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Risk-based multi-criteria design concept of the ITER SDS getter bed

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ABSTRACT

The main objective of ITER tritium Storage and Delivery System (SDS) is contracted to develop an optimal metal hydride bed that can be reveal the unprecedented fueling performance for the Tokamak. One function of the hydride bed is to keep safety requirements in terms of confinement of tritium. The hydride material for storing the deuterium and tritium fuelling gases is being made narrow with depleted uranium (DU) by its good performance. DU also has its own uncertainties, however, in applying it to realize the getter bed system having an all-round capability, especially in aspect of safety. This paper deals with from bed design target to the design variables in terms of comparison of risk-based multi-criteria using HAZOP (risk matrix) analysis. In analysis of the risks, important variables that denotes safety-effective, or cost-effective, or maintainability-effective, or manufacturability-effective are sometimes mutually interrelated with each other. As a conclusion the authors could recommend the way to concentrate and minimize the bed design variables with most meaningful risk-containing components that can be applied to increase the performance of hydride bed. It needs, however, that further study of comparison of risk analyses should be proceeded to complete the hydride bed design.

1. Introduction

A key design objective of the ITER tritium SDS is to develop a metal hydride bed that meets the unprecedented levels of performance required for fueling of the Tokamak and which optimizes the confinement of tritium. The main requirements for the metal hydride storage beds of the ITER SDS are inherent tritium limitation to a certain amount, fast delivery and fast recovery of the hydrogen isotopes and in-bed calorimetry to allow for tritium inventory measurements [1]. One important reason for selection of hydride species which are to be used for storing the deuterium and tritium fueling gases is to minimize the accidental situations; gradual performance degradation and getting of resultant unworkable tritium or generation of dead zone having a certain amount of tritium by disproportionation, such as chemical stability change under rather higher temperature and pressure condition; plugging and getting of resultant uncontrollable hydride bed system in the presence of vacuum pumping system caused by hydride powder migration, and getting of unusable residue inside the hydride bed; and so on. A foremost requirement is the reliability of tritium confinement in all normal, incidental and accidental situations. This need affects not only the structural requirements of the design, but also the selection of particulate filters, as one example, to ensure unacceptable levels of particulates do not exit from the hydride bed. Compatibility with the ITER authorized domain, as represented by the preliminary safety report (RPrS), will be ensured, in particular with respect to waste management [2].

Performance requirements for the bed are obtained from the fuelling needs of the ITER machine. The ability to deliver gas at a high rate and to quickly reload with gas recycled via the isotope separation system place a need for very effective heat transfer for heating and cooling of the hydride material [3]. A separate need to establish and maintain precise static and isothermal temperatures for tritium inventory measurements by calorimetry mean that high levels of thermal isolation are also needed at such times. This ability will be met by locating the storage vessel for the hydride material within an outer jacket which can be gas filled or under vacuum, depending upon the operations being performed by the hydride bed [4].

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Table 1
Functions & requirements of SDS [1,3,4].

	Standpoint	Specification or tool
Fn	1. Safety	Tritium confinement, fire sector, MBA
	2. Tritium accountancy	Tritium inventory estimation
	3. Fueling rate	To keep fueling scenario
Req.	1. Max. tritium/fire sector	Max. 70 g of tritium
	2. In-bed calorimetry	T_2 accuracy: 3 g/8 h or 1 g/24 h
	3. Fueling rate	Max. 110 Pa m^3/s T_2

Fn: function; Req: requirement.
MBA: material balance area of T_2 (tritium).
In-bed calorimetry: to measure tritium amount in bed inside due to the tritium decay heat by in-bed He circulating calorimetry [3,4].

