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Preliminary design study of the hydrogen isotope separation system (ISS) for the fuel cycle of the ITER-FEAT, a fusion experimental reactor, was carried out based on the substantial reduction of hydrogen flow to the ISS resulting from the design study for scale reduction of the formerly-designed ITER. Three feed streams (plasma exhaust gas stream, streams from the water detritiation system and that from the neutral beam injectors) are fed to the ISS, and three product streams (high purity tritium gas, high purity deuterium gas and hydrogen gas) are made in it by the method of cryogenic distillation. In this study, an original four-column cascade was proposed to the ISS cryogenic distillation column system considering simplification and the operation scenario of the ITER-FEAT. Substantial reduction of tritium inventory in the ISS was found to be possible in the progress of investigation concerning of the corresponding flow rate of tritium product stream (T>90 %) for pellet injector which depends upon the operation condition. And it was found that tritium concentration in the released hydrogen stream into environment from the ISS could easily fluctuate with current design of column arrangement due to the small disturbance in mass flow balance in the ISS. To solve this problem, two-column system for treatment of this flow was proposed.

KEYWORDS : ITER-FEAT, Fusion Reactor, Tritium, Cryogenic Distillation, Inventory, Isotope Separation, Operation Scenario, Cascade Configuration, Refrigeration Duty

ITER-FEAT 水素同位体分離システムの設計研究

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核融合実験炉の燃料循環システムの ITER-FEAT 設計作業の一環として、先に設計された ITER の規模縮小に基づく処理流量の減少に対応した水素同位体分離システム(ISS)の概念設計の予備的検討を行った。ISS には三種類のガス流（プラズマ排ガス流、水処理システムから排ガス流及び中性粒子ビーム注入システムからの排ガス流）が供給され、深冷蒸留法により三種類の製品流（高純度トリチウムガス流、高純度重水素ガス流及び軽水素ガス流）が生み出される。本報ではシステムの簡略化と ITER-FEAT の運転シナリオを考慮し、4 塔からなる独自の塔構成からなる ISS を提案した。ISS 内の最大トリチウムインベントリーについては、運転条件に対応して定まるペレット用のトリチウム濃縮流(T > 90 %)の検討の進展によって、低減の可能性を見出した。また現状の塔構成では環境に排出する軽水素排ガス中のトリチウム濃度が ISS 運転中に加わるわずかな流量変動によって容易に変動する可能性を指摘し、この流れに対する 2 塔システムの対策を提案した。

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1. Introduction

The design study of the ITER-FEAT is ongoing considering the reduction of construction cost from the former-designed ITER whose design was reported in the ITER Final Design Report (FDR) [1]. We call the former-designed ITER hereinafter "ITER-FDR" in this report. In the fuel cycle system of the ITER-FEAT [2], a fusion experimental reactor under planning internationally, the Hydrogen Isotope Separation System (ISS) processes three hydrogen isotope streams: a protium (H) rich stream from water detritiation system (WDS) containing a tracer amount of tritium (T), a deuterium (D) rich stream from neutral beam injectors (NBI) containing a small amount of tritium, and a D and T rich plasma exhaust stream coming through Tokamak Exhaust Processing system (TEP) in which impurity components such as helium and carbon are removed. Amount of hydrogen gas fed to the ISS in the ongoing process of the design study of the ITER-FEAT is expected to be much smaller than that in the ITER-FDR [1]. As the current ISS is decided to be designed based on the 500-seconds long fusion operation as the nominal in the ITER-FEAT design, flow rate of the plasma exhaust stream fed to the ISS is 100 mol/h. As the result of recent investigation, the protium rich stream from the WDS to the ISS is much reduced to 160 mol/h in comparison with 785 mol/h in the ITER-FDR where the WDS treats all tritiated water such as cooling water of plasma facing components tritiated due to tritium permeation [3][4] and water wasted from tritium systems. The reason of this large reduction came from the results of recent ITER R&D on tritium implantation into beryllium used as first wall material of blanket with which tritium permeation was estimated to be negligibly small, about 10^{-4} g/day, even after 10-years ITER operation and the necessity of the treatment of the cooling water became less [5]. Due to this significant reduction in water detritiation requirement, combined electrolysis catalytic exchange (CECE) process instead of vapor phase catalytic exchange (VPCE) process has been selected for the WDS in the ITER-FEAT as the catalytic exchange option to realize compact system. Flow rate and composition of the stream from NBI is not changed up to now [1].

Conceptual design of the ISS for the ITER-FEAT was carried out based on plasma operation with a pulse repetition rate of 2 shots/h for 500s-burn each and on a fuelling throughput of 200 Pa · m^3/s. Four-cascade configuration of cryogenic distillation columns was selected currently in it considering an operation scenario of the ITER-FEAT. In the ITER project, DD plasma operation using only deuterium is planned to be done before DT plasma operation using real fusion fuel, deuterium and tritium. During the DD plasma phase, only partial ISS installation is required for removal of protium from deuterium containing a tracer amount of tritium. But full cascade is needed at the DT phase and it will be established by adding three columns to the ISS.

Recently we performed some analytical study on the ISS design. Simulation code used in it for design of the cryogenic distillation columns of the ISS was based on the staged model, and it applied the tridiagonal method [6]. The ISS column design concept adopted in it was based on ISS investigation at the Tritium Process Laboratory (TPL) in Japan Atomic Energy Research Institute (JAERI) and on that at the Tritium System Test Assembly (TSTA) in Los Alamos National Laboratory (LANL) carried out under US-JAPAN collaboration [7][8]. With these two investigations, minimum tritium inventory in the ISS as a total could be investigated. The design conditions used in this study were come from those reported by ITER Joint Central Team (JCT) up to September 1999, and minor changes on the design conditions was added with the progress of ITER-FEAT design work. Some additional calculations were carried out with typical operation options.

2. Simulation Procedure

Packed column is used as the cryogenic distillation column in the ISS of the ITER. Simulation code for present design of the cryogenic distillation column is based on the staged model, and it applied the tridiagonal method [6][9]. For simplification, decay heat and nonideality of hydrogen isotopes are not taken into account in this study because these effects on the design are not estimated to be dominant.

3. Cascade Configuration

The ISS for the ITER-FEAT was designed on the basis of a substantial reduction of protium flow from water detritiation system. Three feed streams (plasma exhaust gas stream, stream from WDS and that from NB injectors) are fed to the ISS. Flow rate and hydrogen isotope compositions of each feed stream used in this study are reported by ITER-JCT as follows. Flow rate of plasma exhaust gas is 100 mol/h with H content of 5 %, and its D/T ratio is planned to vary from 50/50 to 75/25. The fuel gas flow rate of 100 mol/h can meet the condition that all torus cryopumps can be regenerated in a cycle time of 1800s for the plasma operation at a repetition rate of 2 shots/h. Deuterium-rich stream from the NB injectors is 40 mol/h, and its H and T content are 0.5 % and 1 %, respectively. Protium rich flow from the WDS is 160 mol/h which contains a deuterium content of 5.21×10^{-2} % and a tritium content of 5.21×10^{-4} %. These design conditions would be derived for the current operation scenario of the ISS in which the ISS is continuously operated against the 500-seconds long fusion operation in the ITER-FEAT. In this study, a four-column cascade configuration is used. One column is needed for H production and also one is needed for D production. Two columns are needed for T production, one is for T=50 % production and the other is for T > 90 % production. The conceptual flow diagram of the ISS plant proposed in the present work is illustrated in Figure 1.

