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A Quantitative Evaluation of Chemical and Volume Control System Design Simplification

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화학 및 체적 제어 계통 설계 단순화에 대한 정량적 평가에 관한 연구

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Abstract

One of the important features of the advanced nuclear power plants is the system simplification. In this work, a model has been introduced to quantitatively evaluate the system simplification. A few models have been developed for quantitative evaluation of design simplification and the design enhancements of CVCS of the advanced reactors have been evaluated with models based on the entropy concept and the system availability. In addition, operational interface of CVCS with peripheral systems has been considered to develop a new evaluation model in this work. The quantification results for the design of the System 80+ and KSNPP indicate that the simplicity of the CVCS is primarily dependent on the type and number of charging pumps.

요 약

차세대 원자로 설계의 특징중 하나로 설계 단순화를 들 수 있다. 이 논문에서는 설계 단순화에 관련된 의사결정을 지원하기 위하여, 특히 화학 및 체적 제어 계통의 단순화를 정량적으로 평가할 수 있는 모델을 제시하고 있다. 본 연구에서는, 지금까지 연구되어 온 모델들과는 달리 화학 및 체적 제어 계통이 주변 다른 계통들과 기능적으로 어떻게 접속하고 있는가에 관심을 두고 단순화를 평가할 수 있는 모델을 개발하였다. 또한, 이러한 모델들을 System 80+ 그리고 KSNPP의 화학 및 체적 제어 계통에 적용하여 비교, 평가해 보았다. 평가 결과, CVCS의 복잡도는 주로 펌프의 종류와 수에 의존하는 것으로 나타났다.

1. Introduction

In nuclear industry, there are important conditions challenged to meet, which are system safety, economical competitiveness, and public acceptance. Recently, many countries having nuclear power plants are working towards safer and more economical designs. They are developing some kinds of advanced reactors called evolutionary reactors or revolutionary type reactors. One of the important features of these advanced reactors is the system simplification. In this environment, the necessity of model to quantitatively evaluate the various simplified designs is emphasized for decision making[1].

A few models have been developed for quantitative evaluation of design simplification. In this work, we review models based on the entropy concept and the system availability. The design enhancements of CVCS of the advanced reactors have been evaluated with these models. In this work, operational interface of CVCS with peripheral systems has been considered to develop a new evaluation model . The presented model is also based on the entropy concept. In addition, a graphical analysis method has been applied for the construction of this model.

The rest of the paper is organized as follows. Chapter 2 describes functions of CVCS and design enhancements of CVCS of the advanced reactors. Chapter 3 presents models based on the entropy concept and the system availability. Chapter 4 introduces the Operational Interface Diagram, which is the basis of the presented model and Chapter 5 contains discussions about evaluation results.

2. Introduction to CVCS

2.1. Review of CVCS

The major functions of CVCS are summarized as follows :

- Maintain reactor coolant inventory during normal operations, plant cooldown and plant startup
- Provide reactivity compensation for plant transitions and fuel burnup
- Provide a means for functionally testing the check valves which isolate the Safety Injection System (SIS) from the RCS
- Provide Reactor Coolant Pump(RCP) seal injection
- Leak test of the RCS
- Maintain reactor chemistry and purity of the reactor coolant during normal operation and shutdown
- Provide a source of borated water for Engineered Safety Feature(ESF) pump operations

Many pieces of equipment are involved in providing more than one of the functions described and hence there is not a one-to-one correspondence of function and subsystem. The major control system divisions of CVCS are charging, letdown and seal flow regulation, boron control and recovery, and makeup control which itself has five control modes-manual, borate, alternate, dilute and automatic makeup.

2.2. Design Enhancements of CVCS

System 80+ CVCS and KSNPP CVCS incorporate various evolutionary improvements to meet USNRC requirements for new plants and to address requirements of the EPRI for ALWRs [2]. The design enhancements of System 80+ CVCS and KSNPP CVCS may fall into three categories as follows[3] :

- Non Safety Grade CVCS Design
- Letdown Line Improvements
- Use of Centrifugal Charging Pumps

The contents of each category are summarized in Table 1. For convenience, only the design of CVCS of System 80+ has been compared with that of System 80.

