APPLICATION OF MULTI-STATE SYSTEMS IN FAULT TREE ANALYSIS OF A CONCEPTUAL THERMOCHEMICAL HYDROGEN PLANT

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Abstract

In this paper, we propose a new method to improve the performance of top-level events in fault trees (FT) by using multi-state systems. Fault tree analysis (FTA) is used to evaluate the reliability of a conceptual themochemical hydrogen generation plant. Since FTA is a backward-stepping process, basic events determine the performance of top events in fault-trees. Our method aims to improve the performance of basic events (i.e., sensors, or valves) to achieve higher reliabilities by applying multi-state systems under a specific demand.

Nomenclature

m	Index indicating the state, m= 0, 1, …, M
S_i	Subsystem, i is the number of the subsystem
m_{ij}	Sate of component N_{ij}
J	The state of a component
D	Random demand
x_{im}	Performance of subsystem i in state m
Ps(J)	Probability of subsystem i is in state J
ϕ_S	Random variable indicating the state of the subsystem
N	Number of working components in a subsystem
N_{ij}	Component j in subsystem i
P_i	Performance of subsystem i

1. Introduction

Nuclear-based hydrogen generation is a promising way to provide hydrogen for the large market in the future. This paper focuses on one of the most promising methods, a thermochemical Cu-Cl cycle that is currently under development by UOIT, Atomic Energy of Canada Limited (AECL) and the Argonne National Laboratory (ANL). Fault-tree construction of the cycle follows past research conducted by AECL and ANL [1], [2].

The main reason for using FTA to analyze the hydrogen generation system is that FTA has been widely used as a logic and probabilistic technique for probabilistic risk assessment (PRA) and system reliability assessment. A main objective of PRA is to determine the probability and consequences of risks. Therefore, risk assessment which is an important management tool for making critical decisions, and in some cases meeting regulatory requirements, has an important role in PRA. Risk assessment is a three-part process: identify the hazards and their causes, determine the consequences of the hazards, and calculate the probability of their occurrence. FTA is one of the useful tools to solve these problems, especially for a design system [3], [4].

FTA is a systematic and backward-stepping process. In order to use FTA, reliability data needs to be determined [3]. This paper develops a method, called multi-state system analysis, to improve the performance of some basic events in fault trees, such as sensors and valves.

2. Multi-state series-parallel system

In a traditional binary reliability system, there are only two states: working or failed [5]. This is not sufficient for practical representation of real engineering systems. For this reason, multi-state systems are defined. They have more than two states, for instance, completely working, partially working, and completely failed. A multi-state system model is a more flexible tool [6], [7]. A power plant which has states 0, 1, 2, 3, 4 that correspond to generating electricity of 0%, 25%, 50%, 75%, 100% of its full capacity is an example of a multi-state system that has ordered multiple states [8]. Past studies on multi-state systems often assume that all components in a system have the same number of states. However, in a practical situation, each component or each different group of components should have different properties, so the number of states should be different [9], [10]. One of the available solutions is to define the performance or utility for every component in series-parallel systems, which relates to their states. Then, the components in multi-state series-parallel systems can be compared by their performance [7], [11]. The performance is defined as the output ability or the net profit.

In this paper, the following assumptions will be used.
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1. The components in all parallel subsystems are independently and identically distributed.
2. Different subsystems have different state parameters and probability distributions.
3. Each state has its own performance. The performance represents the output ability or the net profit.

A common model of a series-parallel system is shown in Fig. 1.

