

Operation of a simulated non-steady tokamak fuel loop using the tritium systems test assembly

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Abstract

In order to develop a fuel system for a realistic fusion device in near future, a number of experimental campaigns of a simulated fusion fuel loop were performed under practical non-steady conditions at the Tritium Systems Test Assembly (TSTA). Some technical issues specific for non-steady fuel loop were identified and are being investigated further. The overall process loop was operated with non-steady inputs to better interface with pulsed tokamak operation, which requires a rather different and improved processing capability specific to each subsystem. The cryogenic distillation columns in the isotope separation are modified to provide side-stream recycle paths with isotopic equilibration function. This change improved separation characteristics with various feed compositions, and reduces the required number of columns for processing and resulted in a reduced tritium inventory in the isotope separation system (ISS). Another major technical development on the ISS is addition of a number of feed-back control loops that automatically operate the distillation columns stably under changing feed conditions. The plasma exhaust processing system composed of palladium diffuser, catalytic reactor, electrolysis cell and cold trap was operated mainly in the batch mode to handle a broader range of input flow rate and composition in various configurations to minimize tritium loss and inventory. The results demonstrated the overall capability and flexibility of the TSTA loop to serve as a fuel processing system under non-steady conditions; however, they imply that many technical issues arise in operating a practical fuel processing system. These may not be foreseen in the design stage and can only be determined during integrated tests under realistic operating conditions.

1. Introduction

The Tritium Systems Test Assembly (TSTA) at the Los Alamos National Laboratory is a unique facility

that can simulate and test fusion fuel processing systems with reactor-scale throughput and tritium inventory in an integrated manner [1]. It has been operated jointly by the Japan Atomic Energy Research Institute

(JAERI) and the US Department of Energy since June 1987. An objective of the TSTA is to develop, test, evaluate and demonstrate the safe operation of fusion fuel processing loop for future fusion machines. In 1990, a new plasma exhaust processing system, the JAERI Fuel Cleanup (JFCU), designed and fabricated by Japan, was installed in the TSTA as an upgrade [2].

Since 1984 a series of experimental campaigns of the TSTA processing loop have been performed with approximately 100 g tritium in order to simulate and study fusion fuel processing at steady-state. Continuous processing of a simulated plasma exhaust (DT and H mixture, He, CH₄ and N₂) has been successfully demonstrated for up to 25 days [3]. In order to operate a fusion reactor as a viable future energy source, the fuel

processing loop to be attached to it is expected to operate continuously and steadily. The demonstration of such a loop with current technology was one of the primary missions of the TSTA.

However, besides prolonged steady state continuous operation, actual fusion machines will likely require various fuel processing modes. For instance, the International Thermonuclear Experimental Reactor (ITER) will operate as a pulsed machine. Also even for steady-state machines, transient operations for ramp-up, shut down, discharge cleaning or conditioning operation will be needed. The fusion fuel processing loop must handle all of these scenarios, recover tritium in reusable forms, discharge undesired elements, and minimize and track the tritium inventory. It may not be quite obvious that