3. Models for Evaluation of Simplification

3.1. Diagnostic Entropy

Entropy is a measure of the degree of the state randomness. As the states of the system become more random, that is, equally probable, it will become more difficult to identify one state out of many other system states. The definition of entropy is as follows[4] :

$$H = -\sum_{i=1}^{n} P_i \log_2 P_i \tag{1}$$

where P_i is the probability that the system is in some state, and n is the number of possible states.

Table 1. Comparison of the CVCS Design Between System 80 and System 80+

	Current System 80	Change for System 80+
Safety Grade Design	**safety grade**	non-safety grade
Centrifugal Charging Pumps	**three** positive displacement charging pumps	**two** centrifugal charging pumps
Charging Pump Suction Piping	path through the boric acid makeup pumps and **three** gravity feed paths	path through the boric acid makeup pumps and **one** gravity feed
Boric Acid Storage Tank	**Safety grade refueling water storage tank(RWT)**	**Non-safety grade boric acid storage tank(BAST)**
Letdown Line Related	back pressure regulator valves, etc.	fixed orifice, etc.

Based on this concept, the diagnostic entropy can be derived as the following equation[5] :

$$H_D = -\sum_{i=1}^{n} P_i^* \log_2 P_i^* \qquad (2)$$

where P_i^* is the conditional probability that the system is not in the desired state and n is the number of possible states. The mathematical form of P_i^* is as follows :

$$P_i^* = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i} \qquad (3)$$

where λ_i is the failure rate of component i. In this work, the use of no multi-component failure, i.e., rare event approximation simplifies the calcuration of H_D. We should design in a way to minimize H_D to the extent that it is satisfied economically. In order to minimize the value of H_D, the number of undesired system states should be reduced and the reliabilities of the components should be increased. Reducing the number of undesired system states can be interpreted as an effort to reduce the number of components on the number of system states in a design process. Also, using passive components, which have lower failure rates than active components can be interpreted as an effort to make the distribution of the probabilities of the undesired system states uneven as a means of reducing the value of H_D.

3.2. Diagnostic Number of Components

H_D is meaningless by itself : H_D of a system is meaningful only when it is compared with H_D of another system. Therefore, the "Diagnostic Number of Components" has been introduced, which has a meaning by itself[4]. The definition is as follows :

$$N_D = 2^{H_D} \qquad (4)$$

For a N component system, H_D in Eq. (2) will be at a maximum when the value of P_i^* is the same for each of the single-failure states or $P_i^* = 1/N$. Then, $H_D = \log_2 N_D$ where $N = N_D$. Therefore, Eq.(4) is derived. This value has the physical significance of being the number of components of the smallest system, for which failure of any component is possible, which can have the value of H_D. If a system has N_D of x, the system has the same diagnostic difficulty with a system which has x components of equal reliabilities.

3.3. Unavailability

For the availability analysis of CVCS, the interval availability with the plant lifetime interval, from initial start-up through commercial shutdown of the power plants, is the proper measure. However, this average value approaches the steady-state availability as time increases. In most of works, therefore, the steady-state availability is used for availability analysis.

A minimal cut set of a system, which is generated by fault tree method, is a cut set that has no other cut set as a subset[6]. The total system unavailability using rare event approximation is defined as follows :

$$Q_S = \sum_{i=1}^{n} Q(i) \qquad (5)$$

where, Q(i) is the unavailability of minimal cut set i and n is the number of minimal cut sets.

