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Myth of initial loading tritium for DEMO—Modelling of fuel system and operation scenario

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HIGHLIGHTS

- Start up of fusion plant without external source of tritium for initial loading is needed.
- Realistic Power Ascension Tests (PAT) of fusion DEMO is explained and analyzed.
- Typical PATs require years of operation from minimal power and pulsed power output with long dwell time.
- Tritium plant is continuously operated to recover all the tritium produced by the DD and low DT burn.
- Collected tritium is sufficient for the tests at virtually no additional cost or operation time.

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ABSTRACT

Any fusion power reactors such as "DEMO" that achieves tritium self-sufficiency with breeding blankets can produce tritium by DD reaction followed by exponential breeding in the blanket within reasonable total operation period. The present study further suggests that realistic Power Ascension Tests (PAT) of DEMO can produce its tritium to be needed in the series of tests by its own program until reaching steady state full power operation, with no external supply or additional operation costs. Closed tritium fuel plant was described by a system dynamics model, and analyzed considering realistic PATs of DEMO, that will be mainly pulsed DD and low concentration DT. Typical PATs require years of operation from zero power criticality to full power, with pulsed power output and long dwell time between them. Output power is gradually increased in PATs to check the functions of reactor systems and components. In the case of fusion DEMO, zero power criticality corresponds to DD operation. While plasma may be fired in pulses, tritium plant is continuously operated to recover all the tritium produced by the DD and low DT burn. Depending on the different time constant of tritium retention in components, tritium is transferred by deuterium purge, and high concentration tritium is finally collected in the storage, to be available for the next tests at virtually no additional cost. Realistic "initial loading tritium" will be 100 g for commissioning of tritium plant far prior to the plasma operation.

1. Introduction—the myth

It is still widely believed that fusion DEMO reactor will need significant amount of tritium at the beginning of operation. No commercial tritium will be available in the world market in kilograms of quantity after ITER. If DEMO would really require external tritium sources, few such projects could be launched, because the availability of the fuel is not guaranteed. Such a "Myth" of initial loading of tritium further jeopardizes the possibility of fusion as a viable energy source in the future. Under this scenario, initial loading of tritium for the next generation of DEMO reactor can only be started by the fuel produced by the preceding reactors. If it was true, deployment of fusion energy would be, even if it would be successfully developed, extremely slow in the first several decades due to this "doubling time" constraints, and fusion contribution in the world energy supply in this century should be rather limited.

The authors have first pointed out that steady operation of plasma can produce sufficient amount of tritium in a reasonable period of DD operation by DD reaction followed by exponential breeding in the blanket [1]. Regardless of the types of breeding blankets or fusion fuel cycle, if and only if overall tritium breeding ratio (TBR) exceeds unity, typically 1.05 or greater, such a DD start scenario is always possible within the matter of several months of total operation from DD or low concentration DT. We also pointed

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out that without the limitation of the external supply of initial tritium, significant difference of the initial deployment speed of fusion energy can be resulted, because many first generation commercial plants can be constructed at the same time [2]. The succeeding fusion plants will not have to wait for the tritium production by the earlier fusion reactors.

In this consideration, the amount of required production of "initial loading tritium" is considered as equal to at least the total plant tritium inventory, that is a snap shot of the amount of tritium estimated to exist in all the components consists fuel cycle in the steady state full operation. Also in the estimation of the required period for tritium production by DD and low concentration DT operation with exponential breeding, continuous, steady state plasma discharge is assumed for simplified discussion by the authors [1]. In this hypothesis, cost of the operation of plant with external power supply is needed because the low concentration DT operation cannot sustain its plasma temperature due to the low Q value. This additional external electricity and duration of plant operation is regarded as the required cost to substitute external tritium supply, if such an operation is dedicated for tritium production [3].

However, in the realistic operation scenario of fusion plant during the commissioning phase, it is quite obvious that no power plants can start its full power operation at the beginning of commissioning with full tritium inventory. In the commissioning phase, plant output power would be gradually increased to check out and verify all the functions of the components and subsystems. Such operation is called Power Ascension Tests (PAT) that have been conducted in any kinds of newly operated plants. All the power plants are first operated in pulsed modes with minimal power for testing purpose. In the case of the fusion reactor where tritium fuel circulation system is directly attached to the plasma device, distribution of tritium is dynamic and its behavior is rather different from normal steady state operation "snapshots".