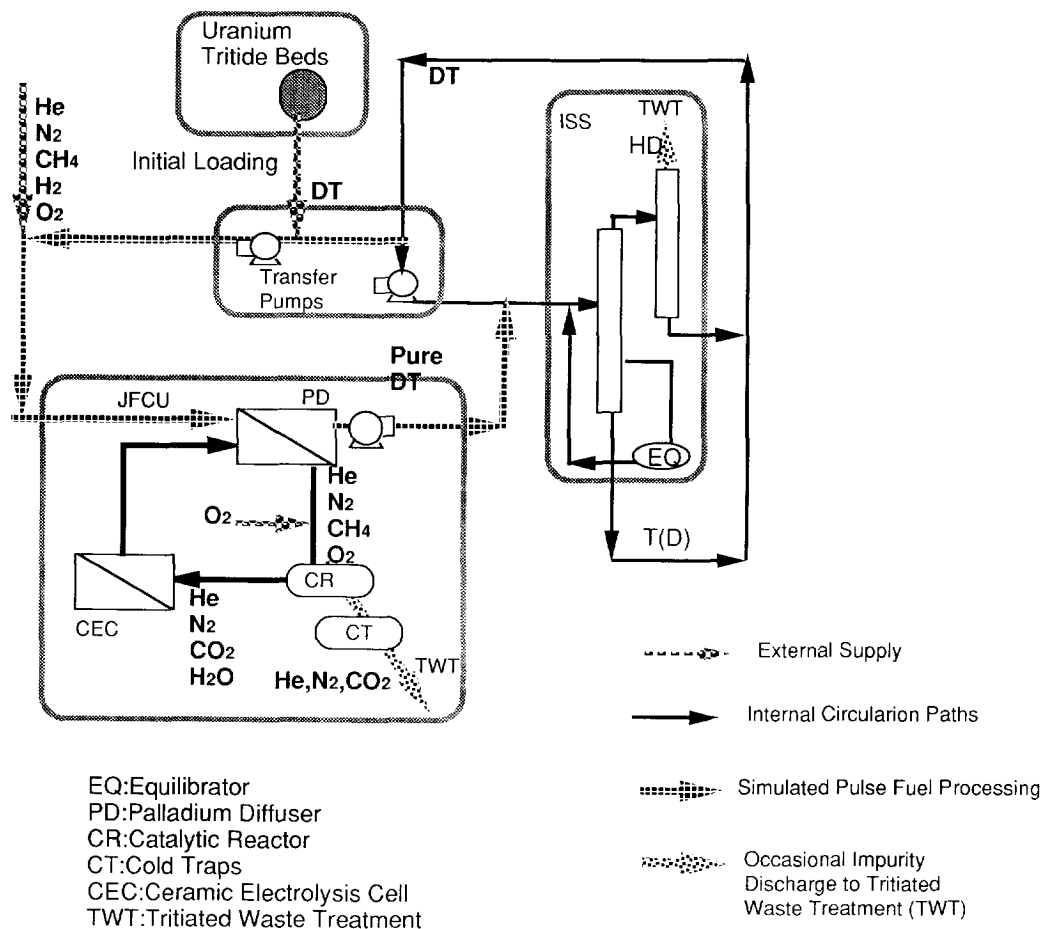


Fig. 1. Simplified schematic of the TSTA loop flow for non-steady fuel processing. Both ISS and JFCU are operated for loop processing and internal recycle.

technical difficulties and problems do exist in expanding the fuel processing system, designed for steady state, to accept various and changing feed and product requirements. Such an operation is unusual for closely integrated chemical plants that are operated in a limited range defined in a chemical flow sheet. The objective of this study is, therefore, to identify the technical issues of operating the fusion fuel loop under practical, non-steady conditions, and to reflect them in improved future fuel system designs.

After the completion of the original five year period of TSTA joint operation, an extended collaboration agreement was initiated in 1992 to conduct further experiments. TSTA has begun integrated fuel cycle tests which process gas streams varying in flow rate and composition to investigate the non-steady fusion fuel processing. This paper describes the results of these experiments and consideration drawn from them.

2. Experiments

Various non-steady conditions for fusion fuel processing were assumed and several experimental campaigns to simulate these conditions were performed using the TSTA fuel processing loop. Typically, pulsed operation of a tokamak will involve: start up of process loop, pulsed fuel feed and exhaust with ramp up, flat-top and ramp down, discharge cleaning and/or conditioning pulses and bakings, possible minor leak, and shutdown and recovery of tritium from the processing system. The TSTA loop was operated to simulate fuel processing in the above modes with changing flow rates and species, processing intermittent impurities, and supply and recovery of tritium.

The required function of the fuel processing loop is assumed as follows.

- (1) To accept intermittent exhaust and process it with minimum delay. Impurities should be removed and all hydrogen isotopes recovered. Processing residual impurity and recovery of tritium from the entire loop is needed at shut down. The system must also be able to process the simulated discharge cleaning that generates a smaller total amount of exhaust with DT concentration.
- (2) To stably operate ISS at varying flow rate, recover and separate tritium for temporary storage for the next discharge. It is not always expected to produce high purity tritium to supply to the tokamak, but the flexibility to handle various separation needs with improved control and minimized inventory is

required. For accounting purposes the quantity and location of all tritium should be known at shut down.