3.4. Cost Modeling

Modeling of the revenue cost lost according to system unavailability, called by Revenue Lost Cost (RLC), is straightforward. The revenue lost cost varies from year to year and these annual revenue lost costs should be discounted for the evaluation of present worth. The present worth of lifetime revenue lost cost due to the CVCS unavailability, RLC, is obtained as

$$RLC = \frac{e_r R Q}{x - y_{er}} \left(1 - e^{(y_{er} - x)T}\right) \qquad (6)$$

where,

y_{er} = escalation rate of revenue lost cost (yr^{-1})
x = discount rate (yr^{-1})
T = plant lifetime (yr)

3.5. Discussions

The above evaluation models are primarily based on the system complexity, which has been focused on the number of the components. The entropy concept is applicable to the measure of simplicity and entropy measure can effectively be used as a decision-making tool for design simplification with simple value-impact analysis. As a result, the diagnostic difficulty of CVCS is mainly dependent on the number and configuration of charging pumps due to their significant contribution to system failure. In addition, higher redundancy of components has insignificant effect on the increase of system availability.

However, the effect of the change into non-safety grade CVCS has not been evaluated in the above models. In other words, the models have not counted for the benefit through the separation of ECCS (Emergency Core Cooling System) from CVCS. A new model, therefore, must be developed to consider and measure the complexity in the interface of CVCS with the other systems.

4. Development of an Interface-Directed Model

4.1. Operational Interface Diagram

In this section, we introduce the Operational Interface Diagram(OID). OID can be used for measuring the interface complexity based on the entropy concept. OID is constructed by the following steps :

1. Find the systems with which CVCS interfaces operationally
2. Identify the relationships of CVCS with the other systems and draw relation lines between them
3. Attach a sign on each relation line properly according to the kind of relationships

If CVCS gives some operational action to the other systems, ' + ' is attached on the according relation line. In the opposite case, ' − ' is attached. As for the others, we can paste 'o' on it. In this work, the design enhancements of CVCS of System 80+ and KSNPP are quantitatively evaluated in comparison with CVCS of System 80. Therefore, the OID's of CVCS of System 80, System 80+, and KSNPP are drawn in Figure 1, 2, 3, respectively in the above manner.

4.2. Interface-Directed Model

Firstly, the number of relation lines can be a measure obtained from the above mentioned OID. This measure can represent the interface characteristics with physical meanings, for example, pipe linings, valves, etc.

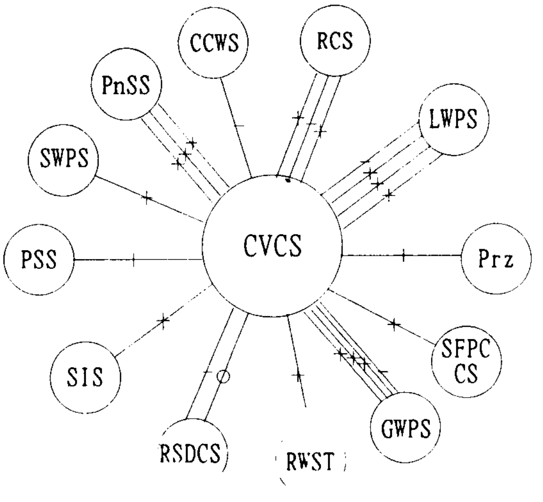
Secondly, the above entropy concept is introduced again to quantify the characteristics in the operational interface aspect. In other words, for structure measurement, chunks are distinguished by their number and kind of relation lines as they appear in an OID. OIDs consisting of a number of similar substructures tend to have lower entropy than those having such regularity. The relative number of components of a chunk to the total number of components is used to measure the entropy-based complexity.

The entropy above mentioned, however, is difficult to compare a system with the other ones in absolute meaning. In this work, we further present an improved evaluation standard based on a modified relative entropy concept. The relative entropy measure, named H_I, can be defined as follows :