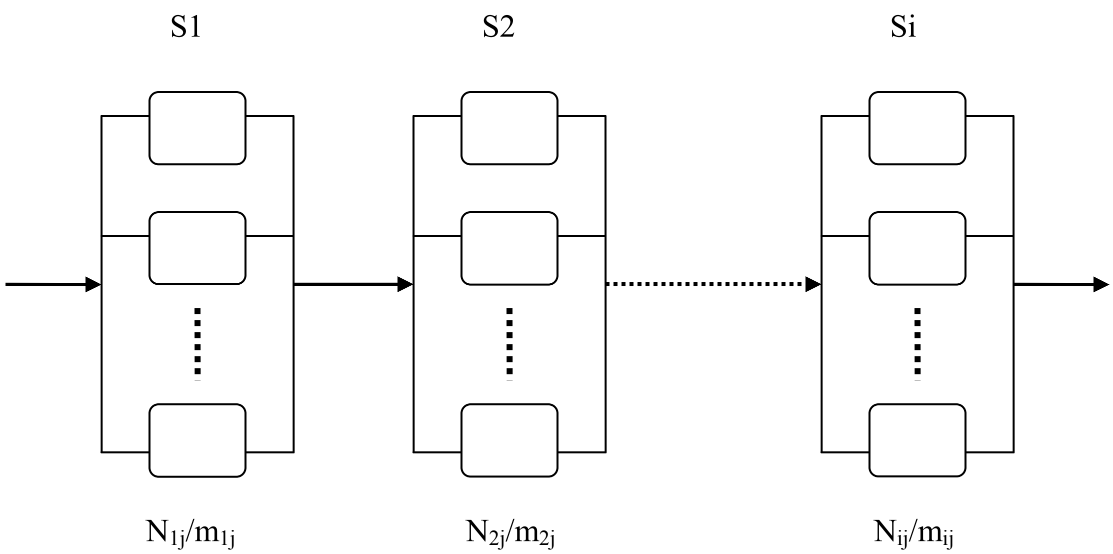

Fig. 1 Schematic of a multi-state series-parallel system

The method of calculating probability distributions of MS series-parallel systems is shown below,

$$\begin{aligned}\Pr((\phi_S \geq J) &= 1-\prod_{j=1}^{N} P_r(m_{ij} < J) \\ &= 1-\prod_{j=1}^{N}\sum_{m=0}^{J-1} P_{ij}(m) \qquad (1)\end{aligned}$$

$$\mathrm{Ps(J)}=\Pr(\phi_S = \mathrm{J})=\Pr(\phi_S \geq J)-\Pr(\phi_S \geq J+1) \qquad (2)$$

Equations 1 and 2 give a way to calculate the probability when a specific subsystem is in a indicated state.

The performance of a subsystem can be calculated as:

$$P_i=\sum_{m=0}^{J} Ps(J)\ x_{im} \qquad (3)$$

$$P_i \geq D \qquad (4)$$

In Equation 3, the subsystem performance is calculated by the sum of the probabilities when it is in state J multiply relevant performance.

Because the probability distribution Ps(J) depends strongly on the number of components in a subsystem, the performance is also decided by the quantity of components. This gives a way to manage MS series-parallel systems to fit random demands (D). Because each subsystem has different states, which have various performances, each x_{im} is different. To fit the random demands (D), the number of working components can be set [10].

4. Example problem

Given an MS series-parallel system, which has 3 subsystems, the probability and performance distribution of components are given in Table 1.

Table 1. Performance distribution of system components

State	S1		S2		S3	
	P_{1J}	x_{1m}	P_{2J}	x_{1m}	P_{3J}	X_{3m}
0	0.1	0	0.05	0	0.1	0
1	0.3	3	0.1	1	0.2	2
2	0.6	6	0.25	2	0.2	4
3			0.25	4	0.5	6
4			0.35	6		

The number of components in the subsystems can be adjusted to meet the demand.

Table 2. Present performance

	S1	S2	S3
Number of working components	2	3	2
Performance	5.49	5.32	5.3

If the demand changes to 5.6, the system cannot meet that demand any longer. Therefore, all of the subsystems need to add more components. By using the equations listed above, it will be a trial-and-error process. Components are added and the updated performance is calculated until $P_i \geq D$ is achieved.