4. Column Design

In present design condition, two main product streams are requested: 25 mol/h T rich stream (Column-4 Bottom) that contains T > 90 % for pellet fuelling, and 40 mol/h D rich stream (Column-3 Top) that contains H < 0.5 % and T < 0.02 % for the NB injectors. High purity H stream (Column-2 Top) is released into the environment after 100 times dilution to prevent hydrogen explosion, therefore it is requested to keep the level of HT concentration in this gas to be lower than 1.8×10^{-5} % before dilution. The tritium concentration after dilution should be lower than 90 Bq/cm^3. The D-T stream (Column-1 Bottom) of D/T ratio 50/50 is requested to contain H < 0.5 %, and the D-stream (Column-3 Bottom) is requested to contain D > 90 %.

The value of height equivalent to a theoretical plate (HETP) used in this study is 0.05m. The liquid hold-up per one theoretical plate is expected to be 5～15 % of its superficial volume. The value of 10 % is adopted for Column-1, Column-3 and Column-4, whereas the value of 12 % is adopted for Column-2 [10]. The liquid hold-up in the reboiler is estimated as 5 % of total liquid hold-up of packed section.

ISS column design was carried out with following design concept. Flexibility in distillation control of each column was considered. Simplification of system was achieved without incorporating side withdrawal streams. Furthermore, number of equilibrators and equilibrator flow rates were limited as small as practicable for reduction of number of circulation pumps, helium refrigeration load and relevant cost. Column devices such as intermediate reboilers and change of column diameter at the intermediate stage were not adopted because they have not been demonstrated in the fusion fuel cycle ISS cascade. The total tritium inventory was reduced as low as possible.

Column parameters of ISS calculated with the conditions above are summarised in Table 1. Compositions and flow rates of key streams in the figure are also listed in Table 2. Calculations cover typical D/T compositions as expected in ITER plasma operation: Case 1 represents equi-molar fuelling with a D/T ratio of 50/50, Cases 2 and 3 are for non equi-molar fuelling in which D/T ratios are 60/40 and 75/25 respectively, and Case 4 has a half T flow rate of Column-4 bottom that of Case 3. Cases 1-4 calculations were made with the same system configuration shown in Figure 1. From the results listed in Table 1, tritium concentration in plasma exhaust gas and that in the highly enriched tritium product stream (T > 90 %) were found to be key parameters for reduction of total tritium inventory and refrigeration duty. The tritium inventory is maximum with Case 1 because the diameters of Column-1 and Column-4 which are decided by Case 3 of lowest tritium composition in the plasma exhaust gas are too large for condition of Case 1. The optimum of diameters of Column-1 and Column-4 is also important for inventory. Substantial reduction of tritium inventory seems to be possible with the progress in the investigation of the correspondent flow rate of tritium product stream (T > 90 %) for pellet. It is recommended to change the flow rate of tritium product stream to the tritium storage and delivery system (SDS) in correspondence with the D/T compositions of plasma exhaust gas. In case that the bottom flow rate of Column-4 (T > 90 %) is reduced from 25 mol/h (Case 3) to 12.5 mol/h (Case 4), total tritium inventory and the refrigeration duty are reduced to be 71 % and 73 %, respectively. Those reductions are achieved in Case 4 by the smaller diameters of Column-1 and Column-4 than those of Case 3. On the contrary, the larger flow rate of tritium product stream for pellet is natural in correspondence with the higher D/T compositions of plasma exhaust gas (Case 1). The concept of changing flow rate of tritium product stream for pellet in correspondence with the D/T compositions of plasma exhaust gas will be possible to reduce maximum tritium inventory and maximum total hydrogen isotopes inventory because the diameter of Column-4 can be smaller than that shown in Table 1.

5. Tritium Inventory Estimation for the design based on ITER-FDR concept

From safety point of view, tritium inventory is one of the key issues for the ISS design. The tritium inventory shown in Table 1 is estimated for the ISS design based on our experimental investigation of ISS. On the other hand, design concepts involving low inventory packing and change of column diameter at its intermediate stage, which were not adopted in our design study because of their effectiveness were not clearly demonstrated yet, was adopted by ITER-JCT for the ISS in the ITER-FDR design to minimize the tritium inventory as low as possible. Tritium inventories of the system proposed in this study (Case 1-3 in Table 1) were recalculated with the following ITER-FDR condition [2]. For Column -1, -2 and -3, vapor flow rate, HETP and liquid holdup were 0.15 m/s, 0.05 m and 12 %, respectively. For Column-4, the ISS concept of column diameter change at the intermediate stage in the ITER-FDR was adopted. That is, vapor flow rate, HETP and liquid holdup were 0.12 m/s, 0.05 m and 10 % in the upper column section (Stages 1 - 2) and 0.15 m/s, 0.025 m and 7 % in the lower section (Stages 3- 30), respectively. The liquid hold-up in the reboiler was estimated as 2.5 % of total liquid hold-up of packed section.

Summary of column parameters recalculated with ITER-FDR design conditions is listed in Table 3. As compared with Table 1, total tritium inventory and total hydrogen isotope inventory of each case in Table 3 are about 80 % of those in Table 1. Those reductions are mainly achieved due to the compact design of Column-4 where design concepts of low inventory packing and change of column diameter at the intermediate stage are adopted.

Although these concepts are not adopted in existing ISSs in the world, they will be valuable to minimize the inventories once their effectiveness is demonstrated experimentally.

6. Consideration of HT Fraction Control in the Released Stream

Tritium fraction in high purity protium stream (Column-2 Top) is one of key parameters because this protium flow is released into environment with tritium concentration of 90 Bq/cm^3 or lower after 100 times dilution with nitrogen to prevent hydrogen explosion. Column-2 top product stream contains a tracer amount of tritium as HT form. This HT fraction must be controlled to be less than 1.8×10^{-5} % HT before dilution to prevent hydrogen explosion. Tritium concentration must be less than regulation limit of stack release (90 Bq/cm^3 after dilution). However, small disturbance in mass flow balance may generate large change in HT concentration in the Column-2 top product stream because HT fraction in the flow is very small. HT concentration is not sensitive to the reflux ratio, and much increase of inner flow is required to lower HT fraction.

