AN AXIOMATIC DESIGN APPROACH OF NANOFLUID-ENGINEERED NUCLEAR SAFETY FEATURES FOR GENERATION III+ REACTORS

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A variety of Generation III/III+ reactor designs featuring enhanced safety and improved economics are being proposed by nuclear power industries around the world to solve the future energy supply shortfall. Nanofluid coolants showing an improved thermal performance are being considered as a new key technology to secure nuclear safety and economics. However, it should be noted that there is a lack of comprehensible design works to apply nanofluids to Generation III+ reactor designs. In this work, the review of accident scenarios that consider expected nanofluid mechanisms is carried out to seek detailed application spots. The Axiomatic Design (AD) theory is then applied to systemize the design of nanofluid-engineered nuclear safety systems such as Emergency Core Cooling System (ECCS) and External Reactor Vessel Cooling System (ERVCS). The various couplings between Gen-III/III+ nuclear safety features and nanofluids are investigated and they try to be reduced from the perspective of the AD in terms of prevention/mitigation of severe accidents. This study contributes to the establishment of a standard communication protocol in the design of nanofluid-engineered nuclear safety systems.

KEYWORDS : Nanofluid, Nuclear Safety Features, Safety Injection, In-vessel Retention, Axiomatic Design

1. INTRODUCTION

Imagine using an advanced coolant having a superior heat removal performance to water coolant to improve current water-cooled reactors with any specified design. Imagine, too, that the coolant is a so-called nanofluid with higher thermal properties that can replace water coolants since the fluid can secure the success of emergency core cooling or secure in-vessel retention of a core melt to prevent potential containment failure more tightly. And then there would not be any safety concerns rising up even though we would be able to design higher-power reactors to achieve better economics. Such an innovative cooling technique has been developed for Generation III+ reactors featured with improved economics and safety. Known as a nanofluid or a nanoparticle-fluid mixture, it consists of metal or metal-oxide nanoparticles and a base liquid, as well as a stabilizer for enhancing colloidal stability because a nanofluid could be classified as a new engineered colloidal dispersion. The colloidal suspensions have substantially shown the nuclear society intriguing thermal performances regarding four points: (1) increased thermal conductivity (~150%), (2) increased single-phase heat transfer coefficient (~60%), (3) increased critical heat flux with extended nucleate boiling regime (~200%), and (4) improved quenching efficiency. Although there is a lack of agreement of the experimental data in the literature and a lack of understanding of the physical mechanisms describing nanofluid thermal performances, the present work was motivated by the fact that a nanofluid formulation could not be tailored to show the desired properties for nuclear systems if we do not consider it together with nuclear safety systems characterized inherently by various couplings in a system engineering [1].

Potential nuclear safety systems adopting the nanofluid coolants in current water-cooled reactors can be engineered features such as an Emergency Core Cooling System (ECCS), External Reactor Vessel Cooling System (ERVCS), and In-Vessel/Ex-Vessel Core Catcher Systems. The objective of this study is to design a new system, a nanofluid-engineered nuclear safety system for current Generation III/III+ reactors. Although conceptual design studies of nanofluid applications to enhance the in-vessel retention strategy of an AP1000 and the ECCS of an EPR have been previously performed by Buongiorno et al. [2] and Chupin et al. [3], respectively, it is likely to be biased in developing or evaluating such design processes because the entire design activities are usually characterized by designers' heuristic knowledge. Also, it is noteworthy that we can expand the application of nanofluids into both PWRs and BWRs because ABWRs also consider adopting an in-vessel retention strategy to mitigate severe accidents in terms of concerns about larger power capacity raised to ~1800 MWe [4-5]. In order to scientifically design so-called nanofluid-engineered systems, the present design work adopts Axiomatic Design (AD), which is one of the representative methodologies suggested to provide a systematic design process [6].

The AD principles explain a systematic design process as a method to avoid the cost and delays caused by iterative development. One of the lessons learned in engineering may be nearly all significant development cost over-runs or delays have their roots in ill-defined requirements during the synthesis phase [reference, http://www.dfss-software.com/default.asp]. In the design of Nuclear Power Plants (NPPs), such a cost over-run can definitely affect economics as well as safety, which is more important for preventing radiological disasters. Consequently, it is worth evaluating the design processes to identify vulnerabilities and create innovative ideas for a better solution.

The authors have attempted to use the AD principles to resolve a few individual problems. That is, the AD theory has been applied to evaluate the designs of ECCSs of an OPR1000 and APR1400 [7] and used to develop a standard protocol in designing nanofluids [8]. This paper presents the nanofluid-engineered nuclear safety system design with integrating nanofluid knowledge and several experiences utilizing the AD principles.

2. BACKGROUND: SYSTEM DESCIRIPTIONS AND THOERIES

In order to design nanofluid-engineered nuclear safety systems, we first need to review the conventional designs and new design for Generation III/III+ nuclear safety systems coping with the worst accident scenario tested in the licensing process. And then we need a brief review of nanofluid knowledge achieved so far and the AD theory.

2.1 Brief Review of Accident Scenarios and Safety Systems

The general objectives for designing nuclear safety systems for Generation III+ are as follows: (1) to provide an engineered safety feature for a large reactor generating; and (2) to provide an engineered safety feature that can accommodate severe accidents within the design. The bounding accident threatening nuclear safety is, although extremely unlikely, a loss-of-coolant accident resulting from a large, double-ended break in the primary coolant system, which has long been considered the worst accident that could happen [9]. As a safety measure, nuclear engineers have designed ECCSs which are tested in the licensing process to prove nuclear cores can survive even the worst accident. However, the Three Mile Island accident in 1979 changed the nuclear society's beliefs about successful core cooling [10]. In some cases, although the engineered ECCS is definitely working during an accident, there could be a core melting accident/severe accident resulting in the possibility of vessel failure due to the relocation of the melted core materials in the lower vessel head. Considering the severe accident, in-vessel retention (IVR) of core debris through an external reactor vessel cooling (ERVC) has been implemented for light water reactors (LWRs) [10]. The current review is intended to figure out the applicable cases of nanofluids.

(1) LOCA and ECCS for PWR. For nanofluid implications to the safety system, accident details introduce us to the complex fluid-dynamics and heat-transfer phenomena of the system which can make the need/advantages of nanofluid features in terms of design requirement and implication methods. The most important accident scenario of a LOCA includes the three phases blowdown, bypass/refill, and reflood. We will look briefly over the LOCA phenomena and how an ECCS works based on Vigil and Pryor's accident simulation [9].

