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IoT-Integrated Fractal Analysis for Assessing Structural Integrity and Cooling Stability in Post-Accident NPPs

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사고 후 원전의 구조적 무결성 및 냉각 안정성 평가를 위한 IoT 통합 프랙탈 분석

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Abstract This study analyzes system behavior and safety during severe accidents involving coolant inflow into the reactor core and building. Although this integrated configuration is not a standard safety system, its cooling effectiveness has been validated through operational plant cases. To identify geometric regularity in complex accident environments, Fractal algorithms and Internet of Things (IoT) monitoring were integrated, with coolant accumulation modeled via Boolean-based numerical simulations. Results show safety indicators rising gradually following initial damped oscillations. By day 90, the system reached thermal equilibrium, ultimately stabilizing in a steady-state with constant-amplitude oscillations, confirming long-term stability.

Key Words : Internet of Things (IoT), Nuclear power plants, Safety, Fractal, Simulations, System dynamics

요 약 본 연구는 중대사고 시 냉각재가 노심 및 건물 내부로 유입되는 복합 상황을 가정하여, 시스템 거동과 안전성 확보 가능성을 분석하였습니다. 이러한 혼합 구조는 설계 기준상 표준 계통은 아니나, 실제 발전소 사례를 통해 냉각 유효성이 입증된 바 있습니다. 본 논문에서는 사고 환경의 기하학적 규칙성을 규명하고자 프랙탈 알고리즘과 IoT 기술을 융합 적용했으며, 건물 내 냉각재 축적 상황을 불리언 기반 수치 시뮬레이션으로 모델링하였다. 분석 결과, 안전성 지표는 초기 감쇠 진동 후 점진적으로 상승하였습니다. 사고 90일 경과 시점에서는 열적 평형에 도달하며, 일정 진폭 내에서 유지되는 정상 상태(Steady-state)의 진동 평행선을 그리며 최종 안정화됨을 확인하였습니다.

주제어 : IoT, 원자력 발전소, 안전, 프랙탈, 시뮬레이션, 시스템 동역학

1. Introduction

After previous severs accidents in the nuclear power plants (NPPs), the post-accident analysis (PAA) is investigated in the aspect of complex algorithm as the fractal theory. These accidents are under disorder conditions where the designed safety injection systems for the emergency and residual heat removal functions were failed and then eventually had gone to be out of control. There are comparisons in 〈Table 1〉 in which the characteristics of previous three

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severe accidents. The status of Fukushima and Chernobyl is under incomplete situations of the cooling. So, the status of integrity of the plant is going in continuing of nuclear heat and cooling as the form of the fuel and structure mixtures. Additionally, IoT systems are introduced and modeled to enhance accident processing, including speed and accuracy of accident processing.

〈Table 1〉 List of post-accident treatment

Variable	Method	Status
Three Mile Island	Isolation in containment	Core melted
Chernobyl	Isolation by concrete	Incomplete and new covering
Fukushima	Isolation in water pool	Incomplete and continuous radiation leak to environment

It is studied to consider the integrity of the post-accident when the coolants are pouring into the core and reactor building. Although this is not a designed safety system, currently two plant sites are in the stable states using this kind of mixed structures. In the geometrical analysis where it is to find out the formalized regularity, the fractal algorithm is to be utilized in the NPPs' case. The molecular levels are investigated in the fuels and facility structures with whom the analysis would show regularities as the atomic mass numbers and the ratio of the atoms. This reflects the original meaning of fractal geometry where the self-similarity concept is used for the analysis.