With looking at insight to design hydride getter bed in detail there are quite a few variables to be taken into account; in aspects of safety-effective, maintainability-effective, cost-effective and manufacturability-effective, and so forth of risks. Every elementary component which is considered as assembled device of the hydride bed—for example, from the choice of electric heater type and capacity, inside surface area of calorimetric helium coil, filter opening size and thickness, even to the choice of horizontal or vertical type in bed installation—must influence to optimize the concept of overall hydride bed design. In other words, this approach is to be classified into a multi-criteria decision making problem. Recently a few researchers report a kind of design tool using various decision making methods. Risk-based design margin in heat exchanger design [5] and electricity distribution [6], natural gas ship design and operation [7] and so forth. In case having lots of uncertainties just like hydride bed design, risk-based HAZOP (Hazard and Operability) study is used in most of decision making [5–7]. In ITER safety analysis HAZOP study and RAMI (Reliability, Availability, Maintainability, Inspectability) analysis are the formal requirements to estimate and to reduce the system risk [8,9]. Considering uncertainties in hydride bed design system, RAMI analysis may be limited to be applied as design concept criteria.

In this paper the HAZOP approach, risk matrix study, is utilized to analyze the design variables that have uncertainties to impede the concretization of the critical values or reliable data in construction of hydride bed which is composed of more than tens of components. With an assistance of HAZOP the prior characteristics on risk-based components could be suggested to take into account its specification at first.

2. Hydride bed design variables

2.1. Functions, requirements of the hydride bed

The functions and requirements of the ITER tritium SDS is introduced in several ITER documents, especially in SRD (System Requirement Document) or DD (Design Description). Here Table 1 summarizes the function and requirement of the ITER tritium SDS [1,3,4]. The most important function of the SDS is to keep the system safety such as double confinement (including process system and building system, or in the process double pipes or double outer envelope, i.e., utilization of jacket-type container, etc.) to prevent tritium release to the outside. Thus, in aspect of shelter of environment from the tritium treating process most of SDS is contained in the glove box (GB) system and is surrounded with the inert gas, nitrogen (or argon) gas [1].

2.2. Bed design target, parameters and uncertainties

Focusing on the hydride bed system design, there must be some design parameters and still uncertainties that are come from the outside worldwide not to realize the component or the manufacturing assembly product. Whatever the cause, the authors summarized that tens of major elementary targets are the real things to make it actualize the bed substance like following Table 2.

Table 2
Performance target of hydride bed design.

No.	Target	Note
1	Delivery rate	Table 1
2	Absorption rate	As fast as
3	Pressure drop	As low as
4	Flow through design	He-3
5	In-bed calorimetry	Table 1
6	Life time	As long as
7	Separation performance	T_2 getter
8	Physical size	Fit in GB
9	Capability	Getter cap.
10	Reload cycle	Steps
11	Pressure capability	Gas press.
12	Design pressure	
13	Fire sectorization	Resistance
14	Overpressure protection	
15	Bed utilization	Max. use
16	No particulate outside filters	
17	Susceptibility to blanketing	
18	Decommissioning	
19	RAMI	
20	Recovery from complete heater failure	
21	Pyrophoricity (DU)	Oxidation
22	Internal deflagration	
23	Heel (T_2)	Retention
24	Seismic	SIC
25	Low permeation into GB	
26	Avoid eutectic formation	Fe-U
27	Heat load to GB environment	Quick remove

3. As low as: related to the flow through and the conductance which affects the desorption rate of hydrogen isotope gas from getter bed to downstream.
4. He-3: to minimize He-3 blanketing effect.
6. As long as: e.g., 10,000 cycles or hopefully 10 years.
7. Separation performance: T_2 capturing capability.
8. Fit in GB: as small as possible to locate in the glove box system.
9. Getter cap.: Max. T_2 storage capacity.
10. Steps: bed operation procedure like cycling of cool-down, reload, heat-up, and so on.
11. Gas press.: withstand He-3 build-up pressure.
13. Endurance 2 hours at 300 °C.
21. Self-extinguishing at oxidation with O_2, H_2O.
24. SIC: Safety Important Component confinement.
25. Fe–U: Prevent the eutectic point in Fe–U system.