BLOWDOWN of the primary water coolant (~15 sec). If we presume a sudden large break in the cold-leg pipe, water coolant rapidly breaks out from the primary system due to the large pressure difference between the primary system (150 bar) and the containment (~1 bar). The escaping water rate is limited by the choking phenomenon or critical flow. When the pressure of the primary system has fallen to the saturation pressure, the water flashes to steam and a two-phase mixture comes out. During blowdown, the pressurizer tries to maintain the pressure by keeping all the water out of the hot leg. At the event, the engineered safety feature of a high-pressure injection system, consisting of low-flow-capacity pumps, starts to work automatically in an early blowdown and injects emergency coolant into the cold legs. In this phase, the core may be damaged by the reduction of heat transfer from the fuel rod generating decay heat after vaporization of the coolant [9].

BYPASS/REFILL of lower plenum (~10 sec +~10sec). The second phase of the accident starts when pressure of the primary system decreases down to that of the nitrogen in the accumulator (45 bars). Then, the check valves that normally isolate the accumulators from the primary system open, and the expanding nitrogen injects water into the downcomer through the intact cold leg. However, at first, water from the accumulator cannot reach the lower plenum, which means it is swept around the downcomer and out the broken cold leg. That is the bypass of emergency water from the accumulator due to a countercurrent flow of steam. Such steam is due to a kind of flashing as the system pressure falls and boiling by heat transferred from structural materials. Water from the accumulator continues to bypass the lower plenum for approximately 10 seconds. Refill begins when the countercurrent steam velocities decrease resulting in water penetrating the lower plenum. Refill lasts for about 10 seconds and ends when the water level in the lower plenum reaches the bottom of the fuel rods [9].

REFLOOD of core. The third phase of the accident starts when water refills the reactor vessel and quenches the fuel rods, which is called reflood of the core. The main source of emergency coolant for a reflood in conventional reactors is water pumped into the cold legs by the low-pressure injection system. The injection activates automatically when the primary system pressure falls below about 6 bars. At the beginning of reflood, the fuel rods are relatively hot because heat transfer has not been very effective during most of the blowdown and all of the bypass/refill. Consequently, when water first covers the bottom of the fuel rods, it is unable to wet the cladding surface because the temperature of the surface is much beyond the Leidenfrost one, which is a critical temperature for water to be able to wet a hot surface in terms of film boiling. Eventually, the cladding temperature falls below the minimum stable film-boiling temperature, the liquid wets the surface, the fuel rods cool by the efficient mechanism of nucleate boiling, and their temperature at the elevation drops sharply to near the water temperature, which is the rods are quenched. The quenching progresses from bottom to top as the core is reflooded but some top-down quenching also occurs due to entrained droplets at the same time. In the quenching mechanism, the quench front is an important point at which the fuel-rod temperature has dropped rapidly to near that of the reflooding water [9].

This brief review is based on the reference [9] including Fig. 1 which shows the safety systems and LOCA. The ECC water injection strategy is shown in Fig. 2 [11].

(2) LOCA and ECCS for BWR. The conventional ECCS equipped in BWRs, which is characterized by an overpressure injection to suppression pool, high pressure injection system and low pressure injection system, has evolved to adopt passive systems which means relying on driving forces like gravity and natural recirculation rather than active systems such as pumps more easily compared to PWRs. If a pipe leaks or

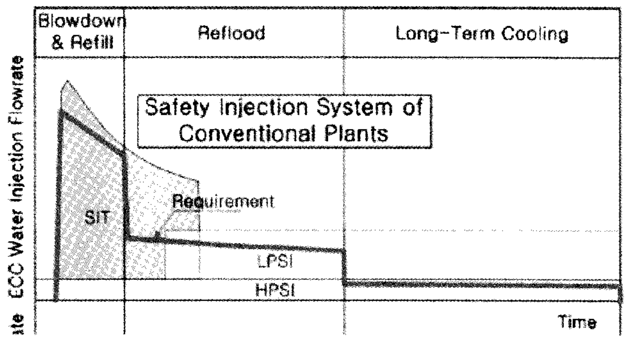


Fig. 2. Time vs. Water injection rate from an ECCS during a LOCA [11]

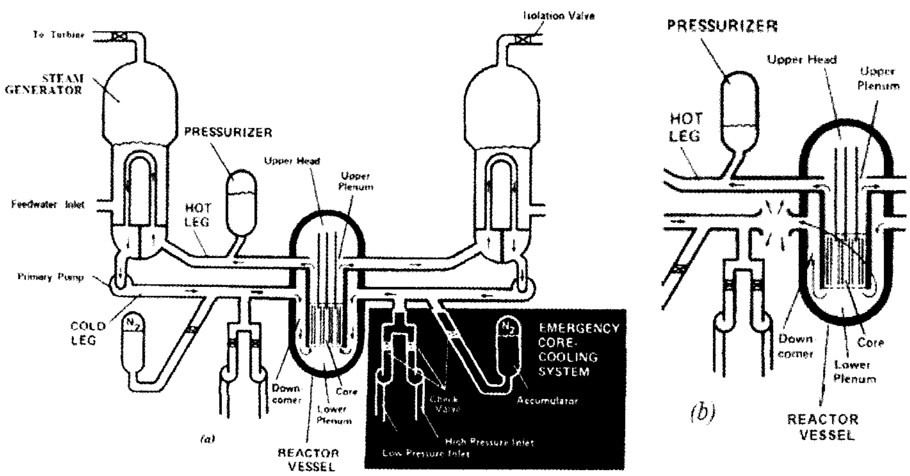


Fig. 1. Coolant Flow Pattern through the Primary System of a Pressurized-water Reactor: (a) during Normal Operation when Coolant Flows down the Downcomer and up through the Core and (b) Early in a Blowdown when Coolant Flows up the Downcomer and out the Broken Cold Leg [9]

breaks, the feed water system maintains a sufficient water level in the vessel to avoid activating the passive core cooling system. If the water level drops to a level below that expected for common plant events, a timed sequence of depressurization and passive cooling begins. Depressurization begins when the safety relief valves open and transfer steam from the reactor into the suppression pool where it is condensed back into water. This relieves pressure in the reactor pressure vessel. Near the end of depressurization, valves open and allow water to drain from the gravity-driven cooling system (GDCS) pool into the reactor pressure vessel, raising the water level and completing the process of cooling the nuclear core. Because the core has remained cooled through the sequence, the nuclear fuel does not heat up and the fuel tubes remain intact [12].

(3) **Severe accidents and External Vessel Cooling of In-Vessel Retention of core melt.** A severe accident is defined as a type of accident that may challenge safety systems at a level much higher than expected and which causes core melting. After the TMI-2 accident, IVR of core debris through a ERVC was adopted as one severe-accident-management strategy. That is, by flooding the reactor cavity that surrounds the vessel, significant energy can be removed from relocated corium materials through the vessel wall by nucleate boiling on the vessel outer surface. As long as the wall heat flux from the core melt does not exceed the critical heat flux (CHF) limit for nucleate boiling on the vessel outer surface, the reactor vessel is cooled sufficiently that it prevents vessel failure and the release of corium materials to the containment [10].