To design Column-2, one way is to design it with plenty of margin, that is, to design it with much lower HT fraction than that required. We call this design hereinafter "Design A". Conceptual flow diagram of the Design A is illustrated in Figure 2. Design A was carried out with conditions of Case 3 except for adopting the HT fraction condition of 9.0×10^{-6} % in the released stream instead of 1.8×10^{-5} %. HT fraction in the released stream has a possibility to exceed the regulation limit of stack release when the flow rate of released stream is suddenly increased. The low design value of 9.0×10^{-6} % is adopted because HT fraction in the released stream becomes always lower than the regulation limit of stack release (1.8×10^{-5} %) even against the 1 % expectable increase in the steady released stream flow rate of 170 mol/h shown in Table2. Summary of column parameters of the Design A is listed in Table 4. Larger capacity of Column-2 is required in comparison with that of Column-2 of Case 3 listed in Table 1. As a result, slightly larger hydrogen isotope inventory and refrigeration duty are needed.

Another way is to divide Column-2 into two columns; Column-2A and Column-2B. We call this design hereinafter "Design B". Conceptual flow diagram of the Design B is also illustrated in Figure 2. Column-2A is a first column to concentrate hydrogen and HT fraction of Column-2A top stream is designed to be kept to be less than 1.8×10^{-4} %, therefore HT fraction of Column-2B top product stream to environment can be kept much less than regulation limit of stack release (1.8×10^{-5}%). Summary of column parameters of the Design B is also listed in Table 4. The Design B was carried out with conditions of Case 3 except for adopting the HT fraction condition of 5.6×10^{-6}% instead of 1.8×10^{-5}%. By adopting the design value of 5.6×10^{-6}% in released stream in the design B, total hydrogen inventory, total tritium inventory and refrigeration duty are found to be about the same values as the Design A. The Design B has more flexibility in HT fraction control than the Design A. Large change in HT concentration in Column-2A top stream caused by small disturbance in mass flow balance can be absorbed by Column-2B. The change in the HT concentration in the Column-2B top product stream caused by small disturbance in mass flow balance will be negligible because the designed HT concentration in the Column-2B top product stream is much lower than regulation limit of stack release (1.8×10^{-5}%). The Design B is decidedly superior to the Design A from the viewpoint of HT concentration control. The Design B has another merit that only slight tritium inventory is existed in Column-2B whose top stream is released into the environment, which means that potential amount of tritium released into environment in case of accident becomes much smaller.

7. Operation Scenario

Phased construction of ITER was considered with the proposed cascade configuration shown in Figure 1 based on scenario of phased construction of ITER machine [2].

In the ITER operation, DD plasma operation will be done before DT plasma operation. During DD plasma phase, only partial ISS installation with Column-1 only is required for removal of protium from deuterium. Separation of HT stream from water detritiation plant (CECE) is not required during this phase. Separation performance of the column calculated for conditions of flow rate = 100 mol/h, H = 5 %, T = 3.91×10^{-3}% and D = balance, are as follows;

Reflux ratio: 40.0;

Top stream: 8 mol/h (H=60.3 %, D=39.7 % and HT=1.76×10^{-5}%);

Bottom stream: 92 mol/h (H=0.3 %, D=99.7 % and T=3.61×10^{-5}%).

For the DT phase, full cascade is needed to provide D_2 gas for NB injectors and D_2, T_2, D-T gas for gas puffing fuelling and pellet injection fuelling systems. Full cascade is established adding remaining three columns to the ISS system without major changes on Column-1. Summary of column parameters during DT phase is listed in Table 5. Separation performance of the cascade will be maintained while 160 mol/h of hydrogen stream from the WDS plant is not supplied. While pellet injection is not required, D-T mixture for D/T=50/50 fuelling will be provided by Column-1 without Column-4. Flexibility of the proposed cascade was thus proved.

8. Discussion for Change of Design Conditions

Design conditions used in this study are based on those reported by ITER-JCT

[11]. However, the design conditions are gradually changing with the progress of ITER-FEAT design work. Size of each column designed in the present study should be adjusted with the change of design conditions for the hydrogen isotope separation system.

8.1. Change of Flow Rate and Compositions of Stream from WDS

Investigation of optimum hydrogen flow rate from the WDS to the ISS is in progress from a viewpoint of lifetime of solid polymer electrolysis (SPE) membrane in the WDS and of safe handling of high concentration HTO during normal operation and maintenance of the SPE [12]. Hydrogen flow rate from the WDS to the ISS is a dominant parameter for tritium concentration in the WDS plant. As the flow rate increases, tritium concentration in the WDS plant decreases. The flow rate of 160mol/h is determined to keep tritium concentration in the WDS plant less than 3.7×10^{12} Bq/kg from a viewpoint of maintenance. Effect of flow rate from the WDS to the ISS on the ISS design was investigated. Table 6 shows summary of this study where four cases (3A, 3B, 3C, and 3D) were investigated. Flow rate and compositions of plasma exhaust gas of Case 3 were used because size of each column was determined by the condition of this case. Flow rate and compositions of stream from the WDS used were those reported by ITER Joint Central Team (JCT) [11]. The calculations cover assumed range of flow rates. In Case 3A, feed flow rate from the WDS to Column-2 is 20 mol/h and its D fraction and T fraction are 4.17×10^{-3} and

4.17×10^{-5} respectively. For Case 3B, Case 3C and Case 3D, these are 80 mol/h and 1.04×10^{-3} and 1.04×10^{-5}, 160 mol/h and 5.21×10^{-4} and 5.21×10^{-6}, 280 mol/h and 3.00×10^{-4} and 3.00×10^{-6}, respectively. Effect of flow rate on total tritium inventory and total refrigeration duty was found to be negligible. Increase of flow rate effects a slight increase on total hydrogen isotope inventory, and this amount of increase will be permissible. The increase of feed flow rate in Column-2 can be coped with the increase of top product stream including the small change of the column internal vapor flow rate. Hence, impact on Column-3, downstream of Column-2, is also very small.

8.2. Change of Flow Rate and Compositions of Stream from NBI

Investigation of flow rate and compositions of stream from NBI is also in progress from a viewpoint of NBI gas treatment. A set of flow rate and composition condition of plasma exhaust gas and stream from the WDS used in this study is that of Case 3C. Number of the NBI is three and number of diagnostic NB (DNB) injector is one for present ITER. There are several options on NB/DNB working gases. Case-a is an option of D_2 gas for NB injectors and H_2 for DNB injector. ISS feed flow rate, ISS feed composition and ISS product composition in Case-a are those reported by ITER Joint Central Team (JCT) [11]. Case-b is an option of D_2 gas for both NB and DNB injectors. ISS feed flow in Case-b is 84mol/h of deuterium rich stream with small amounts of H and T. Case-b is further divided into three cases in which ISS feed composition and ISS product composition are different one another. Case-c is an option of H_2 gas for both NB and DNB injectors. In the Case-c, ISS feed flow rate, ISS feed composition and ISS product composition are protium of 225 mol/h, 1 %D and 1 %T and H balance, <0.02 %D and <0.02 % T and H balance. Summary of NBI gas treatment options is listed in Table 7.