Table 3. Demand in 5.6

	S1	S2	S3
Number of working components	3	5	3
Performance	5.805	5.75	5.694

3. Fault Tree Analysis

Fault trees constructed for four main chemical reaction processes in the thermochemical Cu-Cl cycle are shown in Appendix A. FTA and the analysis of multi-state systems will be performed separately, since FTA cannot take multi-state basic events. In the current FTA, the reliability data of basic events is usually picked up for a single component [4]. Therefore, multi-state system method gives a way to solve the case if there are couples of same components combined together. Once the number of redundant components is calculated, reliability data of basic events will be re-calculated and improved. The current problem for applying a multi-state evaluation method for basic events in FT is how to define the performance and demands. Because the Cu-Cl cycle is a conceptual hydrogen generation plant, the parameters such as performance and demands, may need to be assumed or taken from other existing systems.

4. Conclusions

This paper has examined a multi-state evaluation method with FTA to improve the reliability performance of top events in FTs. The new concepts will be applied to PRA in a conceptual thermochemical Cu-Cl hydrogen generation plant.

Appendix A – Figures of fault trees

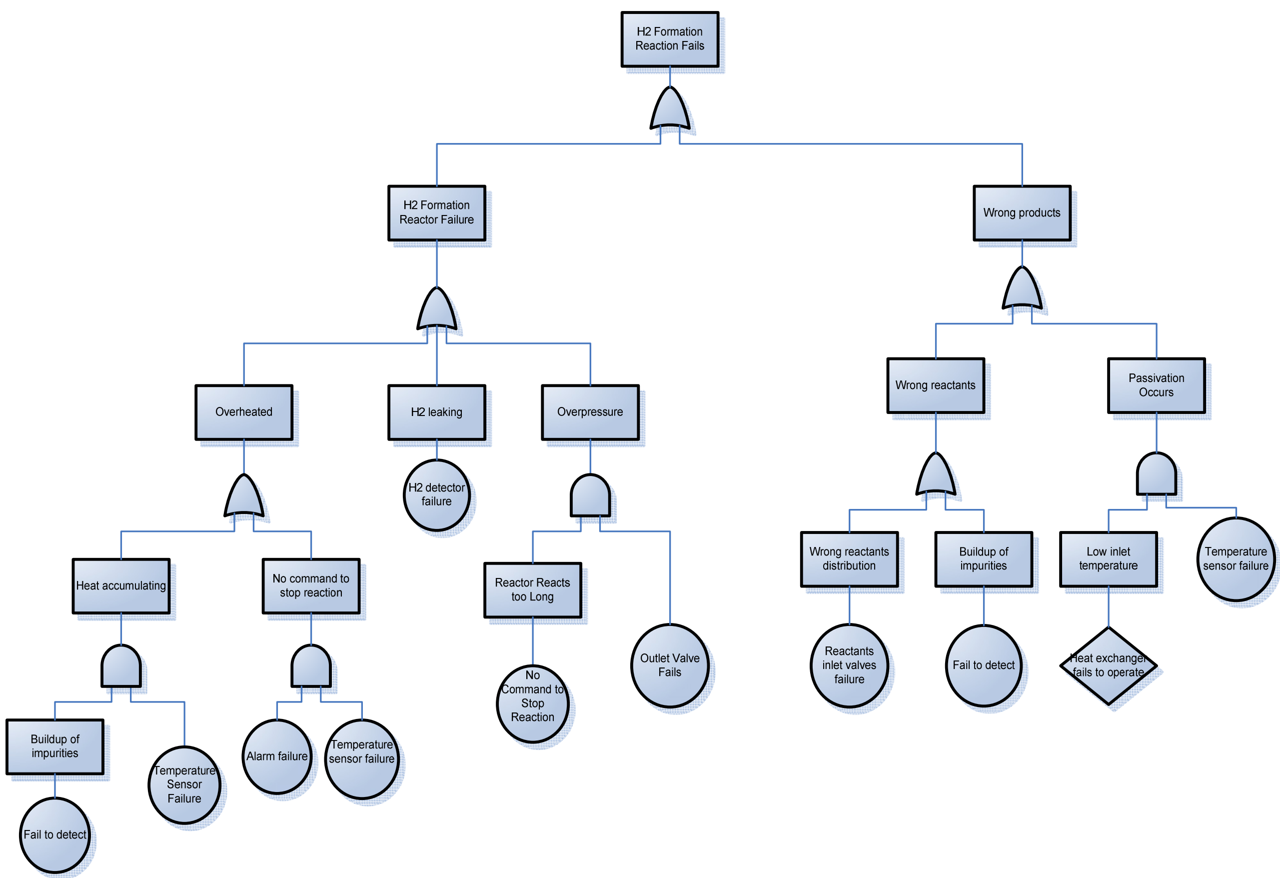

FIGURE 1. FAULT TREE OF HYDROGEN GENERATION REACTOR

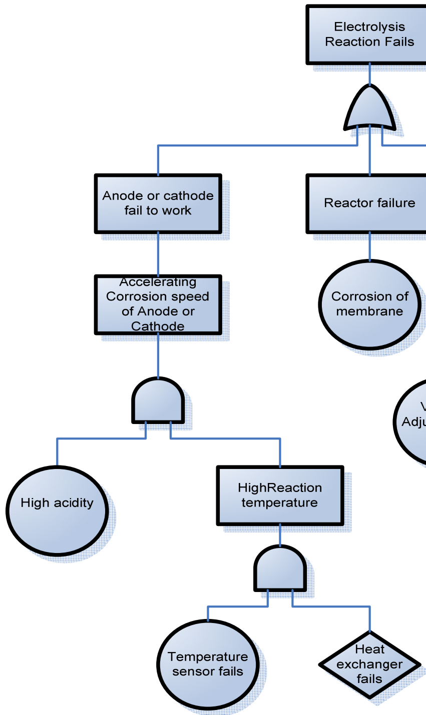

FIGURE 2. FAULT TREE OF ELECTROCHEMICAL CELL REACTOR

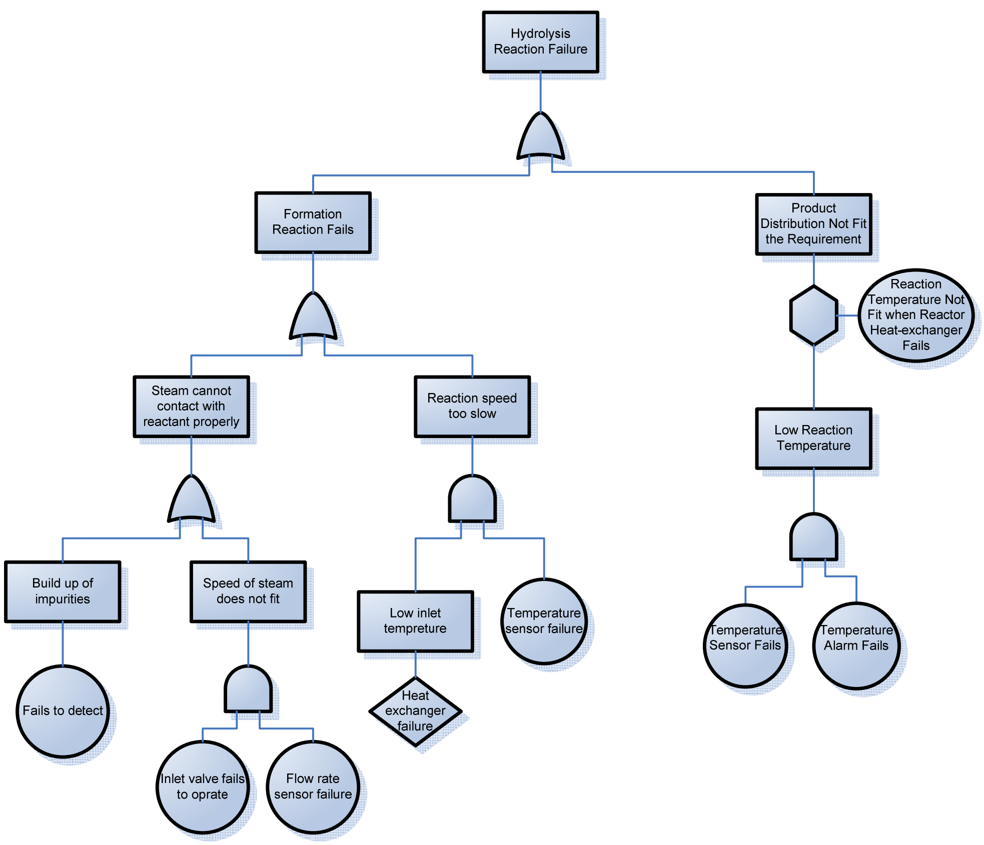

FIGURE 3. FAULT TREE OF HYDROLYSIS REACTOR

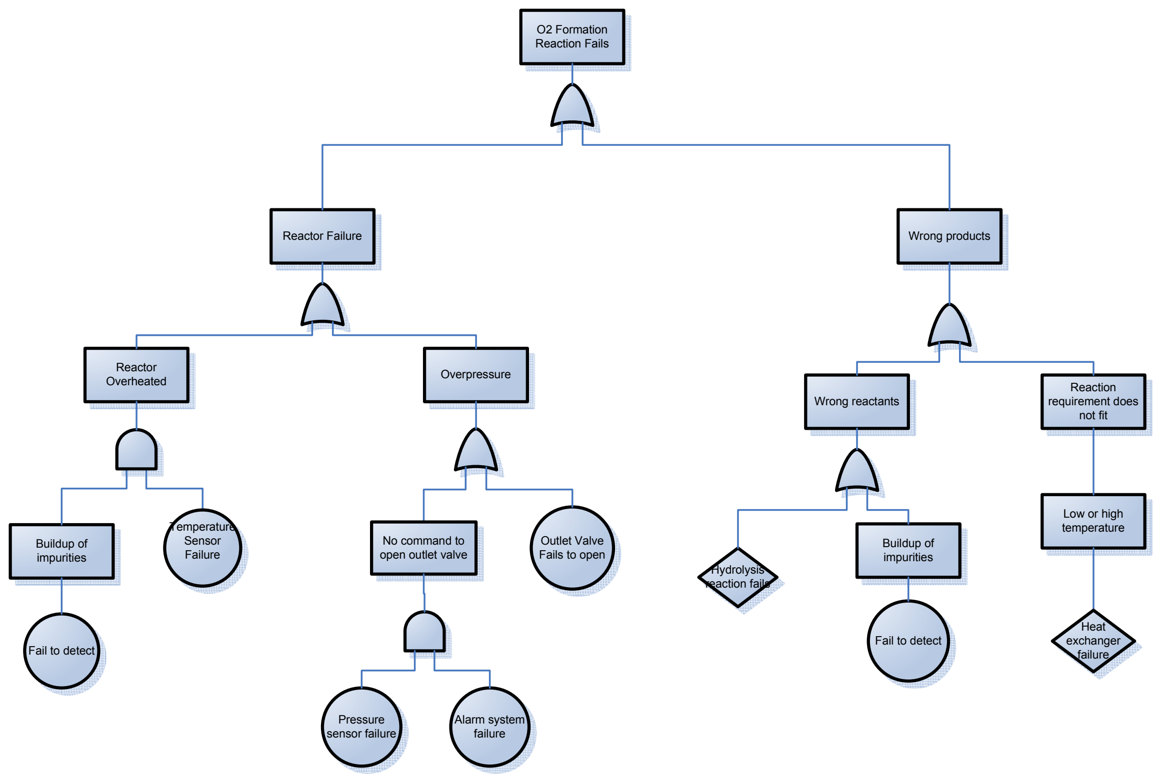

FIGURE 5. FAULT TREE OF OXYGEN GENERATION REACTOR

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