(4) **Core catcher feature of core melt.** In-vessel and ex-vessel core catchers have been proposed to retain materials that relocate during a severe accident, which delays when relocated materials attack the vessel and containment, irrespectively. In fact, the core catchers have been considered as additional safety features because IVR cannot be guaranteed for higher-power-level reactors [10].

2.2 Brief Review of Nanofluids

Nanofluids as liquids that harbor nano-sized particles (or engineered colloids) are a new type of demand-driven coolants. Their initial concepts suggested by S. Choi [13] started with simple ideas that solids have thermal conductivities that are orders of magnitude larger than those of traditional heat transfer fluids such as water, ethylene glycol, and refrigerants; and if we use nanoscale solid particles suspended in liquid well with proper dispersion methods, it is expected that they won't damage a heat transfer surface compared to microscale particles. Naturally, the enhancement of thermal conductivity and dispersion of nanoparticles bring about additional thoughts to the heat transfer community that we can use those for a variety of heat transfer applications in terms of heat transfer and thermal management efficiency. The resulting heat-transfer fluids have been researched to manage heat more efficiently than conventional coolants. In particular, nuclear applications of nanofluids are primarily on CHF enhancement (IVR-ERVC) and quenching efficiency (ECC) in terms of nuclear economics and safety concerns. Such interests for the nuclear society can be easily understood based on the above-reviewed accident scenario and conventional nuclear safety features coping with such accidents. So far the nanofluid research results on both important points are

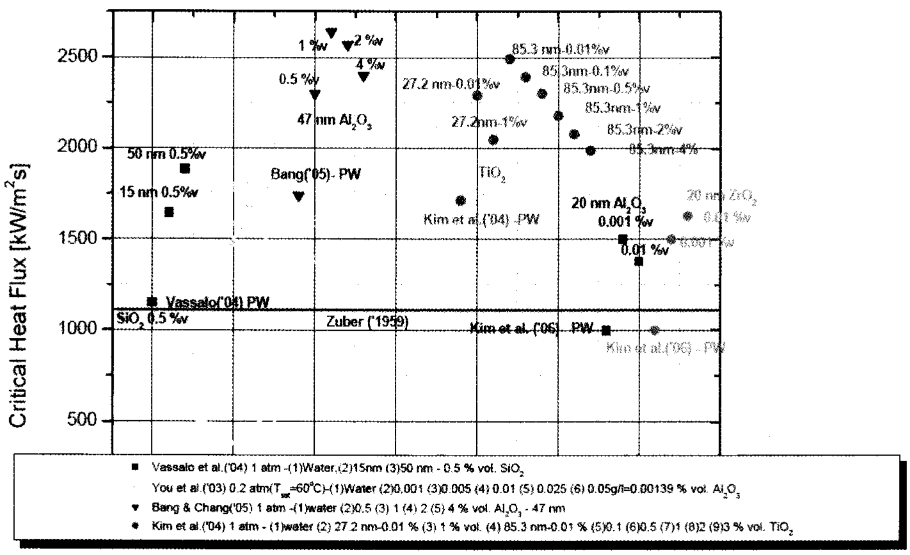


Fig. 3. CHF Enhancement Data by Nanofluids in the Literature [17]

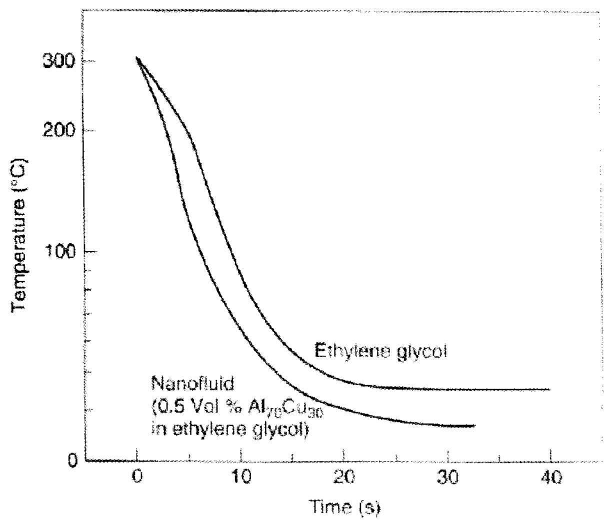


Fig. 4. Comparison between the Quenching Efficiency of Pure Ethylene Glycol and a Nanofluid with $Al_{70}Cu_{30}$-ethylene Glycol [18]

shown in Fig. 3 and Fig. 4. Through the data, nanofluids can enhance up to 200% while the quenching efficiency is improved in terms of faster cooling, although there are still concerns for the lack of various experimental conditions (in particular, geometry) in terms of practical application as well as the lack of agreement of the experimental data even for the same kinds of nanofluids. The main mechanisms of CHF enhancement and quenching efficiency expected by nanofluids are on improved thermal properties of nanofluids (higher heat conduction), and an improvement of liquid surface wettability due to coating, as well as help in breaking down the vapor blankets around a hot surface [14-16]. It is known that the CHF enhancement in nanofluids is due to boiling-induced coating (nanoparticles deposition). This is very similar to the pre-coating enhancement technology to get CHF enhancements in the mechanism of surface wettability improvement. The disadvantage of the pre-coating technology is on the durability for a long lifespan in the nuclear power plant operation. But in the case of nanofluids, once boiling occurs, a nanoparticle can coat the surface to keep a level of surface wettability. This can be called self-recovering coating. The self-healing coating is important in particular for IVR-ERVC because a key technique of the IVR-ERVC margin increase, the pre-coating technique of a vessel, has an issue of longer life-span endurance of Generation III+ (approximately ~60 years). On the other hand, mechanistic changes in quenching performance expected from using nanofluid as a new coolant of an ECCS can be suggested as follows: (1) improved heat transfer coefficient of nanofluids in the quench front (QF), (2) improved thermal dissipation accelerating the QF, (3) locally nonuniform cooling in nanofluids, (4) rupture of vapor blanket/film due to turbulence enhancement, (5) improved radiation heat transfer of nanofluids, and (6) improved surface wettability by nanoparticles [19]. However, the exact physical mechanisms are on-going questions to be answered by many researchers. Although there are more reliable experimental data for both CHF and quenching, it should be noted again that the present work was motivated by the fact that a nanofluid formulation can be tailored to show the desired properties for nuclear systems when we consider it together with features of nuclear safety systems characterized inherently by various couplings in a system engineering.