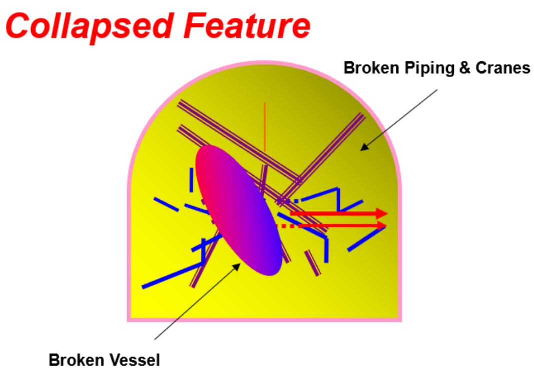
As non-linear complex algorithm, the fractal logic is useful in describing the unexpected phenomena, futuristic expectations, and technological forecasting in which the dynamical prediction of the designed systems is analyzed. Furthermore, the accident scenarios are many uncertainties in event progressions. Disordered features of the facilities are related to many unexpected variables. For example, the collapsing of the structures is a very significant cause to the event scenario. That is, it is impossible to find out the next step of the scenarios. Hence, it is better to regard the situation as the randomized properties than to examine the detail investigations in the accident sites. Treating of post-accident state cannot give the exact data to the operators who should manage the plant operations. It is one of ways to make use of the robotics which could be controlled by the artificial intelligence (AI). Therefore, it is reasonable to manage the disaster state using the non-linear algorithms.

There are some papers which are applied to the technological matters such as the mechanical problems. Petković et al. worked that the fluctuation of the wind is analyzed by the fractal interpolation of the wind where the neural networking algorithm is used [1]. Jalan et al. studied the complex network is incorporated with the fractal characteristics [2]. In addition, Chen et al. showed the spreading morphologies by plasma material in the aspect of fractal dimensions [3]. It has been applied to many fields in the social humanities as well as the scientific technologies.

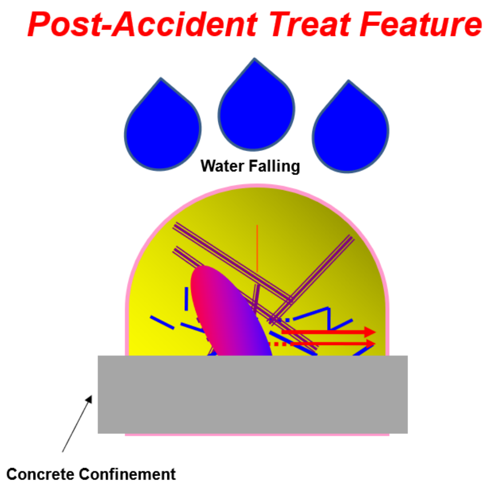
2. Methods

2.1 Conceptual direction

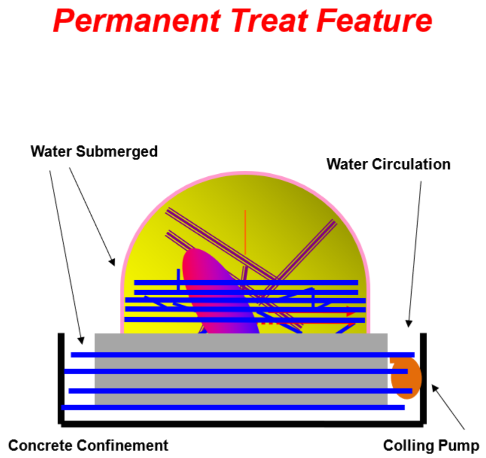
Conventional nuclear safety is based on the regulations in which there are many prevented directions to control the nuclear energy productions in NPPs. However, in the accident like the Fukushima case, there is the unavoidable accident management where the imperative treatments has been done in the accident situations. So, one can imagine the accident concept could be changed from the Preventions to the Isolations, because the repeated action could be done in the changed scale. So, the cooling actions are done in the collapsed structures where even though the coolant system is broken, the cooling is eventually done by the overloaded pouring into the broken containment building in Fukushima case. Figures 1, 2, and 3 show the configurations of reactor features as Collapsed feature, Post-accident feature, and Permanent cooling feature, respectively.



[Fig. 1] Modified physical protection system (PPS).



[Fig. 2] Configuration of post-accident feature.



[Fig. 3] Configurations of permanent cooling feature.

2.2 Fractal theory

It is possible to imagine the managements of NPPs in the situation of disorder state. The fractal shape could be made, because the intended operations as the emergency cooling should be performed.