In Table 2 the numbers are selected arbitrarily and the performance target holds a design target in each case, and it denotes to have component variable(s), or important parameter(s), in single or plural that is not still disclosed. As for default of system condition for design and operation, the maximum or severe system pressure and temperature should be applied in accordance with the nuclear pressure vessel design criteria [10]. In addition, the hydride bed system has two containers which are divided by the primary vessel and the vacuum jacket. The vacuum jacket is necessary to prevent the heat loss by vacuum with some of reflectors [3,4]. And the feed-through electric connector is necessary by basic.

From No. 1 to No. 5 in Table 2 the performance target denotes the bed system function and requirement. The others are design parameters for SDS bed. More than 20 parameters are intermingled with each specification, so the optimal design is too much complex to harmonize the multiple target. Otherwise, it is necessary to reduce the low level of parameters or component variables by decision making with priority estimation.

Now, components which are assembled to complete the getter bed are to be taken into account for the real assay of the hydride bed system variable. If certain uncertainties exist in component variables of the hydride bed system, comparison technique should be introduced.

Table 3
Major uncertainties in ITER SDS getter bed design.

Equipment	Issue	What is Uncertain?
DU bed structure	Performance	No. of beds
	Powder migration	How much?
	Part replacement	Lifetime
	Complex in shape	Fit in GB
Electric heater in bed	Lifetime (durability)	Availability

Table 3 shows the major uncertainties in ITER SDS design and Table 4 shows rearrangement of the hydride bed parameter in terms of risk-effective by accounting component basis.

Table 3 describes that two main uncertainties affect the feasibility and availability of the ITER SDS getter bed. First, the DU bed structure has several uncertainties which are related with each issue and result to the feasibility of the getter bed design. Second, the electric heater in bed which supplies heating source to the bed is the criteria of the bed availability, but it also belongs to an uncertainty.

Table 4 shows simplified classification of the risk-effective results. From Table 2 those risk classes of RAMI, seismic, low permeation into GB, heat load to GB environment, pyrophoricity, and so forth are of importance as well, but in which are classified into also a justifiable mandatory design requirements for the nuclear high pressure vessel equipment. As an another example, fire resistance of the hydride bed which is to stand for the fire accident during 2 h at 300 °C, is to be considered with design criteria of the bed surroundings as well as elimination of bed outside flammable material.

In Table 4 the functions and requirements are related with each other, and it seems that there are some interactions between component variables. Therefore, it is necessary to describe the interaction whether it can show the criticality.

2.3. Interaction of uncertainties, risks

Fig. 1 shows that the sample case of heater selection whether it is dedicated, fixed outside the primary vessel or flexible, or replaceable one heater, double heaters. In general the shelf life of electric heater is greatly depended on the maker, but has rather very short period of time. Even though the preparation of double heater, fixed type outside the primary hydride bed may be done and considering the heat-transfer efficiency by close contact between electric heater and the primary vessel body, the efficiency of overall heat transfer property might be not so good at all, or the redundancy heater diminishes the lifetime to that of the first heater, because of geometric configuration. As shown in Fig. 1 when the tritium inside the hydride bed is not to be used by a sort of heater failure, as the consecutive result the cost-effective risk is much greater than any other risk cases.

Table 4
Rearrangement of targets and related components in hydride bed design.

Fn & Req	Component or design complex variable	Class of risk-effective
High heat-transfer	Low thermal mass	Sf
	Heater lifetime up	Mt, Ct
	Internal inside[*]	Mf
High mass-transfer	Low conductance	Mf, Ct
	Filter size & shape	Mf, Mt
	(high heat-transfer)	
		Sf, Mt, Ct, Mf
Rapid in-bed calorimetry	Low thermal mass	Sf
	Internal inside	Mf
	Bed inside design	Sf, Mf
He-3 blank effect	Flow-through design	Mf
	Bed inside design	Mf
Avoid eutectic design	Protect with copper[**]	Mf, Sf
	Bed inside design	Mf
Avoid particle flee	Filter size & shape	Sf, Mt

Fn: function; Req: requirement.
Sf: safety-effective.
Mt: maintainability-effective.
Ct: cost-effective.
Mf: manufacturability-effective.
[*] Internal inside: newly adopted [11,12].
Bed inside design: design of complex geometry.
[**] Protect with copper: ref. to [13].