2.3 Brief Review of Axiomatic Design Concepts

The AD theory has been developed from the thought that design is being done empirically or heuristically on a trial-and-error basis resulting from so many design mistakes and wasting budget. That is, there exists unknown/unrecognized axioms in the design world to make scientific and logical thinking processes for seeking a best design easily. Axiom is defined as self-evident truth or fundamental truth for which there are no counterexamples or exceptions [6]. An axiom cannot be derived from other laws or principles of nature. Axiomatic design defines the design as an interplay between 'what we want to achieve' and 'how we want to achieve it.' To elaborately characterize the interplay, the AD proposes that the design world is made up of four domains: customer domain, functional domain, physical domain, and process domain. The customer domain is characterized by the needs that the customers or end users are looking for. In the functional domain, the customer needs are interpreted in terms of functional requirements (FRs) and constraints (Cs). To satisfy the specified FRs, we develop a process that is characterized by process variables (PVs) in the process domain. Finally, to produce the product specified in terms of DPs, we develop a process that is characterized by process variables (PVs) in the process domain. In the case of designing a system, the first step is to determine the customer needs/attributes (CAs) in the customer domain that the system must satisfy. Then the FRs and Cs of the system in the functional domain are determined to satisfy the CAs. The FRs must be determined in a solution-neutral environment-defining FR without thinking about the solution in order to come up with creative ideas. FRs must satisfy the CAs with fidelity. The next step is to map these FRs of the functional domain into the physical domain-conceiving design embodiment and identifying the DPs. At the highest level of the system design, DPs may be conceptual entities, which must be decomposed to complete the design. DPs must be so chosen that there is no conflict with the constraints. DPs may be physical parameters or parts or assemblies. This step is creating system architecture. The mapping or interplay between two domains is accompanied with top-down zig-zagging decomposition organizing the design

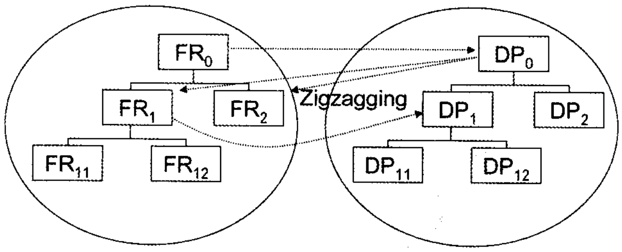


Fig. 5 Zig-zag Design Process [6]

hierarchy linking a high-level conceptual design and a low-level detailed design. This is illustrated in Fig. 5. We start at the top FR. From the top FR, we go to the physical domain to conceptualize a design and determine its corresponding DP. Then we come back to the functional domain to create FR_1 and FR_2 at the next level that collectively satisfy the highest level FR. FR_1 and FR_2 are the sub FRs characterizing the highest level DP. The decomposition process must proceed layer by layer until the design reaches the final stage, creating a design that can be implemented. It is important to keep in mind that sub FRs should be Mutually Exclusive and Collectively Exhaustive (MECE) at each layer. The mapping process between the domains can be expressed mathematically in terms of the characteristic vectors that define the design goals, which are FRs, and design solutions, which are DPs.

$$\{FR\} = [A]\{DP\} \tag{1}$$

where [A] is called the design matrix.

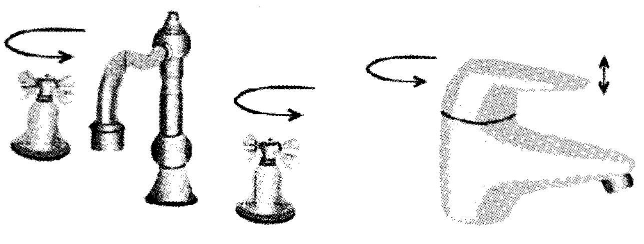
Conventionally, the interaction between a FR and a DP is represented by 'X' in a design matrix. Obviously, all of the diagonal elements in a design matrix must be X. We are using 'O' to represent no functional dependency between a FR and a DP. Sometimes a small 'x' is used to intuitively indicate weak dependencies.

During the mapping process between the functional and physical domains, the following two axioms provided by the AD prevent designers from serious design mistakes and therefore guide them to better design decisions:

Axiom 1: Independence Axiom. Maintain the independence of the FRs.

Axiom 2: Information Axiom. Minimize the information content of the design.

The design matrix helps us to apply the independence axiom in a mathematical manner. To satisfy the independence axiom, the design matrix must be either diagonal or triangular. When the design matrix [A] is diagonal, each of the FRs can be satisfied independently by means of one DP. Such a design is called an uncoupled design. When the matrix is triangular, the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence. Such a design is called a decoupled design. Any other form of the design matrix is called a full matrix and results in a coupled design. Therefore, developing designs that create either a diagonal or a triangular design matrix corresponds to the systematic design process for a better decision. Unfortunately, in the real world, most designs cannot be uncoupled, and a decoupled design is usually considered satisfactory. In any circumstance, a coupled design is to be avoided. The information axiom states that the design with the highest



	DP1: Angle of valve 1	DP2: Angle of valve 2
FR1: Control flowrate	X	X
FR2: Control temperature	X	X

DP1: Handle up-down lifting	DP2: Handle right-left moving
X	O
O	X

Fig. 6. FRs and DPs for Designing Water Faucets [6]

probability of success is the best design, which means 'how can we choose the best design' among the different designs satisfies the independence axiom [6]. For the readers' better understanding, an example of design coupling is presented in Fig. 6, where two possible arrangements of the generic water faucet are shown. Assuming two FRs control flowrate and control temperature, Fig. 6 shows the sets of DPs for each faucet design. In the case of the left design, controlling either DP should affect the other FR. That is, the FRs are not independent so the compromise of FRs should be obtained after several iterations. This is a coupled design. As opposed to the left design, the DPs in the right design do not affect the other FR so any design changes to improve a FR can be done independently, which should be a more valuable design attribute. In terms of the AD theory, this is an uncoupled design.

3. DESIGN PRACTICES FOR NANOFLUID-ENGINEERED NUCLEAR SAFETY FEATURES

3.1 Analysis of Conceptual Designs of a Nanofluid Injection System by using Axiomatic Design

In this section, we look over previous ECCS designs that use nanofluids in the ECCS in the literature from the viewpoint of design axioms.

3.1.1 Designs for ECCS

Chupin et al. [3] suggested three design options to apply nanofluids to an ECCS system, in particular, for a so-called nanofluid injection tank. The design suggestions are compared with each other on the basis of the results of reverse engineering driven by AD. One of the key messages of AD is that we must think of design in terms of functional requirements. That is, we should clarify "what we want to achieve" before we proceed. The top FR of this idea must be to provide nanofluids to the core in order to improve the quench speed enhancing the rewetting of the core during a large break loss of coolant accident (LB-LOCA). Therefore, we may define a top FR and DP set as follows:

FR_0: Provide nanofluids to the core during a LB-LOCA;

DP_0: Nanofluid Injection Tank

When we decide on sub-level FRs that are necessary to implement the nanofluid injection tank, we consider requirements such as time to inject, mixing capabilities, cost, space requirements, safety impact, sampling of the nanofluid, and material compatibility [3]. Among the conceptual requirements or a kind of customer attribute, we need to find the proper functional requirements in the functional domain. Here, cost, nanofluid safety (toxicity), and sampling as well as space limitation can be considered constraints (Cs). Therefore, FRx can be stated as

FR_1: Provide sufficient inventory nanofluids

FR_2: Provide the nanofluids to the core within a very short time (10-20 secs.)

