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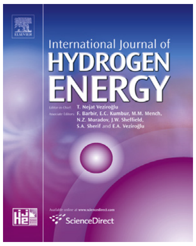

# Optimal design of the multi-bed storage system in fusion fuel cycle under periodic demand based on the state-task network representation

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ABSTRACT

This paper proposes an optimization model for the design of the multi-bed storage system which is a main fueling facility in fusion fuel cycle of nuclear fusion. The objective of the problem is to minimize total number of equipment, getter beds and buffer vessels, in the multi-bed storage system under periodic demand. The mathematical model is formulated as a mixed integer nonlinear programming problem based on the State Task Network (STN). To simplify the problem, team and cycle-based operation is assumed. Moreover, to ensure safety of the design, a worst-case operation condition is provided. The proposed model is applied to the inductive operation mode. With parametric sensitivity analysis, the model is expected to provide many useful insights to determine the number of units and to guide future research.

## Introduction

Power generation using nuclear fusion has the potential to meet future energy requirements. Overall nuclear fusion system consists of two parts: the Tokamak for main reaction and fusion fuel cycle for fueling including main reactants, tritium (T) and deuterium (D). The deuterium-tritium (DT) fuel cycle is composed of several subsystems for storage, fueling, separation, pumping, and detecting [1–4].

Among subsystems, the storage system is one of the most important systems in terms of two main functions: 1) storing

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returned residual tritium and deuterium after fusion reaction and 2) supplying them to the Tokamak at the required timing. The stability of fusion reaction in the Tokamak is significantly influenced by design and equipment specification of the storage system.

Due to this importance, many studies have been conducted to develop storage equipment with high storage ability and safety [5–12]. Until now, uranium or zirconium-cobalt has been focused as a good storage medium. However, due to high cost of medium material, one storage equipment is expected to be expensive. Moreover, it has been shown that multi-beds more than ten units are needed in the storage system for continuous fuel delivery [13]. These two results indicate high capital cost of the multi-bed storage system.

To reduce total cost, the appropriate number of units must be determined, but only one work has been performed to achieve that goal [13]. Previous authors evaluated the appropriate number of units by performing case studies on several configurations of the storage system, focusing on the minimum flow rate in the storage system. The results are useful, but mathematical optimization was not applied, so the optimality of the results is not assured.

The mathematical modeling and optimization has been used and applied to various kinds of processes and systems. Traditionally, optimal process design and operation schedule of chemical process have been obtained successfully by mathematical modeling [14–18]. In recent decades, this approach has been extended to be applied to new technology such as fuel cells and battery systems in order to achieve various goals, for example, to analyze system stability [19–21], maximize performance [22–24] or minimize system cost [25–28]. However, until now, there is no research for the storage system of fusion fuel cycle.

In this work, a mathematical model for optimal design of the multi-bed storage system is proposed to minimize the capital cost and to find the globally optimal number of units. Based on the analysis in Section system description in which the multi-bed storage system has a configuration similar to that of a single-product semi-continuous plant with bypass lines in chemical plant, the model is expected to consider batch or continuous process design methods [29,30].

Two methods can be used: batch-oriented and network-based. The network-based design approach is more appropriate in that it allows consideration of complex system configuration and several operational conditions. Three well-known network-based models have been introduced: the State Task Network (STN) [31–33], the Resource Task Network (RTN) [34–38] and the maximal State Task Network (mSTN) [38–43]. The mSTN is more efficient than the STN or RTN [43], and STN-adapted and the RTN-adapted model have been suggested; these are better than the STN or RTN [43]. However, despite these conclusions, the formulation of the proposed model is based on the STN; the reason is that mSTN and the adapted models focus on how to configure the network, given a process network superstructure. For that, they represent the information about what equipment exists at a state node and use a binary variable that states whether or not the equipment is used. These requirements complicate the task of determining the number of units that should be installed. In contrast, state and task nodes of the STN only focus on the amount of material transformed. With small modification, the STN approach is more suitable to calculate the required number of units than are the mSTN and other approaches.

In addition to the STN, two special approaches are applied. First, the team-cycle based approach is applied. The ‘team’ component of this approach acknowledges the fact that the operation of equipment is much longer than one cycle period of a demand. The ‘cycle’ component considers the periodic demand of the Tokamak and the cyclic operation of equipment. According to this approach, the problem includes decision variables like optimal cycle time, number of teams and amount of equipment allocated per team. Second, a worst-case scenario approach is suggested, with the goal of finding a design solution that can satisfy all changeable demand cases.

The rest of the paper is organized as follows. Detailed descriptions of the storage system and its operation features including the specification of demands and returns are presented in Section system description. Next, solving approaches and the STN representation are described in Section design approach. Problem statements with objective, decision variables and assumptions are given in Section problem statement. The mathematical model for the design problem which is formulated as mixed-integer nonlinear programming is presented in Section mathematical model. The formulation is applied to the inductive operation mode to determine optimal design in Sections case study and results and discussion. Concluding remarks are given in Section conclusion.

## System description

When developing a design model, operational features of the system, particularly the storage system and separation system must be understood. This section describes system structure, equipment, flow pattern of demands and returns.

### *Structure and equipment*

The structure of the multi-bed storage system for fueling can be simplified as a sequential single product process [13] (Fig. 1). It consists of two lines: $T_2$ line through which mainly (≥80%) $T_2$ is transferred, and the $D_2$ line through which mainly (≥80%) $D_2$ is transferred. Each line includes getter beds and buffer vessels, which are installed in parallel. Material flow between stages has full-equipment connectivity [31], which means that materials can flow among all available units in each stage simultaneously.

The getter bed is a unit for safe storing fuels including tritium. The operational features of the bed are the same as those of a general absorption tower in which materials are absorbed or desorbed in response to temperature changes. Operation consists of four steps: absorption → heating (+evacuation) → desorption → cooling (Fig. 2). Absorption and desorption operations are each completed in 30 min; heating and cooling operations each require more than 1 h.

The buffer vessel is a unit for temporary storage, and is similar to a general storage tank in chemical plants. In a buffer vessel, hydrogen isotopes remain gaseous, so they pose a