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Hypothetical daily operation model of fuel cycle in tritium plant

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ABSTRACT

This paper describes a design model for the fuel cycle of a tritium plant; the model considers both the fueling line and the Neutral Beam Injector line. The fuel cycle typically consists of a 16-h of burn-and-dwell operations followed by an 8-h silent shift, so the behavioral changes of fuel cycle of the tritium plant are influenced by both an hourly cycle of burn-and-dwell operations and 24-h cycle. To provide a tool to optimize the tritium inventory level, and to gain insight into the behavior changes of the fuel cycle, a mathematical model is developed. The model mainly focuses on the Isotope Separation System, which holds the largest amount of gaseous and liquid tritium. The optimization problem is formulated as a mixed integer linear program model with linear constraints. An inductive operation scenario is presented to illustrate the applicability of the proposed model. The obtained minimum tritium working inventory in ISS is 103.498 g in the inductive operation scenario.

1. Introduction

The main function of the fuel cycle of a tritium plant is to provide a required amount of fuel to a fusion reactor; another function is to reprocess the large amount of unburned fuel that the fusion reactor emits. In the ITER experimental tokamak reactor, the operation cycle consists of 16 h of repeated burn-and-dwell operations during the day, then a *silent shift* and system check at night [1]. Consequently, the behavior of the fuel cycle changes on a 24-h cycle, and is affected by the hourly cycle of burn-and-dwell operations.

The tritium plant must ensure production of the required amount of tritium, under the constraint that the amount of fuel inside the system must not be allowed to exceed a safe level. Many researchers have developed fuel cycle models that track the amount of tritium inside the equipment. Early fuel cycle models were developed based on the concept of residence time [2]. To increase the accuracy of models, information such as average non-radioactive loss reaction and the tritium decay time was incorporated in a black box model characterized by general tritium residence time. In addition to black box models, several approaches were adopted to develop dynamic fuel cycle modes such as X-TRUFFLES [3], CFTSIM [4], DYNSIM [5], and TRIMO [6].

However, few studies have been conducted to indicate the tritium inventory during a burn-and-dwell cycle, and a daily cycle in terms of safety. Because ITER restricts the tritium inventory in each unit to avoid severe damage if the tritium leak, reduction of tritium inventories is an urgent challenge in fuel cycle modeling.

Therefore, the goal of this study is to provide a tool to optimize the tritium level especially in the Isotope Separation System (ISS), and to report information on daily trends and hourly trends in the tritium level. This work is original in suggesting both daily cycle and the burn-and-dwell hourly cycle of the tritium inventory in the fuel cycle by proposing the same mathematical model that considers both the fueling line and the Neutral Beam Injector (NBI) line. We propose a mixed-integer linear programming (MILP) model that suggests the optimal scheduling to minimize the tritium inventory level inside the ISS.

2. System description

2.1. Fuel cycle of tritium plant

We focus mainly on the ISS, in which all hydrogen isotopes are collected and separated by cryogenic distillation. To minimize tritium level in the entire fuel cycle (Fig. 1), ISS is a key component in that it is allowed to hold the largest in-vessel tritium inventory, 700 g [7].

To perform efficiently and to provide the desired product, the minimal inventory required in the fuel cycle is called *base inventory*. For example, the base we need a different approachinventory is 0 in the torus cryopumps, but sizable in the ISS. For practical plasma operations, additional inventory called *working inventory* must be available. In this paper, we aim to minimize working inventories.

The main function of ISS is to accept hydrogen isotopes from the Tokamak Exhaust Process (TEP) system, producing pure gas, and

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Nomenclature

Indices and sets

i Tasks
j Units
n Event points
s States
$I^{ISStoBV}$ Tasks of delivering fuel from ISS to BV
$I^{BulkStorage}$ Tasks of dehydriding reaction of bulk storage
J^{BV} Buffer vessel

Parameters

$Bstarttime_i$ $Bfinishtime_i$ Start time and finish time of dehydriding reaction task i (sec)
dur_i^{fix} Fixed duration of task i (sec)
β_i Rate constant of task i (Pa m3/s)
F_0 Initial inventory or unit j (Pa m3)
F^{max} Maximum inventory or unit j (Pa m3)
H Big value

Variables

$wv_{i,n}$ Binary variables that assign the task i at event point n
$B_{i,n}$ Size of task i at event point n (Pa m^3)
$F_{j,n}$ Inventory of unit j at event point n (Pa m^3)
$ST_{s,n}$ Amount of state s at event point n (Pa m^3)
$Iniratio_j$ Initial ratio of inventory of unit j
$T_{\max}$, $T_{\min}$ Maximum/minimum inventory in ISS (Pa m^3)
dur_i Duration of task i (sec)
$T^s_{i,n}$, $T^f_{i,n}$ Start/finish time of task i at event point n (sec)
$Istart_i$ Start time of task i (sec)

transferring hydrogen to the Storage and Delivery System (SDS). The nuclear fusion reaction in the tokamak produces exhaust gases that are collected in the Vacuum Roughing System (VRS) and moved to the TEP. VRS are composed of cryopumps and roughing pumps. Fuel gases processed in the TEP are transferred to ISS and delivered to the Fueling System (FS) through buffer vessels (BVs). On the other hand, the gas flow from Neutral Beam Injector (NBI) are collected to the aforementioned VRS and moved to bulk storage System of SDS.