FR_3: Provide good mixing with RCS and IRWST coolants

FR_4: Provide good material compatibility in terms of stability of nanofluids

Here, three conceptual design options can be used to decide the proper design parameters in the physical domain.

According to design option #1 [3]: charging to the SIS accumulators.

DP_1: Nanofluid volume with the higher concentration as coolant of existing accumulators

DP_2: 45 bar nitrogen gas of accumulators

DP_3: Cold leg injection: no change of installation location of accumulator

DP_4: Materials of accumulator: no change

To check the coupled relations, the design matrix may be written as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ x & X & x & O \\ O & x & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \tag{2}$$

The small x indicates that the element has a relatively small effect of other DPs on each FR corresponding to a DP. For example, the relation of FR_2 and DP_1 can be a small x because the highly concentrated nanofluid has a higher viscosity.

According to design option #2: New nanofluid accumulators, a small volume of tank and 45 bars nitrogen gas are featured. However, there are no outstanding changes in design parameters.

DP_1: Nanofluid volume with the highest concentration as coolant of new accumulators

DP_2: 45 bar nitrogen gas of accumulators

DP_3: Cold leg injection: new installation of accumulator

DP_4: Materials of accumulator: no change

To check the coupled relations, the design matrix may be written as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ x & X & x & O \\ O & x & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \tag{3}$$

According to design option #3: non-pressurized tanks, connected to the sump lines of the IRWST

DP_1: Nanofluid volume with high concentration as coolant of a new small tank

DP_2: Lowhead safety injection pump for the new small tank (30 secs.)

DP_3: Connection to sump line of a new small tank in a LHSI (Lowhead safety injection)

DP_4: Titanium: new material of new small tank

To check the coupled relations, the design matrix may be written as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ x & X & x & O \\ O & x & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad (4)$$

Here, the lowhead safety injection pump delays the injection time over the FR if the time of injection is 30 secs, which might be too late for nanofluids to contribute to increasing the quenching speed.

So far, we performed a reverse engineering for the design options proposed by Chupin et al [3] in terms of AD to check which designs would be superior. Apparently, the three designs have a design matrix with a similar level of coupling. As noted in the reference [3], a better design seems to be judged by the above-mentioned constraints. Moreover, some important FRs have been missed and more points to be considered with the whole ECCS systems. We will deal with this in section 3.2.

3.1.2 Designs for IVR-ERVC

This section is intended to look over previous applications of nanofluids to IVR-ERVC in the literature. The IVR-ERVC is needed in case reflooding by an ECCS does not occur quickly enough to prevent core damage. Buongiorno et al. [2] suggested three conceptual design options for an AP1000 and we will analyze those designs by using the AD theories. The top FR of the nanofluid injection system for an IVR-ERVC could be clarified to provide nanofluids to the reactor cavity in order to enhance the CHF margin of the reactor vessel during a severe accident of core melt and relocation. Therefore, we define a top FR and DP set as follows:

FR_0: Provide nanofluids to flood the reactor cavity during a severe accident;

DP_0: Nanofluid injection system for IVR-ERVC

When we decide sub-level FRs that are necessary to implement the nanofluid injection tank, we consider requirements such as time to inject, nanofluid cavity mixing, space requirements, and cost. Space requirements and cost can be considered constraints (Cs).

FR_1: Provide sufficient inventory nanofluids

FR_2: Provide the nanofluids to the cavity within a time frame (70 mins after core exit temperature reaches 648°C)

FR_3: Provide good mixing with RCS and IRWST coolants

FR_4: Provide good material compatibility in terms of stability of nanofluids

Three conceptual design options of Buongiorno et al. [2] can be used to decide the proper DPs in the physical domain.

According to design option #1: Direct cavity injection.

DP_1: Nanofluid volume with a higher concentration as coolant of accumulators

DP_2: Static head pressure (gravity) by the elevation of a tank above IRWST (discharge head) or slight overpressure

DP_3: Direct cavity injection with spargers (distance, flow path)

DP_4: Materials of accumulator

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ x & X & x & O \\ O & x & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad (5)$$

It is noted that design option #1 includes two injection tanks and a cross-tied line for redundancy, which is related to the number of physical equipments that delivers the role of a DP. From the viewpoint of AD, it is to increase the probability of success of the FRs which means decreasing the information contents in Axiom 2. In the probabilistic safety assessment (PSA), it means the frequency of accident occurrence (information contents) will be lowered positively.

According to design option #2: Injection into the IRWST recirculation lines

DP_1: Nanofluid volume with a higher concentration as coolant of accumulators

DP_2: Static head pressure (gravity) by the elevation of a tank above IRWST (discharge head) or slight overpressure

DP_3: IRWST lines (distance, flow path)

DP_4: Materials of accumulator

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ x & X & x & O \\ O & x & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad (6)$$

According to design option #3: Injection into the IRWST

DP_1: Nanofluid volume with a higher concentration as coolant of accumulators

DP_2: Static head pressure (gravity) by the elevation of a tank above IRWST (discharge head) or slight overpressure

DP_3: IRWST (distance, flow path)

DP_4: Materials of accumulator

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ x & X & x & O \\ O & x & X & O \\ O & O & O & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad (7)$$

So far, we tried to perform a reverse engineering for the design options in terms of AD to check which designs among the pre-existing conceptual designs would be superior. Mostly, the decision for a better design might be dependent on the constraints as shown in the AD approach designing ECCSs.

3.2 Axiomatic Design of Nanofluid-Engineered Nuclear Safety Systems

3.2.1 Nanofluid-Engineered Emergency Core Cooling Systems

A systematic design process of nanofluid-engineered emergency core cooling systems requires an overall system engineering. In the above section, we tried to ask this and investigated design matrixes for conceptual designs of nanofluid-engineered safety features. In this section, we will decompose the design matrixes and get to know the root cause of the couplings. The ideas of eliminating such couplings will be examined and a new nanofluid engineered safety feature which is decoupled will be proposed. Fig. 7 shows the design domain world of an ECCS in terms of the new system design.