2.2.1 Self-similarity

In our world, there are same statistical repeating feature as the variable scales like the leaf of trees or coastlines [4]. One of most important examples is the Koch curve where the similar shapes are repeated eternally [5]. The dynamical description for the Koch curve is done as the dynamical scaling [6-8]. There are the measure of similarity as [5],

$$N\varepsilon^{D_s} = 1 \tag{1}$$

D is the similarity dimension, N is the self-similarity segment, and ε is the scaling ratio. So, for the line, area, and volume, respectively,

$$L = N\varepsilon = 1 \tag{2}$$

$$A = N\varepsilon = 1 \tag{3}$$

$$V = N\varepsilon = 1 \tag{4}$$

Therefore, equation (1) is,

$$D_S = \frac{\log(N)}{\log(1/\varepsilon)} \tag{5}$$

So, one can find that in the case of 8 segment and 1/4 length of its parent, the value is,

$$Ds = \frac{\log(8)}{\log(1/(1/4))} = \frac{\log(2^3)}{\log(1/(1/2^2))} = \frac{3\log(2)}{2\log(2)} = 1.5 \tag{6}$$

2.2.2 Applications in nuclear accident

In the application of nuclear viewpoint, it is able to be considered as the nano-scopic investigation, because the molecular level interactions happen in the disordered state where coolants, and nuclear materials are mixed. Fig. 4 shows the configurations of reactor features as Basic concept of cooling and Fractal analysis. So, there is the comparison between fractal theory and atom related modification. For example, in the cooling application, the atomic numbers in water could be used as 1.0 of hydrogen and 8.0 of oxygen. The total mass number of hydrogen is 2.0 and the ratio of element numbers is 2.0.

$$D_H = \frac{\log(2)}{\log(1/(2/3))} = \frac{\log(2)}{\log(3/2)} = \frac{\log(2)}{\log(3)-\log(2)} = 1.709511 \quad (7)$$

Similarly, the total mass number of oxygen is 16.0 and the ratio of element numbers is 1/3.

$$D_O = \frac{\log(16)}{\log(1/(1/3))} = \frac{\log(2^4)}{\log(3)} = \frac{4\log(2)}{\log(3)} = 2.523719 \quad (8)$$

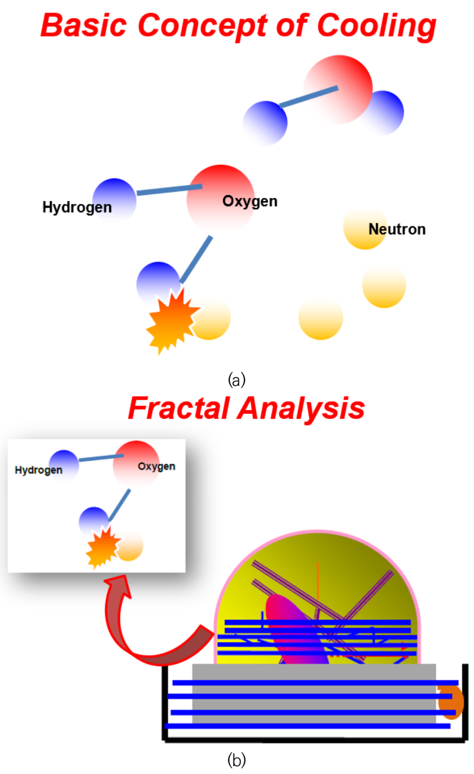
In the case of carbon dioxide coolant,

$$D_C = \frac{\log(12)}{\log(1/(1/3))} = \frac{\log(12)}{\log(3)} = 2.523719 \quad (9)$$

Similarly, the total mass number of oxygen is 32.0 and the ratio of element numbers is 2/3.

$$Do = \frac{\log(32)}{\log(1/(2/3))} = \frac{\log(2^5)}{\log(3/2)} = 8.547556 \quad (10)$$

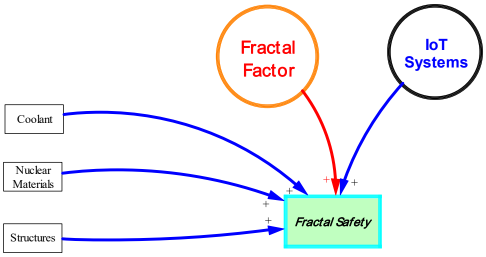
Therefore, it is important to make D value should be distributed completely to cover the nuclear materials in the collapsed features



[Fig. 4] Configurations of nano-scopic reactor features (a) Basic concept of cooling and (b) Fractal analysis.

