A New Reliability Allocation Method Based on PSA and AHP for Fusion Reactors

Ming Sun, Taosheng Li, Jie Yu, Daochuan Ge, Ying Bai, and Longlong Tao

Abstract: Reasonable and feasible reliability index allocation is significant for improving safety and reducing costs for fusion reactors. Although the reliability index is allocated when designing some key systems, reliability allocation is not implemented from the overall layer to the system and component layers for fusion reactors. In this contribution, fusion reactors are divided into different layers by applying the Analytic Hierarchy Process (AHP); these layers include the overall layer, system layer and component layer, failure mode layer, etc. Combining the Probabilistic Safety Assessment (PSA) model for fusion reactors and AHP, the reliability index is allocated from the overall layer to the system and component layer. Firstly, a new reliability index allocation method based on PSA and AHP for fusion reactors is proposed. Secondly, the PSA model for an in-vessel LOCA accident of fusion reactors is selected as a case study to demonstrate the applications of the proposed method. Lastly, the relationship between PSA, items safety classification and reliability allocation are discussed. The allocation results indicate that the proposed method provides a more systematic reliability allocation scheme and contributes to improving the safety and economy of fusion reactors.

Keywords: reliability allocation; PSA; AHP; fusion reactor

1. Introduction

Compared with fission energy, fusion energy has the characteristics of clean and efficient rich nuclear fuel and less radioactive products. Therefore, it is considered the ultimate energy for human society. Since the United States exploded the first hydrogen bomb in 1952, for which the huge energy released by the hydrogen bomb was uncontrolled, human beings have been exploring controllable nuclear fusion. The Tokamak is regarded as an important device for realizing controllable nuclear fusion. The Tokamak device is mainly composed of a polar magnetic field that generates, confines and heats plasma, a longitudinal magnetic field that ensures the stable discharge of circumferential plasma current, and a Vacuum Vessel (VV) that provides appropriate discharge conditions. The generation-I Tokamak devices include ATC in Princeton University, ORMAK in Oak Ridge National Laboratory, TFR400 in France, Cleo in Britain, Pulsator in Germany and JFT-2 in Japan. Subsequently, some countries established large-scale generation-II Tokamak devices on the basis of the generation-I Tokamak devices and made great progress. Representative Tokamak devices include PLT in Princeton University, Doublet in General Motors, T-10 in the former Soviet Union and ASDEX in Germany. In order to further explore the properties of high-temperature plasma under fusion ignition conditions, some countries began to build the generation-III Tokamak devices, such as TFTR operated in 1982 in the United States, JET operated in 1983 in Europe, JT-60 operated in 1985 in Japan and T-15 in the former Soviet Union. The generation-III Tokamak devices have basically obtained significant fusion
energy and made important progress. In order to further verify the scientific feasibility and key engineering technical problems of Deuterium-Tritium (D-T) plasma fusion, the International Thermonuclear Experimental Reactor (ITER) project was launched. As early as the 1950s, China had performed nuclear fusion research. The Southwestern Institute of Physics of China National Nuclear Corporation built HL-1 in 1984 and transformed HL-1 into HT-1M in 1992. The Institute of Physics and Institute of Plasma Physics, Chinese Academy of Sciences have successively built CT6, HL-6B, HT-6M and superconducting Tokamak HT-7 in 1994. In 2006, the Experimental and Advanced Superconducting Tokamak (EAST) was successfully developed in the Institute of Plasma Physics, Chinese Academy of Sciences [1].

Reasonable and feasible reliability index allocation is significant to the safety and economy of fusion reactors. Reliability index allocation has been effectively applied in the fields of electronic systems, aviation and aerospace systems, and remarkable benefits have been achieved. Reliability allocation has been widely used in Nuclear Power Plants (NPPs), but the reliability index allocation method is not implemented through the design process of NPPs, which obviously does not fully play a role in reliability allocation [2]. A fusion reactor, which mainly involves machinery, control, nuclear physics, plasma physics, thermal hydraulics and other disciplines, is a complex engineering system. Compared with NPPs, the fusion reactor has significantly different characteristics in neutronics, tritium, safety and reliability assessment and safety concept. In order to control the technical risk of fusion reactors, the ITER organization proposed the Reliability, Availability, Maintainability, Inspectability (RAMI) approach, which evaluates the reliability and availability of systems of fusion devices from the probability perspective [3]. The Probabilistic Safety Assessment (PSA) method is adopted to evaluate the Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) for NPPs, but the applications of PSA in fusion reactors are still in the exploratory stage. The probabilistic safety goals, Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) for fusion reactors have not formed a consensus. Therefore, the PSA methodology for fusion reactors has not been established.