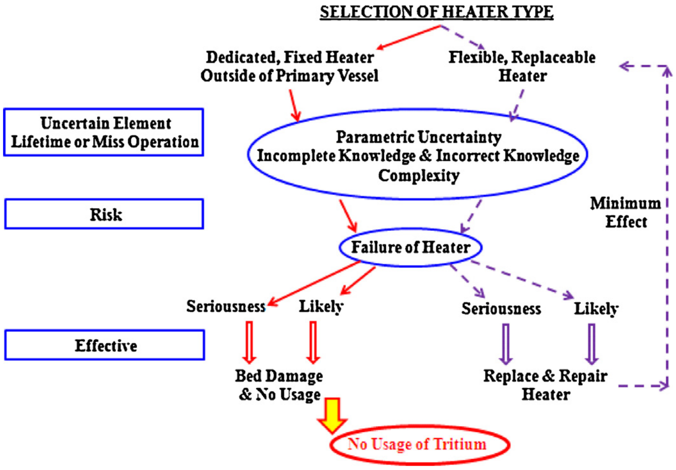


Fig. 1. Interaction of uncertainty, risk and effectiveness in heater selection.

Similar to the electric heater case, in function or requirement risk of mass-transfer problem in Table 4 is more complex than that of only heater problem, because of the complexity including heater problem in transfer phenomena approach. Therefore, for more precise comparison among the elementary components there need a sort of comparison method. In the next chapter HAZOP (risk matrix) analysis is to be suggested.

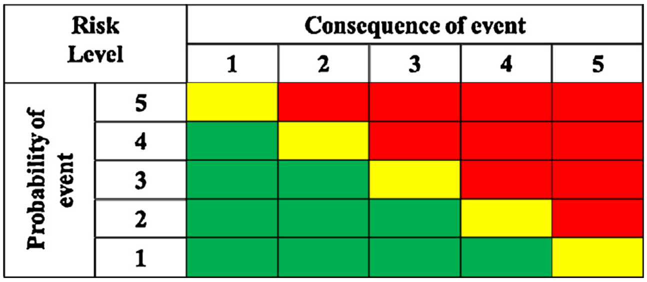
3. Comparison of risks using HAZOP assets

3.1. Cost-effective case (electric heater)

As illustrated in Fig. 1 the electric heater works for heat generation. When it comes to heating up the hydride bed the hydrogen isotope gas is to be released to outward of the hydride bed. Here the main component of the hydrogen isotope is tritium. For normal fueling the tritium is cycled by absorbing, storing, and desorbing procedures in order at the position of getter bed inlet and outlet region in SDS. If the tritium is residing for a long time in hydride form, this means no work for fueling and long storage. Thus, when the electric heater is failed to heat up, the cost-effective risk comes out. This kind of risk is not only fatal to the SDS but also to the whole fuel cycle system. This extreme case of tritium detention should be avoided by providing redundancy heater or by using replaceable heater.

For risk mapping a risk-based categorization of asset is applied. In this example, Fig. 2 shows the typical risk matrix that shows probability of the event or accident and the consequence of the event in terms of amplitude of risk [6]. Tables 5 and 6 show the probability and consequence (severity) scale used in the risk matrix of the heater failure.

Table 7 recommends that the cost-effective risk can be inverted from the Table 6, severity scale. The cost of tritium which is worthy of fuel for the fusion process will be bound in the dead getter bed.



Risk Level		Consequence of event				
		1	2	3	4	5
Probability of event	5	🟨	🟥	🟥	🟥	🟥
	4	🟩	🟨	🟥	🟥	🟥
	3	🟩	🟩	🟨	🟥	🟥
	2	🟩	🟩	🟩	🟨	🟥
	1	🟩	🟩	🟩	🟩	🟨

Fig. 2. Typical risk matrix in HAZOP asset.

Table 5
Probability scale of electric heater failure.