2.3 Modeling for simulations

The simulations are assumed as 100 days period. Fig. 5 shows the modeling results from a simulation using the Vensim code, a system dynamics (SD) framework. SD has been used not only for humanities and social science analysis but also for complex scientific and technological problems [9-15]. This is the software for the technological assessment of the interested topics [16]. The design of modeling is constructed by connecting of the related events to the issue. In this model, the basic variables as Coolant, Nuclear Materials, Structures, and IoT Systems are quantified. Here, IoT systems refer to various Internet systems for accident processing. In the case of Coolant, it is equated as, if then else(random 0 1 () 〈 0.6, 0, 1) (11)



[Fig. 5] SD modeling for the design.

This means if the random numbers between 0 and 1 is lowered than 0.6, it is 0. Otherwise it is 1. So, the Boolean values are obtained. Especially, the values are accumulated from 0. This shows the incoming coolants are accumulated in the collapsed structures of containment building. Here, the numerical values that serve as criteria for each are determined based on expert judgment.The other three cases are similar. That is, in the case of Nuclear Materials, it is,

if then else(random 0 1 () 〈 0.3, 0, 1) (12)

This means if the random numbers between 0 and 1 is lowered than 0.3, it is 0. Otherwise it is 1. The nuclear fuel and its related materials are assumed as 3/10 of total materials in the building. 〈Table 2〉 shows the list of each variable. In addition, there is the Fractal Factor where the random numbers are compared with a value that is obtained by normalized one of the fractal calculation. From equations (7) and (8),

$$\frac{1.709511}{1.709511+2.523719}=0.403831 \qquad (13)$$

〈Table 2〉 List of variables.

Variable	Quantity
Coolant	if then else(random 0 1 () < 0.6, 0, 1)
Nuclear Materials	if then else(random 0 1 () < 0.3, 0, 1)
Structures	if then else(random 0 1 () < 0.6, 0, 1)
IoT Systems	if then else(random 0 1 () < 0.3, 0, 1)
Fractal Factor	if then else(random 0 1 () < 0.403831, 0, 1)
Fractal Safety	(Coolant + Nuclear Materials + Structures + IoT Systems)*Fractal Factor

So, Fractal Factor is,

if then else(random 0 1 () 〈 0.403831, 0, 1) (14)