At the development of an advanced ECCS, the attribute the customer is looking for is to increase the rate of cooling in the core during a LOCA. In general, the primary purpose of an ECCS is to remove decay heat and to prevent core damage during all the phases of a LOCA for all break sizes. Therefore, we need to combine both attributes. The present design work is implemented by referring to the

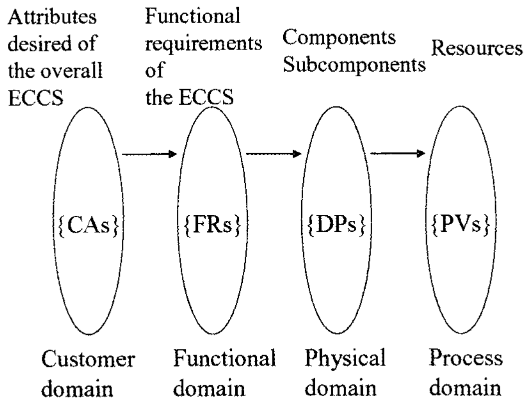


Fig. 7. Design Domains for Synthesizing ECCSs Based on Suh's Framework [6]

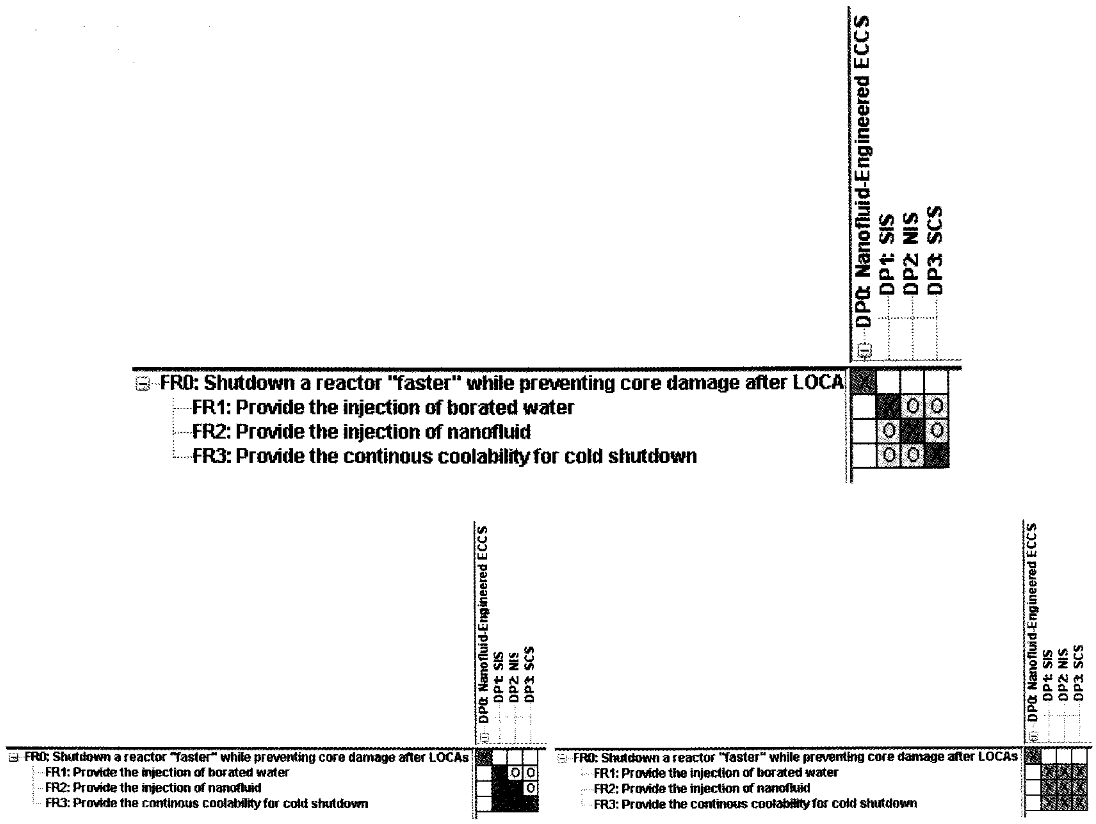


Fig. 8. Uncoupled Design, Decoupled Design, and Coupled Design Created by Acclaro DFSS™

axiomatic design matrix of an ECCS of the APR1400. The ECCS of the APR1400 has been defined as two thermal-hydraulic sub-systems for the timely management of all LOCA phases: SIS and SCS. A SIS is designed for the injection of borated water to a RCS following a LOCA. A SCS is used to reduce the temperature of a RCS to cold shutdown during normal as well as accident conditions. In particular, the SCS is manually actuated using heat exchangers as a heat sink instead of a separate water inventory after the end of the SIS injection mode. However, in the present study, although a big advantage of a nanofluid-engineered feature is the reflood phase before the end of the injection mode as noted below, we need to consider the SCS system together here because the SCS uses the refilled inventory of the reactor core.

The top FR and DP can be stated as

FR_0: shutdown a reactor "faster" while preventing core damage after a LOCA

DP_0: Nanofluid-engineered ECCS

We decide on sub-level FRs that are necessary to implement the nanofluid-engineered ECCS. For this, we are decomposing with modifying an axiomatic design tree diagram for an APR 1400 according to the attributes for nanofluids. We propose three sub-FRs and DPs set.

FR_1: Provide the injection of borated water

FR_2: Provide the injection of a nanofluid

FR_3: Provide the continuous coolability for cold shutdown

DP_1: Safety Injection System (SIS)

DP_2: Nanofluid Injection System (NIS)

DP_3: Shutdown Cooling System (SCS)

Every step that we decompose a sub-level for detailed design, we should check the coupled relations. According to the AD theory, the design matrix of this level of FRs and an uncoupled design can be written as shown in Fig. 8.

The reason why we show the uncoupled Design Matrix (DM) is that the design is the best one in terms of AD theory, which reminds us to make efforts to realize the relationship when we do the system design as shown in Fig. 7. In the reality of a thermal-hydraulic system, the general design matrix can be either decoupled or coupled as shown in Fig. 8. It should be noted that both the decoupled and coupled designs can successfully satisfy the given functional requirements. The point is cost over-runs due to useless iterative design processes, and this is caused by a circular dependency, for example, component A affects B which affects A again, creating a coupling between design features. In the case of decouple designs, such a circular dependency may be negligible as long as couplings are recognized where to work. In order to renovate a coupled design to a decoupled design, off-diagonal couplings should be chosen such that a circular dependency is not generated or is eliminated such that a different DP is introduced.

For sub-level FRs and DPs, we need to consider a phase of the LOCA for the nanofluid to be needed to achieve our goals. As was reviewed in section 2, phase-by-phase accident management is the most important in leading to the successful operation of an ECCS during the LOCA. Fig. 9 shows the APR1400 operation strategy for time versus water coolant flowrate. Here, the key thing is to figure out the nanofluid application spots considering the phase-by-phase accident management because the main mechanism of nanofluids to contribute to the advanced feature of an ECCS might be on the improvement of quenching speed resulting in knocking down the PCT much faster. Therefore, the beginning stage of the reflood phase is the key target for nanofluids to be delivered certainly to the lowest part of the core for a new advanced ECCS.