Fig. 1 shows an example of a configuration of the TSTA fuel loop that could process gas from discharge up to several hours in length, with several pulses per day. In this case, the ISS column is configured for a 2 column cascade with sidestream recycle. A sidestream from an isotopic separation distillation column is withdrawn, equilibrated and reinjected to the same column. Although the flow through the tokamak would be intermittent, it is not realistic to operate the fuel cycle in short pulses. Therefore when feed to and discharge from the torus stop, the fuel loop should be operated in an internal recycle mode. In Fig. 1, ISS is operated with all the product sent back to the feed, and JFCU is isolated and gas in the system is recycled. The fuel processing loop can be quickly reconfigured to include tokamak. This non steady state operation was simulated and tested.

Initial loading of the DT mixture was fed from the uranium tritide beds (UTBs). Simulated impurity gases such as methane, oxygen (moisture) and nitrogen were supplied from an external source. For the purification of the hydrogen isotopes, JFCU was mainly used with configurations of palladium diffuser, catalytic reactor and ceramic electrolysis cell. The impurity elements were removed and exhausted to the tritium waste treatment system (TWT). The ISS generated D_2 , DT and T_2 product streams and removed H from the hydrogen isotope mixture. In the ISS, combinations of one, two and four distillation columns, either with or without the sidestream recycle path, were tested to achieve various separation needs. It should be noted that the ISS is expected to perform various functions, such as producing pure T_2 , H-free DT, pure D_2 and T-free H streams under different operating scenarios. The pure tritium produced was sometimes off-loaded and recovered for future experiment at the end of a run. The figure shows the different modes of the operation of the loop. Subsystems are continuously operated and flow path and flow rates are changed to simulate pulse. At the end of the each run, tritium accounting in the loop was accomplished by carefully measuring the tritium before transfer to the UTB for long-term storage.

The objectives of the experiments were to:

- (1) operate the loop to simulate the feed and processing of exhaust with pulsed tokamak operation. That is, run JFCU in batch mode and feed ISS intermittently;