Summary of case study is listed in Table 8. Change of feed flow rate from 40 mol/h (Case 3C-a) to 84 mol/h (Case 3c-1b) causes an increase on total hydrogen isotope inventory and total refrigeration duty. Change of tritium composition in the feed stream from 1 % (Case 3C-1b) to 2 % (Case 3C-2b) also causes a slight increase on total hydrogen isotope inventory and total refrigeration duty. Change of tritium composition in the product stream from 0.02 % (Case 3C-2b) to 1 % (Case 3C-3b) results a large decrease on total hydrogen isotope inventory and total refrigeration duty. Required tritium composition in high purity deuterium stream is a key parameter for hydrogen isotope inventory and total refrigeration duty. Choice of protium as NBI gas needs partial change of cascade configuration. Conceptual flow diagram of the ISS plant for NBI protium gas treatment option is illustrated in Figure 3. Choice of protium as NBI gas (Case 3C-c) results in a large increase of total hydrogen isotope inventory and total refrigeration duty because of substantial increase of feed flow in Column-2.

9. Summary

Results of the present study are summarised as follows:

1. Tritium concentration in plasma exhaust gas as well as that in highly enriched tritium product stream were found to be key parameters for the reduction of total tritium inventory and refrigeration duty. The optimization of diameters of Column-1 and Column-4 is also important for the reduction of tritium inventory in the ISS. Substantial reduction of tritium inventory seems to be possible with the progress in the future investigation of the correspondent flow rate of tritium product stream (T > 90 %) for pellet. It is recommended to change the flow rate of tritium product stream to the SDS in correspondence with the D/T compositions of plasma exhaust gas.
2. Design concepts such as low inventory packing and change of column diameter at the intermedeate stage of a column were adopted in the ITER-FDR ISS design. Total inventory and refrigerant duty were found to be reduced by adopting these design concepts. Though these concepts are not yet adopted in existing ISSs in the world, they will be valuable to minimize the inventories once their effectiveness is surely proved by the experimental demonstration.
3. Tritium concentration in released stream into environment must be controlled to be kept smaller value than that permitted. Small disturbance in mass flow balance in the ISS may generate a large change of tritium concentration in this stream, and two-column system for treatment of this flow was found to be

effective.

4. ISS configuration proposed in this study meets the phased construction of the ITER. Only Column-1 is required in DD plasma phase for protium removal from deuterium. For DT phase, full cascade should be established by adding remaining three columns to the ISS without major changes on Column-1.
5. Design conditions are gradually changing with the progress of the ITER-FEAT design work. Some additional calculations were carried out with typical options. Size of each column designed in the present study should be adjusted with change of design conditions for ISS, but it becomes to be an easy task to adjust size of each column because its method was established in this study. The qualitative aspects of this study are not vitiated regardless of the change of the design conditions.

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References

[1] "ITER Final Design Report", IAEA (1998).

[2] Glugla M et al.: "The Tritium Fuel cycle of ITER-FEAT", submitted to Fusion Technol..

[3] Yoshida, H. et al.: "Status of the ITER Tritium Plant Design", Fusion Eng. and Des., 39-40, 875 (1998).

[4] Iwai, Y. et al. "Design Study of Feasible Water Detritation Systems for Fusion Reactor of ITER Scale", J. Nucl. Sci. and Technol., 33, 981(1996).

[5] Iseli M.: "Recalculation of Tritium Inventories and Permeation", Private Communication (1999).

[6] Kinoshita M. "An Efficiency Simulation Procedure Especially Developed For Hydrogen Isotope Distillation Columns", Fusion Technol., 6, 574 (1984).

[7] Yamanishi, T. et al.: "Experimental Apparatus for cryogenic Isotope Separation Process in the Tritium Process Labolatory", Fusion Technol., 14, 495 (1988).

[8] Yamanishi, T. et al.: "Single Column and Two Column H-D-T Distillation Experiments at TSTA", Fusion Technol., 14, 489 (1988).

[9] Iwai, Y. et al.: JAERI-Tech 2000-02, "Study on Cascade Configuration and Hydrogen Isotope Inventory of Cryogenic Distillation Columns for Isotope Separation System of the ITER Tritium Plant" (1999). [in Japanese]

[10] Sherman R. H. et al.: "Experimental Results from Hydrogen / Deuterium Distillation at the Tritium Systems Test Assembly", Fusion Technol., 6, 625 (1984).

[11] Yoshida, H.: Private Communication

[12] Iwai, Y. et al.: "A Design Study of Water Detritation and Hydrogen Isotope Separation Systems for ITER", Fusion Eng. and Des., 49-50, 847 (2000).

Table1 Summary of calculated column parameters of ISS proposed in this task

		Case1	Case2	Case3	Case4
Plasma Exhaust Gas	H/D/T ratio	5/47.5/47.5	5/58/37	5/71.25/23.75	5/71.25/23.75
Column 1	D [cm]	7.29	7.29	7.29	6.84
	R [-]	6.00	7.00	8.00	8.00
HETP: 5 cm	EQ [mol/h]	92.9	180.0	320.0	290.0
Vapor Flow Rate	T [g]	84.09	68.96	59.11	55.24
: 13 cm/s	L [mol]	48.1	48.3	48.3	42.5
Liquid Holdup: 10%	H [W]	53.8	107.7	201.8	174.6
Column 2	D [cm]	7.05	7.05	7.05	6.99
	R [-]	2.40	2.34	2.28	2.30
HETP: 5 cm	EQ [mol/h]	200.0	200.0	200.0	200.0
Vapor Flow Rate	T [g]	4.25	4.42	2.83	3.01
: 10 cm/s	L [mol]	91.9	91.9	91.9	90.3
Liquid Holdup: 12%	H [W]	91.2	89.9	87.6	88.4
Column 3	D [cm]	5.87	5.87	5.87	5.16
	R [-]	9.00	7.30	6.20	6.20
HETP: 5 cm	EQ [mol/h]	100.0	100.0	100.0	100.0
Vapor Flow Rate	T [g]	3.96	2.07	1.19	1.01
: 10 cm/s	L [mol]	45.4	45.4	45.4	35.1
Liquid Holdup: 10%	H [W]	122.0	99.0	84.0	84.0
Column 4	D [cm]	5.30	5.30	5.30	3.35
	R [-]	2.43	2.90	3.95	1.55
HETP: 5 cm	EQ [mol/h]	121.3	146.3	160.0	78.5
Vapor Flow Rate	T [g]	48.42	47.79	46.93	19.39
: 15 cm/s	L [mol]	14.1	14.1	14.1	5.6
Liquid Holdup: 10%	H [W]	140.0	167.4	221.8	89.9
Total T Inventory [g]		140.72	123.24	110.06	78.65
Total Inventory [mol]		199.5	199.7	199.7	173.5
Total Refrigeration Duty [w]		407.0	464.0	595.2	436.9

Case4:T2 stream from ISS is reduced from 25 mol/h to 12.5 mol/h.