According to the sequential behavior of a reactor vessel, the DP_1 is decomposed of two specific FRs. The customer attributes of an APR1400 have been changed compared to those of an OP1000 in terms of passive safety systems. That is, a typical PWR can have the following FR and DP set.

FR_{11}: Provide coolant during blowdown phase of a LB-LOCA

FR_{12}: Provide coolant during bypass/refill phase of a LB-LOCA

FR_{13}: Provide coolant during reflood phase of a LB-LOCA

DP_{11}: HPSIP

DP_{12}: SIT

DP_{13}: LPSIP

On the other hand, we use the following set for the APR1400.

FR_{11}: Provide coolant with a high flow rate to the reactor to reflood the core in a short period (to meet 10CFR50.46 peak cladding temperature acceptance criteria - cooling)

FR_{12}: Provide coolant with a flow rate to the reactor in any pressure condition to prevent the core uncovery.

DP_{11}: SIT-Advanced

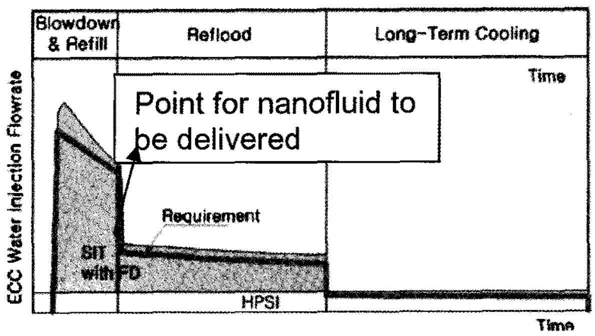


Fig. 9. Role of the SIS Components with Time Versus Water Injection Flowrate [11]

DP_{12}: (HP)SIP

To create neutral FRs to meet the selected DPs, we consider four basic factors to complete a system: engine, transmission, control unit, and working unit. These four components are a kind of metaphoric representation in synthesizing technical systems. Only when all these

Table 1. DPs of Subcomponents at the Second and Third Levels

	SIT-Advanced	SIP	NIS	SCS
	x=11	x=12	x=2	x=3
DPx1	Tanks	IRWST	Tanks	SCHx
DPx2	Pressurized nitrogen	SIPs	Pressurized nitrogen	SCPs
DPx3	Passive actuation	Automatic actuation	Passive actuation	Manual actuation
DPx4	Valve arrangement	Valve arrangement	Valve arrangement	Valve arrangement

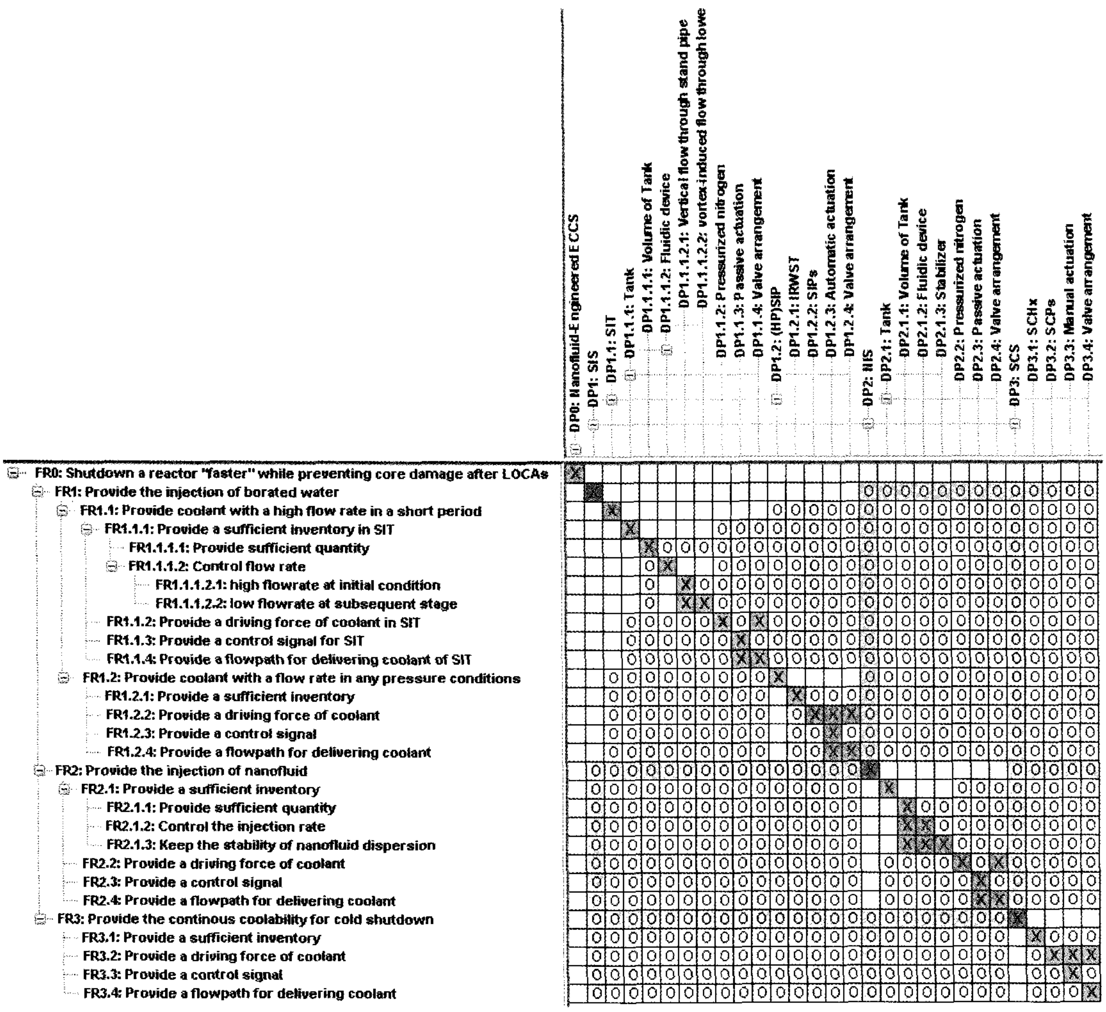


Fig. 10. Design Matrix of Nanofluid-engineered ECCS Created by Acclaro DFSS™

components provide their minimal capability can a system perform its functions [7,8,28]. On the basis of these factors, we use the developed FRs and the corresponding DPs shown in Table 1.

FR_{x1}: Provide a sufficient inventory (where x equals 11, 12, 2, or 3)
FR_{x2}: Provide a driving force of coolant (where x equals 11, 12, 2, or 3)
FR_{x3}: Provide a control signal (where x equals 11, 12, 2, or 3)
FR_{x4}: Provide a flow path (where x equals 11, 12, 2, or 3)

For NIS, we can adopt either SIT-like subcomponents or SIP as far as nanofluids can reach the bottom of the core in the beginning phase of reflood as we consider the expected nanofluid mechanisms. However, SIT-like subcomponents would be desirable in pursuit of a passive system in an advanced nuclear system. Nanofluid as a mixture of nanoparticles and water requires keeping the stability of dispersion while the fluid is injected to the core and making the proper mixing with the other borated water inventory.