RAMI analysis has been performed for some relevant systems of fusion reactors, such as RAMI analysis for ITER fuel cycle system [4], RAMI analysis for ITER Control Data Access and Communication (CODAC) functions [5] and RAMI analysis for DEMO HCPB blanket concept cooling system [6]. Bargallo E performed RAMI analyses for the IFMIF accelerator facility and first availability allocation between systems [7]. Maisonnier D summarized the RAMI analysis in ITER and DEMO and recommended adopting a reliability growth program for future fusion devices [8]. Zio E proposed an integrated DSA and PSA methodology [9], and Bellaera R applied the integrated methodology to the superconducting magnet cryogenic cooling circuit for fusion energy systems [10]. Hong Y integrated a deterministic approach with fault tree analysis for reliability assessment of generation and transmission systems [11]. Wang Z proposed a risk assessment methodology on the basis of the accident characteristics for fusion reactors [12]. Wang D proposed the probabilistic safety goals with dose vs. frequency and assessed the accident consequence frequency for fusion reactors by applying PSA [13]. Borysiewicz M applied Value Tree Analysis (VTA) in order to improve further the risk management of the nuclear facilities [14]. Yang J applied a genetic algorithm to the reliability index allocation of NPPs [15]. Tong L proposed a reliability allocation method based on a fault tree and dualistic contract [16].

The reliability index allocation for fusion reactors only focuses on the system layer, and the reliability allocation is performed when designing some key systems. It is less to allocate the overall layer reliability index to the component layer reliability index throughout the whole design process for fusion reactors. In this contribution, the importance of fusion reactor reliability index allocation and literature review are presented in Section 1. Subsequently, fusion reactors are divided into an overall layer, system layer and component layer by applying Analytic Hierarchy Process (AHP) and combining the PSA model and AHP; a reliability allocation method based on PSA and AHP for fusion reactors is proposed.
in Section 2. The in-vessel LOCA accident of fusion reactors is selected as a case study to demonstrate applications of the proposed method in Section 3. Some conclusions are drawn in Section 4.

2. A New Reliability Allocation Method Based on PSA and AHP

2.1. Framework of the Proposed Method

The main approach of the proposed method is to divide the fusion reactor into different layers by applying AHP, which are the overall layer, system layer, component layer, failure mode layer, etc. Then, the reliability indexes of fusion reactors are allocated from the overall layer to the system layer, component layer, etc. The reliability allocation process of the proposed method for fusion reactors is summarized in the following steps (presented in Figure 1).

Figure 1. Framework of the proposed method.

(1) Identification of the overall layer probabilistic safety goals for the fusion reactors;
(2) Decomposing overall layer probabilistic safety goal to system layer reliability index based on the ETA model and proportional coefficient;
(3) Decomposing system layer reliability index to component layer reliability index based on the FTA and proportional coefficient;
(4) The experts should review all the layers’ reliability indexes and finally select the appropriate reliability indexes for fusion reactors.

2.2. Identification of Probabilistic Safety Goals for Fusion Reactors

The current probabilistic safety goals and their limits for fission reactors in some countries are summarized in Table 1. The principle, structure and system for fusion reactors are greatly different from fission reactors, so the probabilistic safety goals and their limits for fission reactors may not be fully applicable to fusion reactors. Identification of probabilistic safety goals and their limits for fusion reactors require joint discussions and final determination by relevant experts, organizations and regulators. Referring to the probabilistic safety goals and their limits for NPPs, the LERF, which is expressed by \( O \), is selected as the preliminary probabilistic safety goal for fusion reactors in this contribution.
Table 1. Probabilistic safety goals and their limits for fission reactors in some countries.

<table>
<thead>
<tr>
<th>Countries</th>
<th>CDF/Reactor Year</th>
<th>LERF/Reactor Year</th>
<th>Public Risk/Reactor Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>$10^{-4}$ (in service), $10^{-5}$ (new built)</td>
<td>$10^{-7} \sim 10^{-5}$</td>
<td>/</td>
</tr>
<tr>
<td>America</td>
<td>$10^{-4}$</td>
<td>$10^{-6}$</td>
<td>/</td>
</tr>
<tr>
<td>Japan</td>
<td>$10^{-4}$</td>
<td>$10^{-5}$</td>
<td>(Acute death in the NPPs)</td>
</tr>
<tr>
<td>Canada</td>
<td>$10^{-4}$ (in service), $10^{-5}$ (new built)</td>
<td>$10^{-5}$</td>
<td>/</td>
</tr>
<tr>
<td>Sweden</td>
<td>$10^{-5}$</td>
<td></td>
<td>/</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>$10^{-4}$ (in service), $10^{-5}$ (new built)</td>
<td></td>
<td>/</td>
</tr>
<tr>
<td>France</td>
<td>$10^{-6}$</td>
<td></td>
<td>/</td>
</tr>
<tr>
<td>Germany</td>
<td>$10^{-6}$</td>
<td></td>
<td>/</td>
</tr>
<tr>
<td>Slovakia</td>
<td>$10^{-4}$</td>
<td></td>
<td>/</td>
</tr>
</tbody>
</table>