D: Column Diameter, R: Reflux Ratio, EQ: Equilibrator Flow Rate, T: Tritium Inventory,

L: HDT Inventory , H: Refrigeration Duty

Table 2 Calculated results for key streams

Stream Number		Design Requirement	Case1	Case2	Case3	Case4
Flow ①	H [frac.]		9.763E-01	9.712E-01	9.709E-01	9.709E-01
	D [frac.]		2.374E-02	2.885E-02	2.909E-02	2.909E-02
	HT [frac.]	<1.8E-5*	1.280E-07	1.750E-07	1.766E-07	1.753E-07
	Flow Rate [mol/h]		169	170	170	170
Flow ②	H [frac.]	<5.0E-3	1.571E-04	1.830E-04	2.709E-04	2.135E-04
	D [frac.]		9.997E-01	9.996E-01	9.995E-01	9.996E-01
	T [frac.]	<2.0E-4	1.900E-04	1.879E-04	1.949E-04	1.949E-04
	Flow Rate [mol/h]	>40	40	40	40	40
Flow ③	H [frac.]		4.468E-06	8.724E-06	2.136E-05	1.480E-05
	D [frac.]	>9.0E-1	9.027E-01	9.537E-01	9.790E-01	9.757E-01
	T [frac.]		9.732E-02	4.625E-02	2.098E-02	2.431E-02
	Flow Rate [mol/h]		18	36	65	128
Flow ④	H [frac.]	<5.0E-3	2.574E-03	4.542E-04		1.196E-04
	D [frac.]		5.099E-01	5.094E-01		4.906E-01
	T [frac.]		4.875E-01	4.901E-01		5.093E-01
	Flow Rate [mol/h]		48	29	0	42
Flow ⑤	H [frac.]		1.140E-07	1.661E-08	2.778E-09	3.319E-09
	D [frac.]		9.920E-02	9.965E-02	9.829E-02	9.820E-02
	T [frac.]	>9.0E-1	9.008E-01	9.003E-01	9.017E-01	9.018E-01
	Flow Rate [mol/h]	25 (Case4 : 12.5)	25	25	25	12.5

* The permisible release level of HT concentration after dilusion is less than 1.8×10^{-7} %.

Note: The description of 1.0E-2 means 1.0×10^{-2}.

Table 3 Tritium inventories calculated with ISS design conditions of ITER-FDR

	Column Diameter [cm]	Tritium Inventory			HDT Inventory [mol]
		Case1 [g]	Case2 [g]	Case3 [g]	
Column1	6.78	87.28	71.58	61.35	50.13
Column2	5.75	2.827	2.942	1.88	61.12
Column 3	4.79	3.14	1.651	0.95	36.31
Column4	6.75 (upper) 5.30 (lower)	20.09	19.83	19.36	5.30
Total		113.34	96.00	83.54	152.86

Table4 Summary of desighed column parameters of ISS for HT fraction control

		Design (Steady State)*	Design A**	Design B***
Plasma Exhaust Gas	H/D/T ratio	5/71.25/23.75	5/58/37	5/71.25/23.75
Column 1	D [cm]	7.29	7.29	7.29
	R [-]	8.00	8.00	8.00
HETP: 5 cm	EQ [mol/h]	320.0	320.0	320.0
Vapor Flow Rate	T [g]	59.11	59.11	59.11
: 13 cm/s	L [mol]	48.3	48.3	48.3
Liquid Holdup: 10%	H [W]	201.8	201.8	201.8
Column 2A	D [cm]	7.05	7.83	6.79
	R [-]	2.28	3.45	1.87
HETP: 5 cm	EQ [mol/h]	200.0	200.0	200.0
Vapor Flow Rate	T [g]	2.83	2.90	7.56
: 10 cm/s	L [mol]	91.9	113.3	85.6
Liquid Holdup: 12%	H [W]	87.6	132.6	77.9
Column 2B	D [cm]			5.13
	R [-]			1.50
HETP: 5 cm	EQ [mol/h]			0.0
Vapor Flow Rate	T [g]			3.45E-04
: 10 cm/s	L [mol]			47.22
Liquid Holdup: 12%	H [W]			57.6
Column 3	D [cm]	5.87	5.87	5.87
	R [-]	6.20	6.20	6.20
HETP: 5 cm	EQ [mol/h]	100.0	100.0	100.0
Vapor Flow Rate	T [g]	1.19	1.18	1.20
: 10 cm/s	L [mol]	45.4	45.44	45.44
Liquid Holdup: 10%	H [W]	84.0	84.0	84.0
Column 4	D [cm]	5.30	5.30	5.30
	R [-]	3.95	3.95	3.95
HETP: 5 cm	EQ [mol/h]	160.0	160.0	160.0
Vapor Flow Rate	T [g]	46.93	46.93	46.93
: 15 cm/s	L [mol]	14.1	14.1	14.1
Liquid Holdup: 10%	H [W]	221.8	221.8	221.8
Total T Inventory [g]		110.06	110.12	114.80
Total Inventory [mol]		199.7	221.14	240.61
Total Refrigeration Duty [w]		595.2	640.2	643.1

*Design (Steady State) corresponds to Case3 in Table 1. HT fraction in the released stream was 1.8×10^{-5}%.

**HT fraction in the released stream of Design A was 9.0×10^{-6}%.

***HT fraction in the released stream of Design B was 5.6×10^{-6}%.

D: Column Diameter, R: Reflux Ratio, EQ: Equilibrator Flow Rate, T: Tritium Inventory,
L: HDT Inventory , H: Refrigeration Duty

Note: The description of 1.0E-2 means 1.0×10^{-2}.

Table5 Summary of designed column parameters of ISS in DT phase

		Full operation	Without CECE stream	Without stream for pellet fuelling
Plasma Exhaust Gas	H/D/T ratio	5/71.25/23.75	5/71.25/23.75	5/71.25/23.75
Column 1	D [cm]	7.29	7.29	7.29
	R [-]	8.00	8.00	11.00
HETP: 5 cm	EQ [mol/h]	320.0	320.0	320.0
Vapor Flow Rate	T [g]	59.11	59.11	39.62
: 13 cm/s	L [mol]	48.3	48.3	48.3
Liquid Holdup: 10%	H [W]	201.8	201.8	193.1
Column 2	D [cm]	7.05	7.05	7.05
	R [-]	2.28	50.00	2.28
HETP: 5 cm	EQ [mol/h]	200.0	200.0	200.0
Vapor Flow Rate	T [g]	2.83	3.16	1.62
: 10 cm/s	L [mol]	91.9	95.1	95.1
Liquid Holdup: 12%	H [W]	87.6	143	87.6
Column 3	D [cm]	5.87	5.87	5.87
	R [-]	6.20	6.40	6.20
HETP: 5 cm	EQ [mol/h]	100.0	100.0	100.0
Vapor Flow Rate	T [g]	1.19	1.18	0.82
: 10 cm/s	L [mol]	45.4	45.4	45.4
Liquid Holdup: 10%	H [W]	84.0	86.8	84.0
Column 4	D [cm]	5.30	5.30	
	R [-]	3.95	3.95	
HETP: 5 cm	EQ [mol/h]	160.0	160.0	
Vapor Flow Rate	T [g]	46.93	46.93	
: 15 cm/s	L [mol]	14.1	14.1	
Liquid Holdup: 10%	H [W]	221.8	221.8	
Total T Inventory [g]		110.06	110.38	42.06
Total Inventory [mol]		199.7	202.9	188.8
Total Refrigeration Duty [w]		595.2	653.4	364.7

These calculations are based on the conditions of Case3.