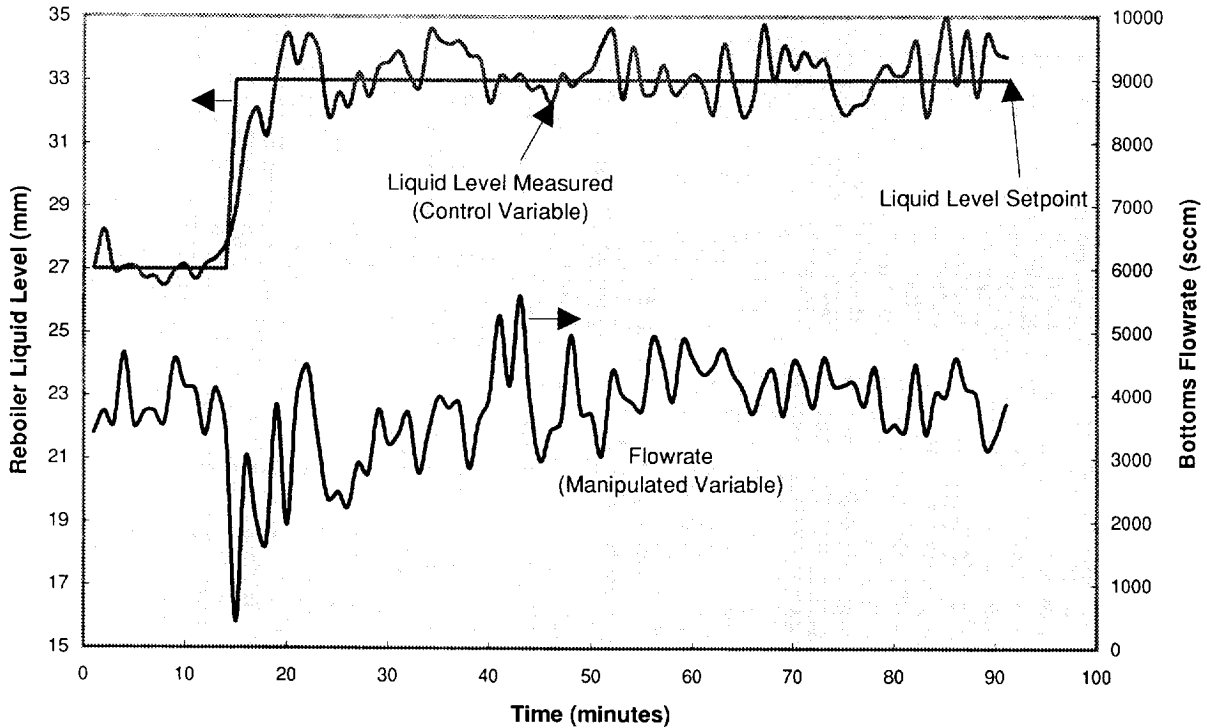


Fig. 2. Example of the distillation column control by reboiler liquid level. Column was stably operated with automatic control of reboiler heat.

- (2) investigate the impurity processing corresponding to various operating scenarios;
- (3) investigate the effect of the side stream recycle flow in the ISS;
- (4) operate a reduced number of ISS columns with relatively small inventories of tritium;
- (5) investigate the response of the ISS to the new control loops;
- (6) demonstrate a practical fuel processing for pulsed tokamak operation and identify future improvements to the fuel processing system.

3. Results and discussion

3.1. Isotope separation

It is preferable to operate the cryogenic distillation columns with continuous steady feed rather than pulsed input. In order to accept changing input, the loop configuration occasionally was switched between loop processing and total recycle of ISS products to the column inlet. Such a change is accompanied with

change of feed flow rate and composition and possibly causes column instabilities such as dry out or flooding. Complete testing of the automatic control system for the distillation columns is important to be able to operate the ISS stably under changing conditions. Three control loops were equipped, tuned and tested on each of the distillation columns. The reboiler liquid level was controlled by changing the bottom flow rate so that material balance is maintained and the column is operated properly. The ratio of flow rates out of the top and bottom is also controlled to keep the column profile stable. Another control loop is used to stabilize differential pressure along the column by controlling reboiler power, so that stable vapor velocity is maintained and column flooding is avoided. These control functions were tested to keep the ISS columns stable with changing set points or feed flow rate between 2 l min^{-1} and 10 l min^{-1} for each column independently. Fig. 2 shows an example of the liquid level control in the reboiler by numerically manipulating the flow rate out of the bottom of the distillation column. The set point is changed from 27 to 33 mm stepwise, and the actual liquid level followed and stabilized. In order to

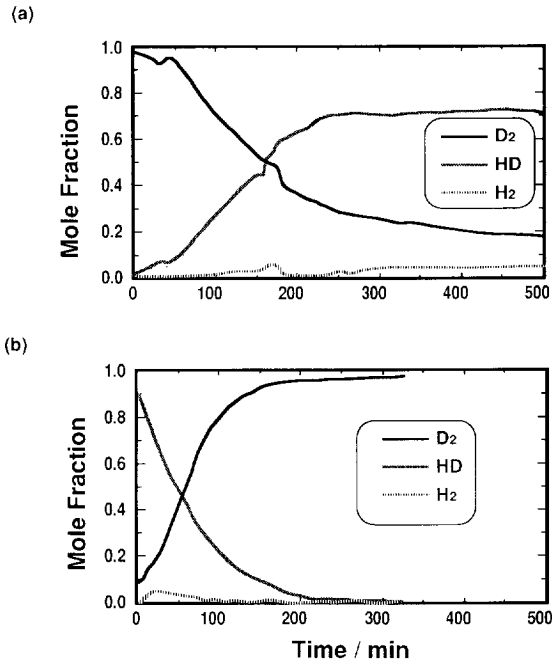


Fig. 3. Effect of the sidestream recycle on reboiler composition for HD system. Upper figure (a) shows the change of the composition in the bottom of the HD distillation column without sidestream recycle, and the lower figure (b) shows the change with recycle.

make this change, flow rate from the bottom was reduced. On the other hand, with the changing feed flow, the liquid level was maintained stable also by changing bottom flow rate. The typical system response was in the range of 10 min. A detailed description and analysis on this control will be presented elsewhere.