Scale	Description	Frequency (per cycles)
1	Improbable	Less than once in 10,000 heating cycles
2	Less probable	Every 2500–5000
3	Probable	Every 1000–2500
4	Very probable	Every 500–1000
5	Highly probable	Every 1–500

Table 6
Consequence (or severity) scale.

Scale	Description	Consequence
1	Insignificant	No damage
2	Small	Minor damage
3	Medium	Medium to serious damage
4	Very serious	More than one heater with serious damage
5	Catastrophic	All heater with serious damage

The worst case is no use of 70 g of tritium. Scale 3 in Table 7 means that the hydride bed stops the fueling work and every tritium inside of the bed should be removed using redundancy heater. Therefore, the choice of redundancy or replaceable heater may be determined by a certain action of comparison.

In case of electric heater failure the consecutive result is driven to the tritium availability. In accordance with the rule of thumb in applying electric heater to the hydride system the risk scoring can be estimated by the following formula:

Risk scoring analysis, $R = P \cdot S$

where R is the risk score number ore residual risk; P is the probability of occurrence of deviation; and S is the severity of the consequence. By applying the rule of thumb on the electric heater experienced to the hydride bed system, $P = {\sim}4$. For S, it is not easy to expect the true value without experience. If $S = 2$ or 3, the SDS hydride bed system has not much cost-effective risk, but the SDS system performance will be decreased rapidly. IF $S \geq 4$, then the whole SDS must be influenced the tritium usage and the whole tritium plant will not work well after the catastrophic event.

Table 7
Consequence (or severity) scale in cost basis.

Scale	Description	Consequence of cost/tritium availability (heater working %)
1	Insignificant	100% T_2 available (100% heater working)
2	Small	100% T_2 available But performance down (90% heater available)
3	Medium	$\leq$100% T_2 available Bed shutdown (50% heater available)
4	Very serious	Not available of T_2 Same to catastrophe (More than 50% heater damage)
5	Catastrophic	No usage of T_2 All heater with serious damage

3.2. Other risks

For considering avoiding interaction with structure material due to Fe–U in Table 4 this risk problem is classified into the safety-effective issue. For flow-through design to prevent the He-3 blanket effect this risk is classified into the manufacturability-effective problem. And to prevent the DU particulate migration the risk approach is also same to the case of interaction with structure material problem with safety-effective.

3.3. Priority in hydride bed design variables

To get an optimal hydride bed design that has complex relations between manufacturing components the comparison of the risk study results from each component or combined function & requirement is helpful for the determination of design priority. Comparing between risks (cost-effective, safety-effective, maintainability-effective, manufacturability-effective) by HAZOP asset and risk matrix is a plausible tool to differentiate and can suggest a guideline what is more important or not than other design variables. However, it is true that it needs more reliable data by experience. Nonetheless, for too much complex design parameter (or component variables) cases such like the ITER SDS getter bed system it is recommendable to determine the priority of the design basis.

4. Conclusion

The main requirements for the metal hydride storage beds of the ITER SDS are tritium limitation, fast delivery and fast recovery of the hydrogen isotopes and in-bed calorimetry to allow for tritium inventory measurements. The ITER tritium SDS hydride bed system has too much complex variable to get an optimal design. In this paper the risk-effective HAZOP asset (risk matrix) is suggested as a tool for multi-criteria decision making problem. As a conclusion the authors could concentrate and minimize the bed design variables through risk analysis. And the further study is to be needed for getting comparison between risk-based case studies and for determination of the priority design component variable.

The followings are the summary of this study:

- To minimize the system parameters of ITER SDS hydride bed design the risk-based multi-criteria design concept was introduced.
- For the optimal SDS hydride bed design, 27 performance targets were generated as constituents of complex and interrelated components or devices including 2 major uncertainties in practical design.
- As one method of risk analysis, HAZOP (risk matrix) was used to compare the degree of risk amplitude in terms of cost-effective or tritium availability in electric heater failure problem (or design). 50% electric heater failure (using redundancy heater) will be influenced as not much cost-effective risk, but the SDS performance will be decreased rapidly.

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