BVs are temporary storage units in which fuel exists in the gas phase. SDS T_2-line and D_2-line are composed of several BVs. The maximum storage amount of D_2-line BVs are five times larger than the T_2-line BVs. Getter beds are the main storage units; they are used to store fuel gases in solid material. Bulk storage system (HBS, DBS) and Neutralizer Supply (NS) are composed of getter beds.

SDS Fueling line (T_2-line and D_2-line) BVs store the required amount of fuel for burn-and-dwell operation and provide fuel to the FS during the day. The Bulk Storage system in SDS stores fuel for the NBI line during the night.

To consider how burn-and-dwell operations and daily changes affect the fuel cycle, both fueling lines (T_2-line/D_2-line in SDS) and NBI-line (NS) are considered. The fuel cycle model consists of the following equipment: TEP, ISS, and fueling line of SDS (T_2-line and D_2-line BV) and NBI-line (NS, HBS, DBS) of SDS. The NB High Purity D/H Supply (HPDHS) system and the NB High Purity H Supply (HPHS) are not included in the model.

2.2. Burn-and-dwell operations and one day operation

ITER is a pulse machine, operated as burn-and-dwell. During inductive operation, fuel is introduced during a 400-s-burn and dwell until the end of a 1800s-period [8]. Sequential pump regeneration of the fueling line occurs during the 16 h of burn-and-dwell operations, and all cryopumps including the NBI line are regenerated overnight during the so-called *silent shift*. The offset timing of the operations is necessary because the fueling line and the NBI line share the same VRS [9]. Accordingly, the fuel that is accumulated during daytime burn-and-dwell operation in NBI is delivered to the Bulk Storage system at night through the dehydriding reaction at the start of the day. While dehydrating reaction of the Bulk Storage System takes place, the fuel of the Bulk Storage system is delivered to ISS during daytime (Fig. 2). The dehydriding reaction of the Bulk Storage System has the most significant effects on the daily trends of the fuel cycle.

2.3. State-task network

The optimization model is formulated based on State-Task Network (STN) [10] which converts a process configuration to a network graph that considers *state* and *tasks*. *State* represents the status of material, such as feed, intermediates and final products; *task* represents processing or transferring operations within units. The model uses a general continuous time representation, which does not compromise feasibility or optimality [11].

In this study, the fuel cycle (Fig. 1) is converted to the STN (Fig. 3) with 20 states and 16 tasks. The feed states are *VRS*, *DBS*, *HBS*, and the fuel gases are transferred to demand states: *NS demand, D_2-RU demand, D_2-FT demand, D_2-RD demand, T_2-RU demand, T_2-FT demand, and T_2-RD demand*, through several intermediate states.

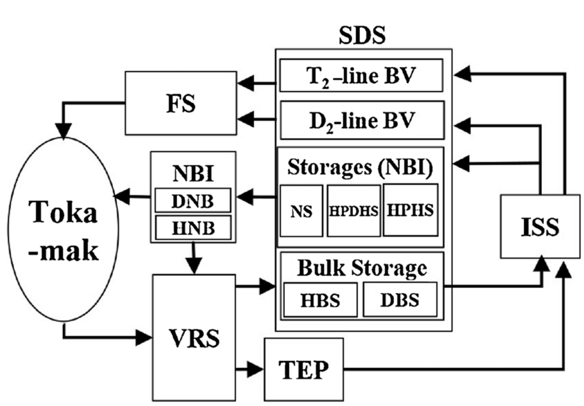

Fig. 1. Fuel cycle of tritium plant. Components and processes are defined in the text.

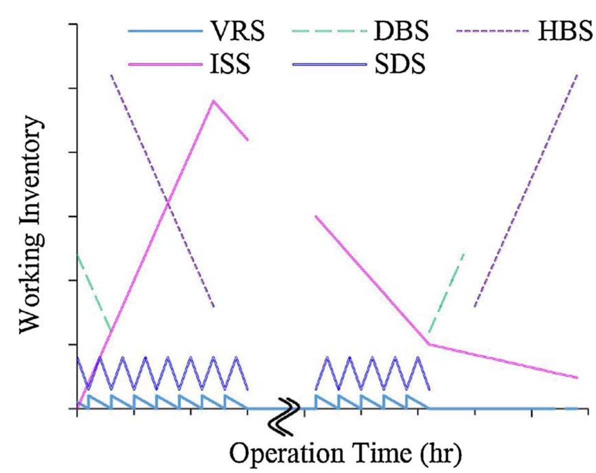

Fig. 2. Working inventory of the fuel cycle during a day.