D: Column Diameter, R: Reflux Ratio, EQ: Equilibrator Flow Rate, T: Tritium Inventory, L: HDT Inventory ,
H: Refrigeration Duty

Table6 Summary of designed column parameters with different WDS conditions in Case 3

		Case3A	Case3B	Case3C	Case3D
Plasma Exhaust Gas	H/D/T ratio	5/71.25/23.75	5/71.25/23.75	5/71.25/23.75	5/71.25/23.75
Stream from WDS	[mol/h]	20	80	160	280
H	[atom frac.]	1	1	1	1
D	[atom frac.]	4.17E-03	1.04E-03	5.21E-04	3.00E-04
T	[atom frac.]	4.17E-05	1.04E-05	5.21E-06	3.00E-06
Column 1	D [cm]	7.29	7.29	7.29	7.29
	R [-]	8.00	8.00	8.00	8.00
HETP: 5 cm	EQ [mol/h]	320.0	320.0	320.0	320.0
Vapor Flow Rate	T [g]	59.11	59.11	59.11	59.11
: 13 cm/s	L [mol]	48.3	48.3	48.3	48.3
Liquid Holdup: 10%	H [W]	201.8	201.8	201.8	201.8
Column 2	D [cm]	5.95	6.31	7.05	7.37
	R [-]	12.50	3.80	2.28	1.25
HETP: 5 cm	EQ [mol/h]	200.0	200.0	200.0	200.0
Vapor Flow Rate	T [g]	1.51	1.67	2.83	1.96
: 10 cm/s	L [mol]	65.4	73.6	91.9	100.4
Liquid Holdup: 12%	H [W]	74.2	75.9	87.6	79.9
Column 3	D [cm]	5.56	5.34	5.87	5.05
	R [-]	6.50	6.40	6.20	5.80
HETP: 5 cm	EQ [mol/h]	150.0	120.0	100.0	100.0
Vapor Flow Rate	T [g]	1.07	0.98	1.19	0.86
: 10 cm/s	L [mol]	40.8	37.6	45.4	33.6
Liquid Holdup: 10%	H [W]	88.1	86.7	84.0	78.6
Column 4	D [cm]	5.30	5.30	5.30	5.30
	R [-]	3.95	3.95	3.95	3.95
HETP: 5 cm	EQ [mol/h]	160.0	160.0	160.0	160.0
Vapor Flow Rate	T [g]	46.93	46.93	46.93	46.93
: 15 cm/s	L [mol]	14.1	14.1	14.1	14.1
Liquid Holdup: 10%	H [W]	221.8	221.8	221.8	221.8
Total T Inventory [g]		108.62	108.69	110.06	108.86
Total Inventory [mol]		168.6	173.6	199.7	196.4
Total Refrigeration Duty [w]		585.9	586.2	595.2	582.1

D: Column Diameter, R: Reflux Ratio, EQ: Equilibrator Flow Rate, T: Tritium Inventory, L: HDT Inventory , H: Refrigeration Duty

Note: The description of 1.0E-2 means 1.0×10^{-2}.

Table7 NBI gas treatment options

		Case3C-a	Case3C-1b	Case3C-2b	Case3C-3b	Case3C-c
ISS feed flow rate	[mol/h]	40	84	84	84	225
ISS feed composition						
H	[%]	0.5	0.5	0.5	0.5	Balance
D	[%]	Balance	Balance	Balance	Balance	1
T	[%]	1	1	2	2	1
ISS product composition						
H	[%]	<0.5	<0.5	<0.5	<0.5	<0.02
D	[%]					<0.02
T	[%]	<0.02	<0.02	<0.02	<1	

Table8 Summary of designed column parameters with different NBI conditions in Case 3C

		Case3C-a	Case3C-1b	Case3C-2b	Case3C-3b	Case3C-c
Plasma Exhaust Gas	H/D/T ratio	5/71.25/23.75	5/71.25/23.75	5/71.25/23.75	5/71.25/23.75	5/71.25/23.75
Column 1	D [cm]	7.29	7.29	7.29	7.29	7.29
	R [-]	8.00	8.00	8.00	8.00	8.00
HETP: 5 cm	EQ [mol/h]	320.0	320.0	320.0	320.0	320.0
Vapor Flow Rate	T [g]	59.11	59.11	59.11	59.11	59.11
: 13 cm/s	L [mol]	48.3	48.3	48.3	48.3	48.3
Liquid Holdup: 10%	H [W]	201.8	201.8	201.8	201.8	201.8
Column 2	D [cm]	7.05	6.89	6.89	6.89	10.67
	R [-]	2.28	2.18	2.18	2.18	2.50
HETP: 5 cm	EQ [mol/h]	200.0	200.0	200.0	200.0	300.0
Vapor Flow Rate	T [g]	2.83	2.13	2.79	2.79	15.2
: 10 cm/s	L [mol]	91.9	87.8	87.8	87.8	210.4
Liquid Holdup: 12%	H [W]	87.6	83.7	83.7	83.7	241.5
Column 3	D [cm]	5.87	7.58	7.89	3.77	7.74
	R [-]	6.20	6.00	6.80	0.75	1.23
HETP: 5 cm	EQ [mol/h]	100.0	250.0	250.0	60.0	100.0
Vapor Flow Rate	T [g]	1.19	2.19	3.27	1.90	0.04
: 10 cm/s	L [mol]	45.4	75.8	82.1	18.7	94.8
Liquid Holdup: 10%	H [W]	84.0	170.8	193.6	21.4	106.6
Column 4	D [cm]	5.30	5.30	5.30	5.30	5.30
	R [-]	3.95	3.95	3.95	3.95	3.95
HETP: 5 cm	EQ [mol/h]	160.0	160.0	160.0	160.0	160.0
Vapor Flow Rate	T [g]	46.93	46.93	46.93	46.93	46.93
: 15 cm/s	L [mol]	14.1	14.1	14.1	14.1	14.1
Liquid Holdup: 10%	H [W]	221.8	221.8	221.8	221.8	221.8
Total T Inventory [g]		110.06	110.36	112.09	110.72	121.30
Total Inventory [mol]		199.7	225.9	232.3	168.9	367.6
Total Refrigeration Duty [w]		595.2	678.1	700.9	528.7	771.7