Stable mixing between injected nanofluid and injected borated water also brings about concerns for the nanofluid volume with a higher concentration and injection rate of nanofluids in the subcomponent of the tank. Such attributes for the tank can be stated as:

FR_{211}: Provide a sufficient inventory
FR_{212}: Control the injection rate
FR_{213}: Keep the stability of nanofluid dispersion
DP_{211}: Volume of Tank
DP_{212}: Fluidic device
DP_{213}: Stabilizer

Fig. 10 shows the overall design matrix including the coupling analysis of the DPs. We used the Acclaro DFSS™ Version 4.3. Fig. 11 shows the tree of the nanofluid-engineered ECCS. The ultimate goal of this study is to give a guideline or roadmap for how to approach the development of a nanofluid-engineered ECCS. The DM and tree shows the possibility of nanofluid-engineered ECCs standard communication protocol for what we should focus on and make an agreement in the study.

4. CONCLUSIONS

A variety of Generation III/III+ reactor designs featured by enhanced safety and improved economics are being

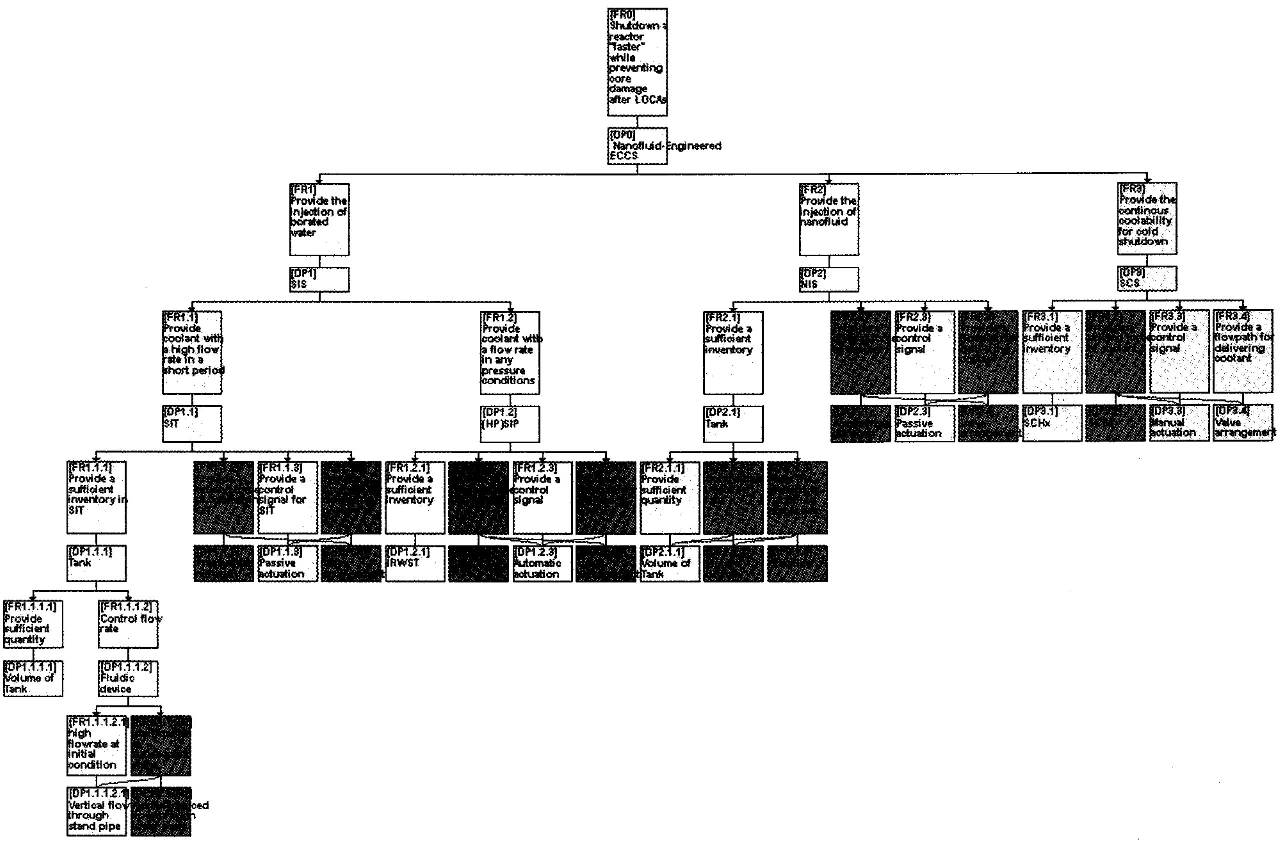


Fig. 11. Tree of Nanofluid-engineered ECCS Created by Acclaro DFSS™

proposed by the nuclear power industry around the world to more realistically solve the future energy supply shortfall. Nanofluid coolants showing an improved thermal performance are being considered as a new key technology to secure nuclear safety and economics. The present work found that there is a lack of comprehensible design works to apply nanofluids to Generation III+ reactor designs, though. In this work, the Axiomatic Design (AD) theory is applied to systemize the design of nanofluid-engineered features combining with safety systems such as an Emergency Core Cooling System (ECCS) and IVR-ERVC System for Generation III+ reactor. As a preliminary study, the present paper shows an axiomatic design analysis of nanofluid-engineered EPR ECCS and AP1000 IVR-ERVC, and the axiomatic design of nanofluid-engineered APR1400 ECCS. This study contributes to the establishment of a standard communication protocol in the design of nanofluid-engineered nuclear safety systems. Further studies are ongoing for the Emergency Condenser System in a BWR as well as the External Vessel Cooling System (EVCS) and In-Vessel/Ex-Vessel Core Catcher Systems for both PWRs and BWRs.

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ACRONYMS

AD	Axiomatic Design
ANPP	Advanced Nuclear Power Plant
CHF	Critical Heat Flux
Cs	Constraints
DP	Design Parameter
ECCS	Emergency Core Cooling System
ERVCS	External Reactor Vessel Cooling System
FR	Functional Requirement
GDCS	Gravity-driven Cooling System
IRWST	In-Containment Refueling Water Storage Tank
IVR	In-vessel Retention
LOCA	Loss of Coolant Accident
LB	Large Break
LHSI	Lowhead Safety Injection
NIS	Nanofluid Injection System
PCT	Peak Cladding Temperature
PV	Process Variable
RCS	Reactor Coolant System
SIS	Safety Injection System
SCS	Shutdown Cooling System
QF	Quench front

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