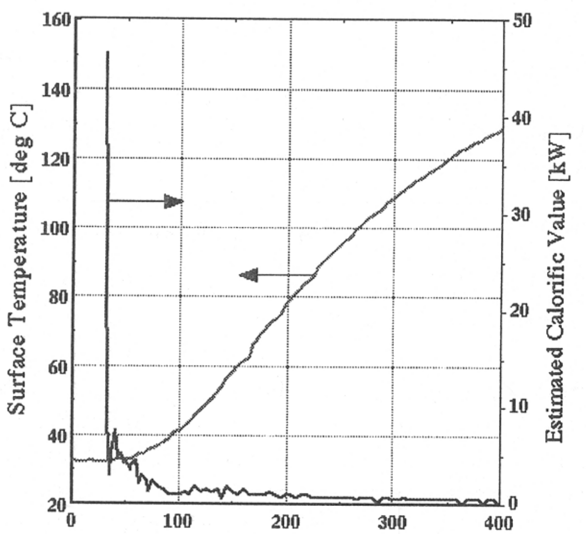


Figure 7 Surface temperature of Ubed and estimated calorific value as function of elapsed time

system. The conclusions of this study are summarized as follows.

1. The intended off-normal test demonstrated that sudden increase of internal pressure was not observed and enough time was found to recover the hydrogen isotope into a storage system if vacuum insulation was maintained and reboiler heaters were turned off immediately, so that the situation of breaking rupture disks is found to be prevented.
2. The validity of the proposed inventory numerical evaluation method is proved by comparison with the experimental data in the ITER-scale large cryogenic distillation columns.
3. The rapid recovery test demonstrated that a hydrogen storage bed is a valid means for rapid recovery of the hydrogen isotope in the distillation columns of the isotope separation system during off-normal conditions.

Through this series of experiments, systematic data was acquired for the safety of a fusion reactor in a sudden loss of cryogenic coolant accident.

NOMENCLATURE

$v_{j\,i}$: Liquid mole density of species i at the j^{th} theoretical stage [mol/m^3]
$x_{j\,i}$: Liquid mole fraction of species i at the j^{th} theoretical stage [-]
$y_{j\,i}$: Vapor mole fraction of species i at the j^{th} theoretical stage [-]
$H_{t\,e}$: Total amount of hydrogen isotopes evaluated by the proposal method [mol]
$H_{t\,m}$: Total amount of hydrogen isotopes loaded in the column [mol]
$H_{L\,C}$: Liquid holdup in the condenser [mol]
$H_{L\,P}$: Liquid holdup in the packed section [mol]
$H_{L\,R}$: Liquid holdup in the reboiler [mol]
$H_{V\,C}$: Gas holdup in the condenser [mol]
$H_{V\,P}$: Gas holdup in the packed section [mol]
$H_{V\,R}$: Gas holdup in the reboiler [mol]
P_j: Pressure at the j^{th} theoretical stage [Pa]
R: Gas constant [Pa m^3/mol/K]
S_j: Superficial velocity at the j^{th} theoretical stage [m/s]
T_j: Temperature at the j^{th} theoretical stage [K]
V: Superficial volume per theoretical stage in the packed section [m^3]
V_1: Volume of condenser [m^3]
V_{LN}: Liquid volume in the reboiler [m^3]
V_N: Volume of reboiler [m^3]
α_i: Coefficient of correlation of species i [-]
γ_i: Liquid holdup ratio species i [-]
ε : Ratio of packing (5%) [-]
ε_1: Liquid ratio against the condenser volume (1%) [-]
ε_j: Liquid ratio against the volume at the j^{th} theoretical stage [-]

(Subscripts)
N: Reboiler
i: Hydrogen isotopes (1=H_2, 2=HD, 3=HT, 4=D_2, 5=DT, 6=T_2)
1: Condenser

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References

1. D. K. Murdoch et al., *Fusion Eng. Des.*, **49-50**, 893 (2000).
2. ITER: ITER EDA Documentation Series No. 16, International Atomic Energy Agency, Vienna, (1998).
3. Y. Iwai et al., Numerical Estimation Method of the Hydrogen Isotope Inventory in the Hydrogen Isotope Separation System for Fusion Reactor , submitted to *J. Nucl. Sci. and Technol.*
4. M. Kinoshita, *Fusion Technol.*, **6**, 574 (1984).
5. R. H. Sherman et al., *Fusion Technol.*, **6**, 625 (1984).
6. J. E. Bechanan, *Ind. Eng. Chem., Fundam.*, 6, 400 (1967)