D: Column Diameter, R: Reflux Ratio, EQ: Equilibrator Flow Rate, T: Tritium Inventory, L: HDT Inventory ,
H: Refrigeration Duty

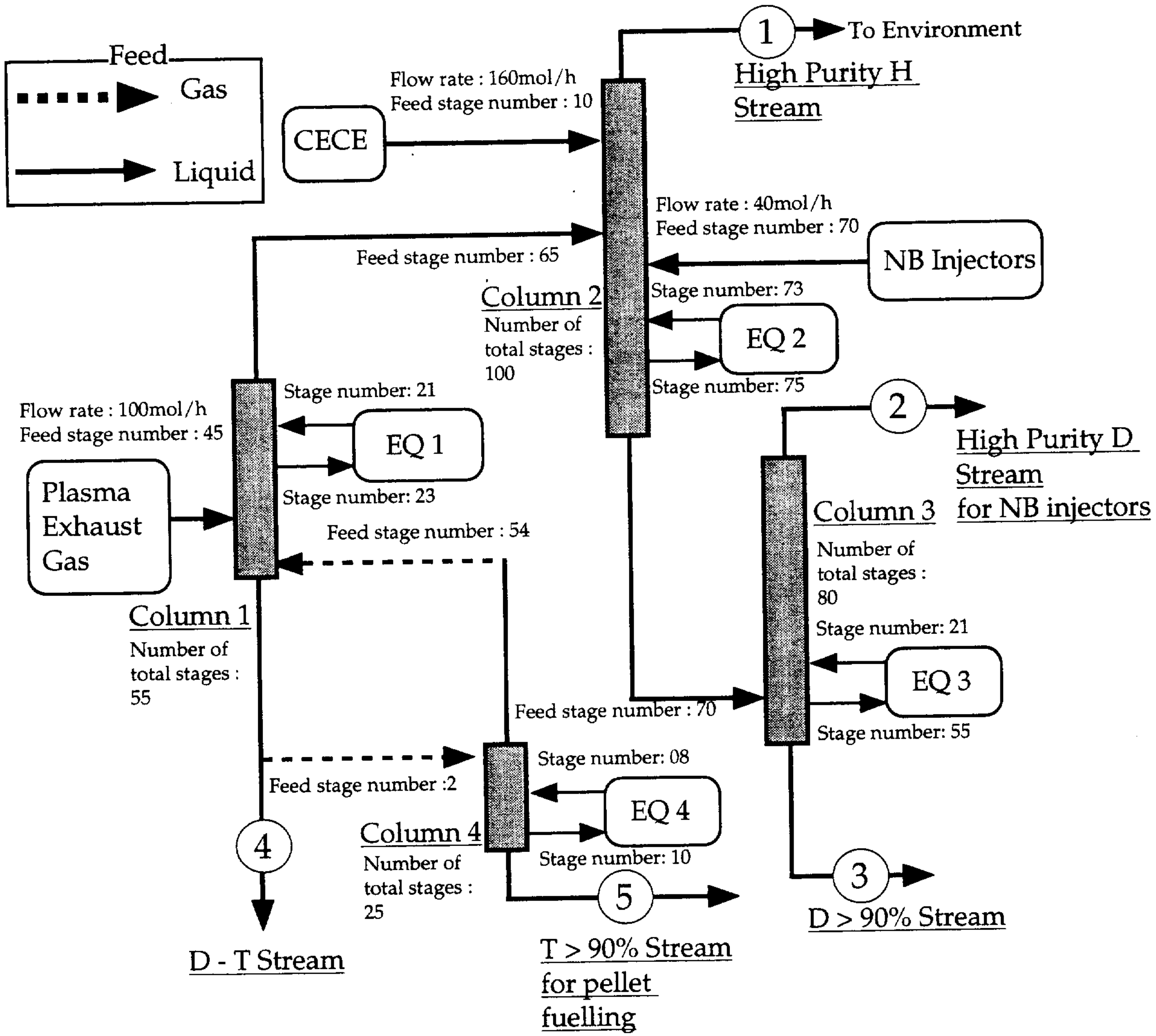
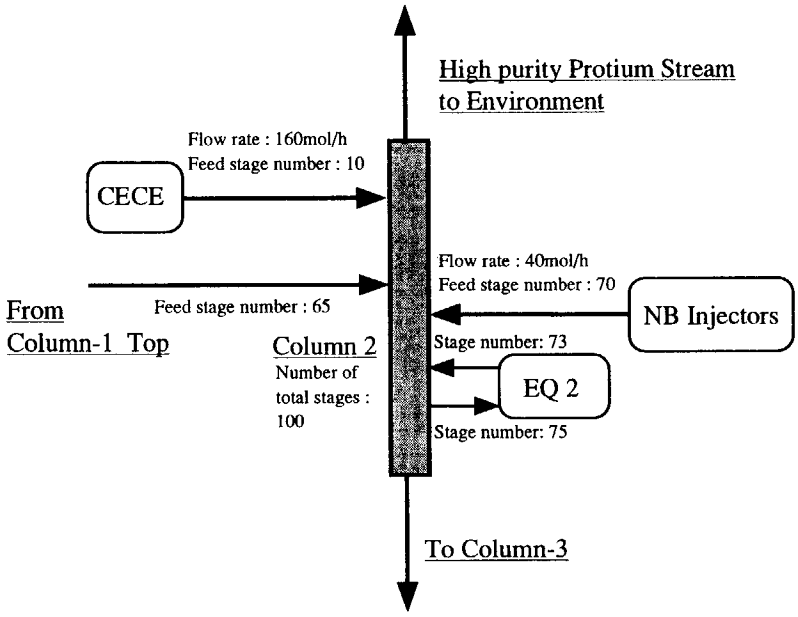
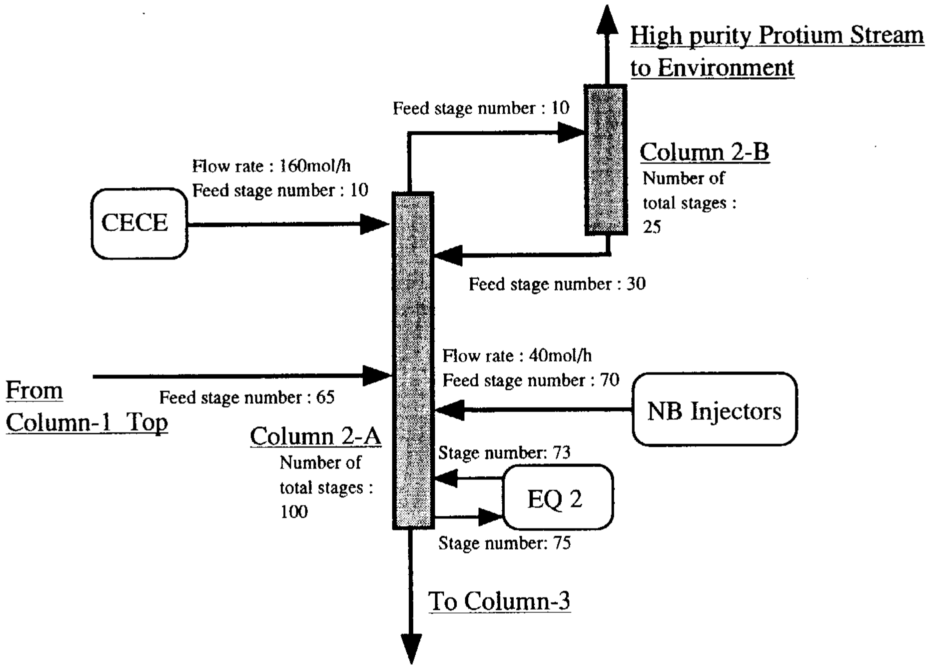