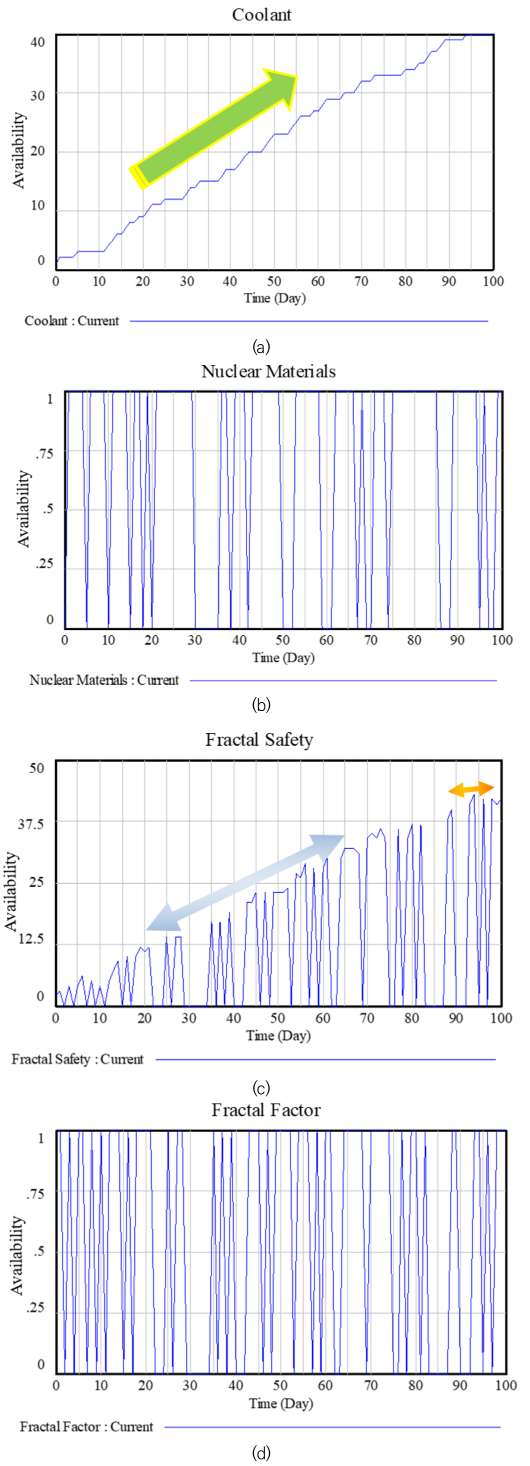
This is the random number based Boolean numbers are related to the value obtained by the self-similarity. Finally, in Fractal Safety, the value is,

(Coolant + Nuclear Materials + IoT Systems + Structures)*Fractal Factor (15)

Each Boolean value is summed and multiplied by the Fractal Factor.

3. Results

The experimental data presented in Fig. 6 provides a comprehensive overview of the system's thermal behavior and stability metrics. In Fig. 6 (a), the results clearly illustrate specific instances where coolant accumulation occurs, suggesting potential bottlenecks in the internal circulation flow. This is further supported by the Boolean logic displayed in Fig. 6 (b) and (c), which maps the operational status and triggering thresholds of the cooling system. Regarding the Fractal Safety index shown in Fig. 6 (d), the availability values exhibit a progressive upward trend characterized by rhythmic oscillations, reflecting the dynamic complexity of the safety margins under stress. Notably, after a duration of 90 days, these fluctuations transition into a steady-state equilibrium. At this stage, the graph maintains a parallel trajectory with consistent, minor oscillations, signifying that the cooling environment has reached a state of long-term stabilization and reliable thermal management. In addition, Table 3 shows the behavior of IoT Systems and Fractal Safety through sensitivity analysis, and it appears that uncertainty has increased as the standard deviation in Fractal Safety increases.



[Fig. 6] Results of simulations (a) Coolant, (b) Nuclear Materials (c) Fractal Factor, and (d) Fractal Safety.

〈Table 3〉 Statistics of result.

Variable	Min.	Max.	Mean	St. Dev.
IoT Systems	0	1	0.68	0.47
Fractal Safety	0	43	13.38	15.03

4. Conclusions

The complex algorithm is used for the post-accident analysis especially for the NPPs' severe accident where the reactor core is melted and collapsed. This extremely dangerous situation is considered as the unmanageable states. So, the fractal algorithm is applied to solve the disordered situations. That is to say, although the post-accident is not the designed state, the reactor building is under stabilized conditions where the radioactive hazards are quite under safety level. The broken nuclear fuels are open to the environments. Even though some radioactive materials leak, the exposure levels have been down to the health protection condition. There are some important points of this study as follows,

- The post-accident analysis (PAA) is studied.
- Fractal theory as complex logic is applied to nuclear disaster.
- The Self-similarity method is examined.
- Industrial applications for PAA are suggested.

This kind of the study could be applied to the other kinds of the industrial disaster such as the environmental pollutions. The oil leak in the sea by the wreck of oil tanker ship could damage to the environment very dangerously. So, the fractal algorithm could be used to analysis of the accident effect. The dynamical simulations are one of the important of considering factors. Hence, the future work should be done in the aspect of the environmental pollutions. In addition, the fundamental science like the fluid mechanics is one of the future topics in the fractal work where the efficiency of NPPs is significantly improved by the analytic studies.