This study investigates the realistic scenario of tritium supply in the commissioning phase of the fusion DEMO plants. For this purpose, tritium fuel system is analyzed by system dynamics methodology, considering generic Power Ascension Tests as the commissioning phase. The results provide typical tritium acquisition strategy and estimation of additional cost concerning initial tritium, that clearly denies the necessity of initial loading tritium.

2. Analysis of tritium fuel system

2.1. System model

The tritium fuel system is described with a generic model. Such attempts have already been successfully described not only steady state, but also dynamic behavior from 1980s with some earlier design of the fusion fuel cycles [4,5]. These models also indicated the required initial loading of tritium from the plants' steady state inventories. In this study, also simplified model is used and the Primary fuel loop is composed of; Fuel Clean Up, Isotope Separation, Fueling&Storage, Vacuum chamber/Plasma closed loop and Blanket that supplies bred tritium to the Isotope separation as shown in Fig. 1. Each components has specific inventory of hydrogen isotopes and their time constants to be analyzed with system dynamics codes. In this study, STELLA™ is used [6].

It should be noted that each components or subsystems of the primary fuel cycle has at least two kinds of tritium inventory, "Active Inventory" and "Inactive(Dead) Inventory", respectively means tritium being processed in the components to circulate in the loop, and tritium trapped and not immediately utilized in the process. In the dynamic analysis of pulsed operations, they should be separately considered, with different time constants and isotopic contents. Isotope exchange occurs among all the components. For instance, the Fuel CleanUp that chemically recovers and purifies plasma exhaust comprises several catalyst beds. The gas stream containing DT mixture is the "Active Inventory" that goes through the beds in seconds with milligrams of inventory, while "Dead Inventory" is adsorbed on the catalysts and stays minutes. In the steady state operation, isotopic contents of both are very similar, however in pulsed operation, they are different due to the different residual time constants. Such difference of the two types of tritium inventory in the components, tritium behavior in the fuel loop is significantly different in steady state and pulsed operation modes. For analysis of realistic commissioning scenario, return from the secondary system such as water detritiation is also considered. Tritium lost from the primary cycle goes to the detritiation systems from effluents to prevent environmental discharge and to improve tritium economy. Recovered tritium from permeation, exhaust gas and contaminated water will eventually be returned to the primary loop, but it takes typically several weeks, and amount will be several grams at largest. Decay of the tritium is regarded as the part of the loss from the primary loop, but will not return. This loss term also contains dissolution into the structural materials or other loss, that decreases the total tritium breeding in the entire system.

Table 1
System parameters used in the SD model.

Parameter	Unit	
G_{DD}	–	0.67
G_{DT}	–	1.1
τ_{ex}	s	1200
τ_{is}	s	1800
τ_{fu}	s	1800
τ_{bk}	s	1.73×10^5
a_i	s^{-1}	1.0×10^{-9}
b_i	s^{-1}	1.0×10^{-6}

Although actual fuel system for the DEMO is not available at present, this general model can describe the variety of process components. For instance, plasma chamber and various plasma exhaust process have various adsorption sites for tritium on the surface, but they can simply be represented by different values of inventory and time constant in the model. Table 1 shows the time constant and parameters used in the system dynamics analysis in this study. Tritium Production for DD and DT neutrons, G_{DD} and G_{DT} are respectively assumed to be 0.67 and 1.1, due to the difference of neutron multiplication reactions that are dependent on neutron energy. TBR is usually defined as the ratio of bred tritium divided by lost tritium. In the case of DD operation, tritium obtained by either DD reaction or reaction of DD neutron with lithium is fewer than unity, however no tritium is consumed. Time constants of active inventory for the tritium process subsystems for plasma chamber, fuel cleanup and isotope separation, fueling and storage, breeding blankets, are expressed as respectively τ_{ex}, τ_{is}, τ_{fu}, τ_{bk}, rates of the tritium loss(decay and extremely long time constant to satulate) and relatively faster process to go to the dead inventory by such processes as isotopic exchange, adsorption and absorption are respectively expressed as a_i and b_i.

Those parameters are strongly dependent on the processes to be selected for each purposes. For instance, if the cryogenic distillation is selected, typical inventory will be 100 g, and their residential time is hours as liquid circulating in the column. Dead inventory on the surface is small. If adsorption based process is used, inventory will be smaller, with larger dead inventory and slower time constant. There may be many possible process selection and system designs for fusion fuel cycle, and the model can be more detailed and sophisticated, however the tritium behavior in the entire loop can be represented by a simple model, with various possible parameters to be assumed or measured for different process components. The behavior of the tritium in the plant, particularly the breed-