2.3. Decomposing Overall Layer Probabilistic Safety Goal into System Layer Reliability Index

After identification of the overall layer probabilistic safety goal for fusion reactors, it is necessary to decompose the overall layer probabilistic safety goal to the system layer reliability index. The reliability allocation from the overall layer to the system layer is mainly based on the ETA model (shown in Figure 2) and proportional coefficient.

Figure 2. ETA model.

Assuming that the probabilistic safety goal LERF for fusion reactors is set to $O_0$, if the LERF calculated by the PSA of the fusion reactor is less than $O_0$, which meets the requirements of the probabilistic safety goal for the fusion reactors, then there is no need to perform large scale reliability allocation between the systems and components of the fusion reactor. It is only needed to make appropriate adjustments and optimizations for the parts where reliability is relatively weak. If the LERF calculated by the PSA of fusion reactors is larger than $O_0$, which does not meet the requirements of the probabilistic safety goal for the fusion reactors, it is necessary to allocate a reliability index to the systems and components for the fusion reactors. The allocation method is to set the proportional coefficient $K$, which is the ratio of the expected LERF value $O_0$ to the LERF value $O_1$ calculated by the PSA of fusion reactors, as Formula (1) shows:

$$K = \frac{O_0}{O_1}$$  \hspace{1cm} (1)

The proportional coefficient $K$ is adopted for the reliability index allocation. The system allocated reliability index $P'$ is equal to the original reliability index $P$, which was calculated by the FTA, multiplied by the proportional coefficient $K$, as shown in Formula (2):

$$P' = K \times P$$  \hspace{1cm} (2)
In order to guarantee the conservativeness of the reliability index for the allocated system, that the value of allocated LERF is less than $O_0$ needs to be proved, i.e., Formula (3) needs to be proved true:

$$\sum S_{jLERF}^\prime < O_0 \quad (3)$$

Referring to the ETA model, the proof process is as Formula (4) illustrated:

$$\sum_{j=1}^m S_{jLERF}^\prime = \sum_{j=1}^m \prod_{i=1}^n P(IE) \times P'(FE_n)$$

$$= \sum_{j=1}^m [P(IE) \times P'(FE_1) \times P'(FE_2) \times \ldots \times P'(FE_n)]$$

$$< K \sum_{j=1}^m [P(IE) \times P(FE_1) \times P(FE_2) \times \ldots \times P(FE_n)]$$

$$= K \sum_{j=1}^m S_{jLERF}^\prime = O_0 \quad (4)$$

In Formulas (1)–(4), $O_0$ refers to the probabilistic safety goal of the fusion reactor, $O_1$ represents the reliability index of the system, $K$ refers to the proportional coefficient, $P$ represents the system failure probability calculated according to the FTA, and $P'$ refers to the allocated reliability index, $S_{jLERF}^\prime$ represents the failure probability of the accident sequence in the ETA model, $n$ refers to the number of function events in the accident sequence, $m$ represents the total number of accident sequences in the ETA model, IE refers to the initial event, and FE represents the function event.

2.4. Decomposing Reliability Index from System Layer to Component Layer

After the identification of the overall layer probabilistic safety goals for the fusion reactors and the decomposition of the overall layer probabilistic safety goal to the system layer reliability indexes, the reliability indexes should be decomposed from system layer to component layer based on the FTA model and proportional coefficient.

On the basis of Section 2.3, assuming a system reliability index of fusion reactors is set to $P_0$, if the system reliability $P$ calculated by FTA is less than $P_0$, which meets the requirements of the reliability index of the fusion reactors, there is no need to perform the large-scale system reliability indexes allocation from system layer to components layer for fusion reactors. It is only necessary to adjust and optimize the weak parts appropriately. If the system reliability $P$ calculated according to the FTA is larger than $P_0$, which does not meet the requirements of the probabilistic safety goal, it is necessary to allocate reliability indexes to the components for fusion reactors. The allocation method adopts the proportional coefficient $K$, which is the ratio of the overall layer probabilistic safety goal to the system reliability index in Section 2.3, and $K$ is applied as Formula (5) shows:

$$K = \frac{P_0}{P} \quad (5)$$

Then the allocated reliability index of components in a system is shown in Formula (6):

$$P'_C = KP_C \quad (6)$$

In order to ensure the conservativeness of the reliability index of the allocated components, that the value of the allocated system reliability is less than $P_0$ need to be proved, i.e., Formula (7) needs to be proved true:

$$P' < P_0 \quad (7)$$

Based on the FTA model, the proof process is as Formula (8) presents:

$$P' = P'_{MCS} + \ldots + P'_{nMCS} = KP_0 < P_0 \quad (8)$$
In Formulas (5)–(8), $P_0$ represents the reliability index of a system of a fusion reactor, $P$ refers to the system reliability calculated by FTA, $P_C$ represents the original reliability of a component, and $P'_C$ refers to the allocated reliability of a component. $K$ represents the proportional coefficient, $P_{MCS}$ refers to the reliability of a Minimum Cut Set (MCS), and $n$ represents the total number of the MCS.

3. Case Study

The typical in-vessel LOCA accident of ITER was selected as a case study in order to demonstrate the applications of the proposed method.

3.1. Preliminary PSA for in-Vessel LOCA Accident

The preliminary PSA model for the in-vessel LOCA accident of the fusion reactor, which includes the ETA model of in-vessel LOCA accident (presented in Figure 3) [17–19] and the FTA model of VVPSS (shown in Figure 4) [20], are adopted as the case study to demonstrate the applications of the proposed method. The main safety systems involved in mitigating the in-vessel LOCA accident include Vacuum Vessel Pressure Suppression System (VVPSS), Suppression Tank Detritiation System (ST-DS), Detritiation System (DS), Drain Tank Detritiation System (DT-DS) and Air Detritiation System (ADS). The components in VVPSS mainly include a safety valve, pressure relief pipe, Suppression Tank (ST), rupture disk and VV. In referring to reliability data [21,22], the unreliability of VVPSS within the mission time is calculated as $1.61 \times 10^{-2}$, and the unreliability of ST-DS, Drain System, DT-DS and ADS within the mission time is initially assessed as $2.00 \times 10^{-4}$, $1.00 \times 10^{-2}$ and $1.00 \times 10^{-2}$, respectively. The LERF caused by the in-vessel LOCA accident is calculated as $1.00 \times 10^{-7}$/reactor year.

Figure 3. Event tree model of the in-vessel LOCA accident.

3.2. Reliability Index Allocation Process

The reliability allocation for fusion reactors includes identification of the overall layer probabilistic safety goals for fusion reactors, decomposing the overall layer probabilistic safety goal to system layer reliability indexes, and decomposing the system layer reliability indexes to the component layer reliability indexes. After review by experts from the perspective of engineering experience, the overall layer, system layer and component layer reliability indexes for the fusion reactors are obtained finally. The ETA for in-vessel LOCA accident and FTA for VVPSS, established in Section 3.1, are selected as the case study to illustrate the applications of the proposed method.

(1) Identification of probabilistic safety goals for fusion reactors

Referring to the probabilistic safety goals status of NPPs in some countries, the LERF is preliminarily selected as the probabilistic safety goal for fusion reactors, and the limit of LERF for fusion reactors is initially determined to be $5.00 \times 10^{-8}$/reactor year.
Figure 4. FTA model of VVPSS.

(2) Decomposing overall layer probabilistic safety goal to system layer reliability index

According to the reliability allocation steps of the overall layer, the probabilistic safety goal for the system layer is proposed in Section 2.3; the ETA model for the in-vessel LOCA accident established in Section 3.1 (shown in Figure 3) is selected to demonstrate the allocation steps of overall layer probabilistic safety goal to system layer reliability index. The proportional coefficient $K$, which is adopted to decompose the overall layer probabilistic safety goal to the system layer reliability index, is calculated as Formula (9) shows:

$$K = \frac{O_0}{O_1} = \frac{5.00 \times 10^{-8}}{1.00 \times 10^{-7}} = 0.5$$  

(9)

The original and allocated reliability indexes of the main systems involved in mitigating the in-vessel LOCA accident are presented in Table 2.

Table 2. Original and allocated reliability indexes of the systems involved in-vessel LOCA accident.