REFERENCES

[1] D. Petkovića, V. Nikolić, V.V. Mitić and L. Kocić, "Estimation of fractal representation of wind speed fluctuation by artificial neural network with different training algorothms," Flow Measurement and Instrumentation. Vol.54, pp.172-176, 2017.

[2] D. Petkovića, V. Nikolić, V.V. Mitić and L. Kocić, "Estimation of fractal representation of wind speed fluctuation by artificial neural network with different training algorothms," Flow Measurement and Instrumentation. Vol.54, pp.172-176, 2017.S. Jalan, A. Yadav, C. Sarkar and S. Boccaletti, "Unveiling the multi-fractal structure of complex networks," Chaos, Solitons & Fractals. Vol.97, pp.11-14, 2017.

[3] S.Y. Chen, G.Z. Ma, H.D. Wang, P.F. He, M. Liu and H.J. Wang and B.S. Xu, "Comparison of solidity and fractal dimension of plasma sprayed splat with different spreading morphologies," Applied Surface Science. Vol.409, pp.277-284, 2017.

[4] B.B. Mandelbrot, "How long is the coast of Britain? Statistical self-similarity and fractional dimension," Science New Series. Vol.156, No.3775, pp.636-638, 1967.

[5] P.S. Addison, Fractals and Chaos: An Illustrated Course, Bristol: Institute of Physics Publishing, 1977.

[6] M.K. Hassan and M.Z. Hassan, "Emergence of fractal behavior in condensation-driven aggregation," Physical Review E. Vol.79, p.021406, 2009.

[7] M.K. Hassan, M.Z. Hassan and N.I. Pavel, "Dynamic scaling, data-collapseand Self-similarity in Barabasi-Albert networks," Journal of Physics A: Mathematical and Theoretical. Vol.44, p.175101, 2011.

[8] F.R. Dayeen and M.K. Hassan, "Multi-multifractality, dynamic scaling and neighbourhood statistics in weighted planar stochastic lattice," Chaos, Solitons & Fractals. Vol.91, pp.228-234, 2016.

[9] S.L.Y. Han, J. Du, L. Xin, Y. Zhao, "Analysis of water resources carrying capacity in North China based on system dynamics," Journal of Hydrology: Regional Studies. Vol.62, p.102878, 2025.

[10] R. Sun, H. Yang and W. He, "Power and energy dynamic characteristics analysis for electric networks considering time-varying angular frequency in power system dynamics," International Journal of Electrical Power & Energy Systems, Vol.172, p.111305, 2025.

[11] M.A. Ahmad, A. Al-Bazi and B. Clegg, "A hybrid multi-agent and system dynamics approach for risk-informed selection of third-party logistics providers in supply chains," Computers in Industry. Vol.176, p.104443, 2026.

[12] M. Alghamdi, S. Alhifthi, N. Alsanabani, K. Al-Gahtani, A. Altuwaim and A. AlSharef, "Modeling the interdependencies of critical factors in hospital facility management: a system dynamics framework," Ain Shams Engineering Journal. Vol.17, No.1, p.103954, 2026.

[13] Y. Ding and J. Yin, "Collaborative strategies for inter-city low-carbon development: integrating cross-game and system dynamics approaches," Ecological Modelling. Vol.514, p.111462, 2026.

[14] T. Liu, M. Chen and C. Wang, "Cause analysis and evolution characteristics of different types of railway accidents based on system dynamics theory," Reliability Engineering & System Safety. Vol.273, p.112334, 2026.

[15] F. Rudolph, M. Jung and A.B. Classen, "Hybrid Simulation Models for high-performance and versatile airport simulations: Integrating System Dynamics and Agent-Based Approaches," Transportation Research Procedia. Vol.94, pp.91-100, 2026.

[16] Ventana, Vensim software, Harvard: Ventana Systems, Inc., 2016, http://vensim.com/.

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