As the result of this control, distillation columns were stably operated with changing feed flow rates for days with minimal manual manipulations. After all the control parameters had been tuned for each column, 2 to 4 interconnected columns were also stabilized. The next major issue for ISS control is the implementation of automatic composition control. Real time composition analysis, using Raman spectroscopy, was implemented in the above tests, but the automatic parameter setting based on the analysis as well as previous simulation studies will be utilized in the future.

The other important improvement necessary for the ISS to handle non-steady fusion fuel is the application of sidestream recycle. Withdrawal of a sidestream from an isotopic separation distillation column followed by equilibration of hydrogen species and reinjection to a

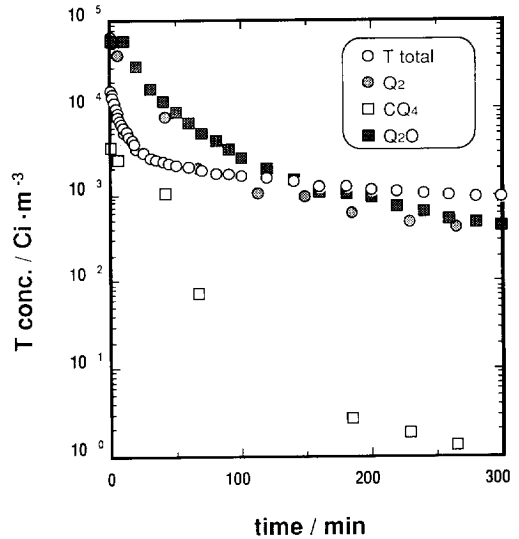


Fig. 4. Change of the concentration of tritiated species and total tritium concentration in the closed processing loop composed of a palladium diffuser, a catalytic reactor and an electrolysis cell. Tritiated impurity was processed by catalytic reaction and electrolysis and tritium was continuously removed by permeation.

different location in the same column offers a means to reduce the number of columns to extract relatively pure homonuclear species. Hence, flexibility, capability to handle a broader range of species and reduced material inventory was made possible. For these experiments, one or two columns were operated and H/D, H/T, and some H/D/T mixtures were separated to simulate various processing needs for non-steady tokamaks. Fig. 3 shows an example of the effect of the sidestream recycle on the bottom composition in the distillation column for H–D system. It is clearly seen that the undesired HD species was decomposed. Detailed analyses are reported elsewhere [4,5].

Implementation of the above mentioned sidestream recycle and automatic control loops for the distillation columns enhances the advantage of interlinked column cascades demonstrated at TSTA. For fusion fuel processing, multiple products are expected to be produced from a variety of feed composition and modes, thus flexible and stable operation of the distillation columns is needed. There generally are two types of configuration of cascade:

- (1) multiple columns are interconnected into one with two products (top and bottom) are obtained. The distillation system at Darlington is a good example;

(2) column cascade to branch the exhaust from upstream and three or more products are generated. TSTA cascade represents this type.

A type (1) system is generally stable with minor changes and easily operated to produce a small number of products. However these are less flexible and almost impossible to handle largely changing feeds. On the other hand, type (2) is more flexible, and even a subset can be operated to meet various separation needs. To maximize the advantage, each column should be independently and stably operated. The several recent experimental campaigns demonstrated that even with changing inputs, the TSTA ISS stably produced multiple products with 1–4 columns interlinked as described earlier.

3.2. Impurity processing

Fuel purification was provided mainly by the JFCU subsystem composed of a palladium diffuser, a catalytic reactor, cold traps/molecular sieve beds and a ceramic electrolysis cell. Simulated torus exhaust gas, which varied in flow rate and composition, mimicking changes expected for practical pulsed DT tokamak operations, was processed by several variation of modes and simplified configurations depending on the amount and species of impurity. When the amount of impurity is small (e.g. tokamak dwell), loop flow either bypasses JFCU or goes through the palladium diffuser while impurities are discharged from diffuser only as required. For intermittent impurity with bound tritium, catalytic treatment immediately followed by electrolysis in batch mode recycle operations were verified. While DT is continuously sent to ISS, impurities are stored and batch processed in the closed loop shown in Fig. 1. Hydrocarbons and tritiated water are decomposed using the catalytic reactor and electrolysis cell, to DT and tritium-free species. When required, tritium-free impurities are discharged either through or bypassing the cold trap/molecular sieve, hence handling of condensed phase water was eliminated. It was a major advantage of this configuration that impurities are processed at relatively small throughput with considerably smaller total inventory, therefore neither generation of water nor handling condensed phase water were major concerns.