<table>
<thead>
<tr>
<th>System</th>
<th>VVPSS</th>
<th>ST-DS</th>
<th>Drain System</th>
<th>DT-DS</th>
<th>ADS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original index</td>
<td>$1.61 \times 10^{-2}$</td>
<td>$1.00 \times 10^{-2}$</td>
<td>$2.00 \times 10^{-4}$</td>
<td>$1.00 \times 10^{-2}$</td>
<td>$1.00 \times 10^{-2}$</td>
</tr>
<tr>
<td>Allocated index</td>
<td>$8.05 \times 10^{-3}$</td>
<td>$5.00 \times 10^{-3}$</td>
<td>$1.00 \times 10^{-4}$</td>
<td>$5.00 \times 10^{-3}$</td>
<td>$5.00 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

(3) Decomposing reliability index from system layer to component layer
The FTA model for VVPSS established in Figure 4 was selected to demonstrate the allocation steps, and the proportional coefficient $K = 0.5$ is also adopted to decompose the system layer reliability index to the component layer reliability index. Referring to the allocation steps from system layer reliability indexes to component layer reliability indexes proposed in Section 2.4, the original and allocated reliability indexes of components in the VVPSS are presented in Table 3.

Table 3. Original and allocated components’ reliability indexes of VVPSS.

<table>
<thead>
<tr>
<th>Component</th>
<th>Safety Valve</th>
<th>Rupture Disk</th>
<th>Pipe</th>
<th>ST</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original index</td>
<td>$1.40 \times 10^{-6}$</td>
<td>$4.00 \times 10^{-3}$</td>
<td>$3.00 \times 10^{-10}$</td>
<td>$6.40 \times 10^{-7}$</td>
<td>$2.50 \times 10^{-5}$</td>
</tr>
<tr>
<td>Allocated index</td>
<td>$7.00 \times 10^{-7}$</td>
<td>$2.00 \times 10^{-3}$</td>
<td>$1.50 \times 10^{-10}$</td>
<td>$3.20 \times 10^{-7}$</td>
<td>$1.25 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

After allocating the reliability index of VVPSS to the component layer reliability index, it is necessary to fully check whether the current industrial design and manufacturing level can meet the reliability requirements. The experts should adjust and review the allocation results iteratively, and the final reliability indexes for system and component layers are obtained lastly.

3.3. Results Analysis

After identification of the overall layer probabilistic safety goals and decomposing the overall layer probabilistic safety goal to the system and component layer reliability indexes for fusion reactors, the reliability indexes of different layers are obtained finally. Based on the allocated reliability indexes, it can be verified whether the current industrial design and manufacturing level of components can meet the reliability requirements of components. If the reliability requirements cannot be met, it is necessary to find a more reasonable scheme among the current industrial design and manufacture level, safety and cost of components. The reliability indexes of systems and components after iterative allocation will be more reasonable and feasible. The proposed method not only can eliminate the weak parts of the design and further optimize the design but also can improve the safety and economy of fusion reactors.

3.4. Discussions

Reliability index allocation is a multi-objective optimization problem involving component reliability, current industrial level and cost. It is worth mentioning that when there is a large gap between the target of LERF and the calculated value, the reliability indexes obtained according to the proposed reliability allocation method may be too conservative. In the future, it can seek a more reasonable reliability index allocation scheme on the basis of this proposed method, e.g., adding a weight factor determined by Fussell Vesely (FV), Risk Achievement Worth (RAW) and Risk Reduction Worth (RRW) importance to the proportional allocation coefficient $K$.

In addition, PSA, PSA-based items safety classification [23] and PSA-based reliability allocation are also multi-objective optimization problems, illustrated in Figure 5. Using more components with higher reliability in the design of fusion reactors may increase the overall safety and reliability of the device, but it will also increase the cost and reduce the economy of the device. Likewise, using more components with lower reliability may reduce the cost, but it also makes the device less safe for fusion reactors. Therefore, it is necessary to find a more reasonable balance between PSA, PSA-based items safety classification and reliability index allocation.
Figure 5. Relationship between PSA, PSA-based items safety classification and reliability allocation.

4. Conclusions and Prospects

In this contribution, a new reliability index allocation method based on PSA and AHP for fusion reactors is proposed firstly. Then, the in-vessel LOCA accident for fusion reactors is selected as a case study to demonstrate the applications of the proposed method. The relationship between PSA, PSA-based items safety classification and reliability index allocation is also preliminarily discussed.

The proposed method allocates the reliability index from the whole to the parts and provides a systematic reliability index allocation scheme for fusion reactors. Reasonable and feasible reliability index allocation can help to improve the safety and economy of fusion reactors. Additionally, the proposed method also can enrich the reliability allocation methods for fusion reactors.

A weight factor should be added to the proportional coefficient $K$ when allocating reliability indexes to different layers in further allocation work. In addition, it is necessary to find a reasonable and feasible scheme for PSA, PSA-based items safety classification and reliability allocation by adopting a multi-objective optimization method in future research work.

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