$$H_I = \sum_{i=1}^{n} P_i \log_n \frac{P_i}{Q_i} \tag{7}$$

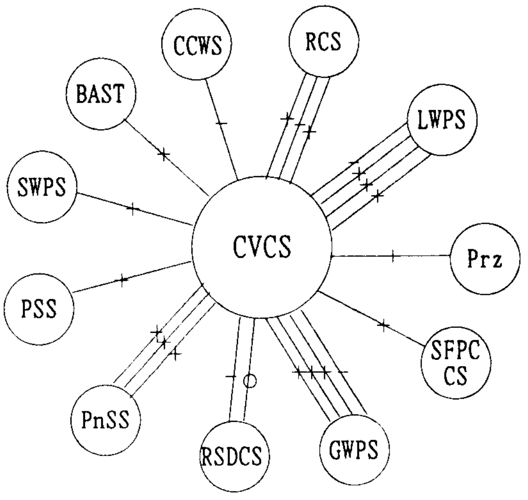
It is most important to define the basis distribution, **Q** for this definition. We define the basis distribution as the probability distribution which has the highest complexity, that is, $Q_i = 1/n$ for all i. Therefore, it is desirable to have the greatest H_I among the measuring distributions **P** that satisfy some constraints. It can be said that H_I is a kind of 'figure of merit' with the respect to the interface entropy.

H_I for system 80 can be computed from the fol-



CCWS : Component Cooling Water System
SWPS : Solid Waste Processing System
PSS : Process Sampling System
SIS : Safety Injection System
RWST : Refueling Water Storage Tank
SFPCS : Spent Fuel Pool Cooling and Cleanup System
Prz : Pressurizer
RCS : Reactor Cooling System
PnSS : Pneumatic Supply System
RSDCS : Reactor Shutdown Cooling System
LWPS : Liquid Waste Processing System
GWPS : Gaseous Waste Processing System

Fig. 1. Operational Interface Diagram of System 80

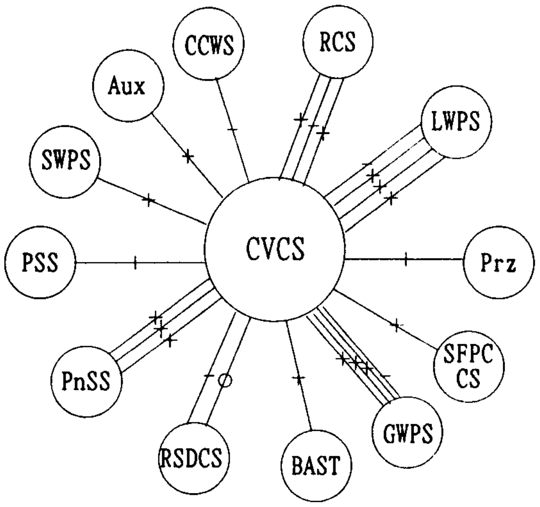


CCWS : Component Cooling Water System
SWPS : Solid Waste Processing System
PSS : Process Sampling System
BAST : Boric Acid Storage Tank
SFPCS : Spent Fuel Pool Cooling and Cleanup System
Prz : Pressurizer
RCS : Reactor Cooling System
PnSS : Pneumatic Supply System
RSDCS : Reactor Shutdown Cooling System
LWPS : Liquid Waste Processing System
GWPS : Gaseous Waste Processing System

Fig. 2. Operational Interface Diagram of System 80+

lowing equivalence partitioning :

{CCWS}, {SWPS, PSS, SIS, RWST, SFPCS, Prz}, {RCS}, {PnSS}, {RSDCS}, {LWPS, GWPS}



CCWS : Component Cooling Water System
SWPS : Solid Waste Processing System
PSS : Process Sampling System
BAST : Boric Acid Storage Tank
Aux. : Auxiliary Systems
SFPCS : Spent Fuel Pool Cooling and Cleanup System
Prz : Pressurizer
RCS : Reactor Cooling System
PnSS : Pneumatic Supply System
RSDCS : Reactor Shutdown Cooling System
LWPS : Liquid Waste Processing System
GWPS : Gaseous Waste Processing System

Fig. 3. Operational Interface Diagram (KSNPP)

In the same way, H_I for system 80+ can be computed from the following equivalence partitioning:
{CCWS}, {BAST, SWPS, PSS, SFPCS, Prz}, {RCS}, {PnSS}, {RSDCS}, {LWPS, GWPS}

H_I for KSNPP can be computed from the following equivalence partitioning :
{CCWS}, {Aux, SWPS, PSS, BAST, SFPCS, Prz}, {PnSS}, {RSDCS}, {RCS}, {LWPS, GWPS}

5. Evaluation Results

In order to calculate the system availability, the failure rates and repair rates of the components are collected from three different sources[7][8][9]. In the calculation of revenue lost cost are given as 30 years and 40 mills/kwhe based on the recommendation of Reference[10]. Table 2 shows the evaluation results.