In the experiments, loop flows of 2 to 8 l min⁻¹ containing up to 3% of impurities (CH₄, N₂, He, O₂) are intermittently fed to the JFCU for 2 to 10 h of pulse. Impurities were processed by various configurations of the JFCU. When little tritiated species are

contained in the impurity, removal of tritium only by permeation was sufficient to reduce tritium level in exhaust down to ca. 100 Ci m⁻³. Tritiated water was decomposed by the electrolysis as required. Tritiated methane was decomposed either with or without oxygen addition. Fig. 4 shows an example of the impurity processing in the closed loop shown in Fig. 1. Prior to this processing, 6 l min⁻¹ of DT with 1% impurity (N₂, and 5% O₂) was continuously fed to the JFCU for 4.5 h. It should be noted that even without external addition of impurities, various impurities such as methane and moisture were separated and observed in the JFCU. After the isolation of the JFCU from the system, stored impurity mixture containing Q₂, Q₂O and CQ₄ species was processed at the flow rate of 10 l min⁻¹ by permeation-Pt-catalyst-vapor electrolysis loop without addition of oxygen. The decrease of total tritium (in Ci m⁻³) was measured with an ion chamber, Q₂O by a hygrometer, and Q₂ and CQ₄ were analyzed by gas chromatography (GC) at the outlet of the catalyst bed and shown for comparison. Total tritium concentration drops quickly at the beginning while free Q₂ exists, but slows down when the concentration of Q₂ is low. The GC analysis of Q₂ at the inlet and outlet of the palladium diffuser indicated that less than 0.5 of feed Q₂ permeated the palladium when the inlet Q₂ concentration was lower than ca. 0.1% and thus slows down the cleaning. It seemed, however, the observed Q₂ is a product of electrolysis of water and the release of moisture from the inner surface of loop was the rate determining process in this cleaning operation. It should be noted that methane was decomposed relatively fast without oxygen addition. Either steam reforming reaction (Q₂O + CQ₄ → CO + 3Q₂) or cracking of methane (CQ₄ → C + 2Q₂) is considered to have attributed, but not identified yet. After the 5 h of this closed loop processing, exhaust was discharged to TWT. Overall decontamination factor (DF) of 7 × 10⁴ was observed as a ratio of total processed tritium throughput at JFCU (1.5 × 10⁶ Ci over 4.5 h) to the tritium released in the discharged exhaust (ca. 20 Ci) for this batch. The values of DF in other batches were similar, but strongly dependent with impurity concentration in the JFCU feed. These values of DF are somewhat worse than oxidation-cold trapping process that showed over 10⁶ [2], but this process involves no handling of condensed water. This configuration and mode is particularly suitable for intermittent plasma exhaust processing, residual impurity processing, and as a shut down procedure of the entire fuel processing loop. For large amount of impurities or quasi steady-state operation, the JFCU can be operated at full

capacity with oxidation and cold traps, that provides better DF for once-through pass.

4. Conclusions

Fuel processing for simulated non-steady tokamak in an integrated closed loop was demonstrated successfully. Overall the TSTA processing system was found to be flexible to accept changing throughput, various impurity modes, and producing various isotopic streams. Automatic control of the ISS columns and the effectiveness of sidestream recycle for this purpose were verified. JFCU process demonstrated the versatile processing modes and configuration to be suitable for various operation needs including avoiding generation of water. These results experimentally demonstrates the advantages of ISS multi-column cascade configurations and JFCU palladium diffuser-catalyst-electrolysis combination in a practical fusion fuel loop under non-steady conditions with reactor-relevant scale and quality.

Some future improvements such as in the composition control and inventory minimization at ISS, and better understanding and further improvements of impurity processing were uncovered. It is pointed out that these technical issues related to non-steady operations, transient behavior, and system control are important

for a practical fuel system, but may not be foreseen in the design and only be uncovered in the realistic experiments.

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