Figure 1 Cryogenic hydrogen isotope separation cascade configuration designed and proposed in this study



Design A: One-column system



Design B: Two-column system

Figure 2 Column-2 design for HT fraction control in the released stream

The Design B (two-column system) is decidedly superior to the Design A (one-column system) from the view point of

1) the control of HT concentration in the released stream and
2) the smaller amount of tritium in the column whose top stream is released into environment.

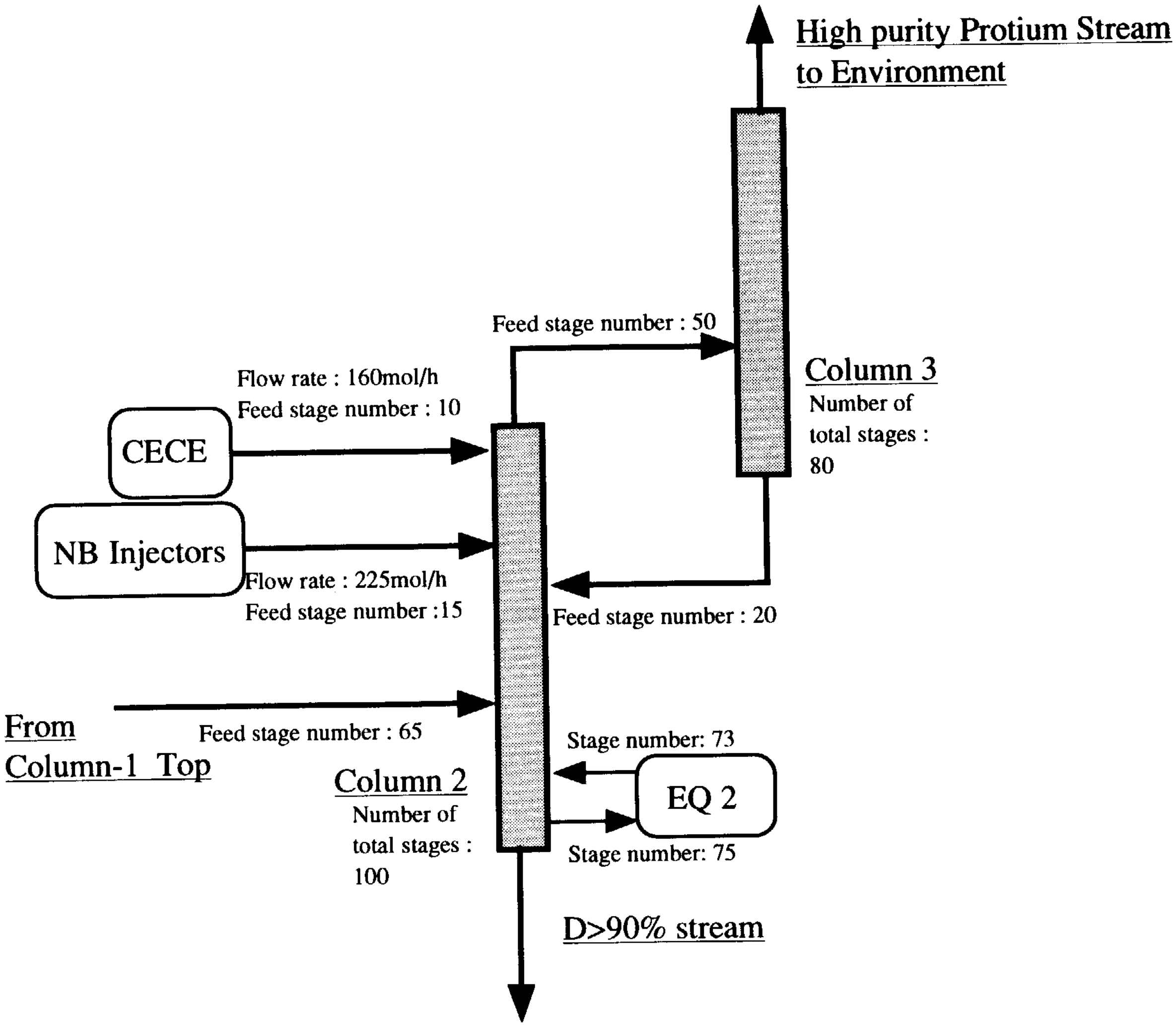


Figure 3 Partial change of cascade configuration by adoption of H_2 as NBI gas

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国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 3　固有の名称をもつ SI 組立単位

量	名称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m{\cdot}kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 2　SI と併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV = 1.60218 \times 10^{-19}\ J$

$1\ u = 1.66054 \times 10^{-27}\ kg$

表 4　SI と共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å = 0.1\ nm = 10^{-10}\ m$

$1\ b = 100\ fm^2 = 10^{-28}\ m^2$

$1\ bar = 0.1\ MPa = 10^5\ Pa$

$1\ Gal = 1\ cm/s^2 = 10^{-2}\ m/s^2$

$1\ Ci = 3.7 \times 10^{10}\ Bq$

$1\ R = 2.58 \times 10^{-4}\ C/kg$

$1\ rad = 1\ cGy = 10^{-2}\ Gy$

$1\ rem = 1\ cSv = 10^{-2}\ Sv$

表 5　SI 接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1. 表1〜5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および 1 u の値は CODATA の1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている。

換算表

力	N（$=10^5$dyn）	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s（$N{\cdot}s/m^2$）= 10 P（ポアズ）（g/(cm·s)）

動粘度　$1\ m^2/s = 10^4$St（ストークス）（cm^2/s）

圧力	MPa（=10 bar）	kgf/cm^2	atm	mmHg（Torr）	lbf/in^2（psi）
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J（$=10^7$ erg）	kgf·m	kW·h	cal（計量法）	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J（計量法）
= 4.184 J　（熱化学）
= 4.1855 J （15 °C）
= 4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）
= 75 kgf·m/s
= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

A Design Study of Hydrogen Isotope Separation System for ITER-FEAT