The quantification results for the design of the System 80+ and KSNPP indicate that the simplicity of the CVCS is primarily dependent on the type and the number of charging pumps. System 80+ has less H_D and slightly better availability than System 80. This is intuitively explainable because System 80+ design has smaller number of components than System 80 in total number of components as well as the number of pumps. Considering H_D and system availability simultaneously, the positive aspects of System 80+ will be more significant because if the

Table 2. Evaluation Results

	System 80	System 80+	KSNPP
No. of Active Component	18	16	21
Diagnostic Entropy, H_D	1.643	1.417	1.887
Diagnostic No. of Comp., N_D	3.12	2.75	3.7
No. of Relation Line	**23**	**21**	**21**
H_I	**0.178**	**0.140**	**0.178**
System Failure rate	2.79E-6	2.59E-6	1.74E-6
Availability	0.92735	0.92736	0.92739

human error probabilities in real time diagnosis is considered, the increase of H_D will result in the decrease of system availability. KSNPP has the smallest system failure rate among three designs due to higher redundancy. But its N_D is highest and the benefit in system availability is insignificant.

As the result of the evaluation with the interface-directed model, it can be said that, though the numbers of relation lines are reduced for System 80+, the simplification does not result in as great figures of merit as expected, at least with the economic view.

6. Conclusions

We have presented the quantitative evaluation models based on the entropy concept and system availability analysis to evaluate the design simplification. Also, the design enhancements of System 80+ and KSNPP CVCS have been quantified in complexity using the presented evaluation models. The entropy concept is applicable to the measure of simplicity and entropy measure can effectively be used as a decision-making tool for design simplification with simple value-impact analysis.

In particular, the interface-directed model has been developed because the effect of the change into non-safety grade CVCS has not been evaluated in the other models. With this model, we can count for the effect through the separation of ECCS(Emergency Core Cooling System) from CVCS. But, the effect of the change into non-safety grade CVCS has not been sufficiently evaluated. Unfortunately, the cost benefit analysis based on the interface-directed model also cannot be performed. A new model, therefore, must be developed to measure in cost the interface of CVCS with the other systems.

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References

1. P.H. Seong, V.P. Manno, and M.W. Golay, "Application of a Power Plant Simplification Methodology: The Example of the Condensate Feedwater System," *Nucl. Eng. Design,* **110,** 33 (1988)
2. R.A. Matzie, R.W. Bonsall, and W.A. Fox, "An Integrated Design Approach for System 80+ for Improved Operations and Maintenance," *Proc. the 7th KAIF/KNS Annual Conf.,* April (1992)
3. Presentation Material for CVCS Simplification, ABB-CE, Inc. (1991)
4. P.H. Seong, "A methodology for Simplification of Light Water Reactor System Design," Ph. D. thesis, Dept. Nucl. Eng., MIT (1987)
5. M.W. Golay, P.H. Seong, and V.P. Manno, "A Measure of the Difficulty of System Diagnosis and Its Relationship to Complexity," *Int. J. Gen. Syst.,* **16,** 1 (1989)
6. N.J. McCormick, Reliability and Risk Analysis, Academic Press, New York (1981)
7. EPRI NP-2592, "PWR Power Plant Pump Reliability Data," *Science Application,* Inc. (1982)
8. DOE/NE-0095, "Nuclear Energy Cost Data Base : A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generation Cost Analysis," U.S. DOE (1988)
9. NUREG-0880, "Safety Goals for Nuclear Power Plant Operation," U.S. NRC (1983)
10. "EPRI ALWR Program, Cost Goal Evaluation-Progress Report," United Engineers & Constructors (1988)