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# Functional reliability analysis of a molten salt natural circulation system

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ABSTRACT

The functional reliability evaluation of a molten salt natural circulation system, the nitrate natural circulation loop, was performed. Improved procedures based on the RMPS were applied, considering all the uncertainties to avoid a mass of epistemic uncertainties for an innovative system and introducing a systematic sensitivity analysis process. The system was modeled using Relap5-MS. An uncertainty analysis package of molten salt fluid, named NCUAPackage, was developed to deal with the source correlation parameters and model uncertainties inside the code. 229 samples of 43 input uncertainty parameters were propagated through Relap5-MS. The result functional failure probability of is 0.039 including two failure modes. Sensitivity analysis screened out the most important parameters and revealed that the observables and input parameters follow good linear relationships. An important finding is that the model uncertainty of the heat coefficient of NDHX shell side contributes a lot to the failure probability. It is necessary to consider the model uncertainty for the design and reliability analysis.

## 1. Introduction

Recently, innovative reactors tend to make use of passive safety features to a large extent in combination with active safety or operational systems. According to the IAEA Conference on "The Safety of Nuclear Power: Strategy for the Future" in 1991, "The use of passive safety features is a desirable method of achieving simplification and increasing the reliability of the performance of essential safety functions and should be used wherever appropriate" (IAEA, 1991). Of great importance and widely application are natural circulation systems that fall under category B passive systems defined in IAEA-TECDOC-626. These are characterized by moving working fluids with no signal inputs, external power sources or forces or moving mechanical parts.

The passive safety systems rely completely on an intelligent use of natural phenomena, such as gravity, conduction and radiation. The use of such systems reduces the probability of system failure caused by the active components and human factors, and eliminate the costs associated with the installation, maintenance and operation of active safety systems that require multiple pumps with independent and redundant electric power supplies (IAEA, 2009). However, the natural driving force are normally weak. The systems can be much more sensitivity to the small changes in the surroundings than activate systems, especially for the natural circulation systems. The passive system may fail its mission, in addition to the classical mechanical failure of its components, for deviation from the expected behavior, due to physical phenomena or to different boundary and initial conditions. That draws attention to a different reliability mode with active ones. The functional reliability concept, which means the probability to perform the required mission was introduced by Burgazzi (Burgazzi, 2003). It describes "functional failure" as that the "load" exceed the "capacity" of a passive system without any mechanical failure of its components.

This work presents a detailed description of functional reliability analysis of the Nitrate Natural Circulation Loop. The Nitrite Natural Circulation Loop (NNCL) is a kind of molten salt natural circulation system. The experimental facility was built by the Shanghai Institute of Applied Physics, Chinese Academy of Science (SINAP, CAS) with the DRACS, a kind of passive decay removal system, as the prototype. The facility is used to study the integral natural circulation characteristics and natural convection heat transfer performance. It is deployed under the Strategic Priority Research Program named the Future Advanced Nuclear Fission Energy sponsored by the CAS. The construction of the facility was completed in 2015, and the commissioning and some experiments were started afterwards. We aim to develop a procedure for the functional reliability analysis of a molten salt natural circulation system and acquire the quantitative functional failure probability of the NNCL. The quantitative results are helpful for the understanding of key factors influencing the system performance and the experiments and design of molten salt natural circulation systems.

## 2. System description

The NNCL, as shown schematically in Fig. 1, was designed with

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**Nomenclature**

| | |
|---|---|
| $a$ | lateral pitch ratio |
| $b$ | longitudinal pitch ratio |
| $D$ | diameter (m) |
| $f$ | friction factor |
| $L$ | length (m) |
| m | order |
| $n$ | numbers of tube rows |
| $N$ | number of code runs, i.e. sample size |
| $Nu$ | Nusselt number |
| $P$ | probability |
| $Pr$ | Prandtl number |
| $Pr_s$ | Prandtl number based on tube wall temperature |
| $R^2_{adj}$ | adjusted coefficient of determination |
| $Re$ | Reynolds number |
| $t$ | T value |
| | maximum output sample value |
| $\beta$ | confidence level |
| $\gamma$ | reliability |

DRACS as the prototype. The reactor vessel is simulated by a molten salt pool with a height of 1.7 m and a diameter of 1.5 m. A circular electric heater around the bottom of the pool provides an adjustable heating power from 20 kW to 40 kW. The NNCL employs $NaNO_3$–$NaNO_2$–$KNO_3$(7-40-53) as the circulation medium in the pool and the loop. The DHX employs a shell-and-tube heat exchanger design containing 30 folding tubes with inner/outer diameter of 20/25 mm at a length of 3 m. Similarly, a total of 15 folding tubes of the same size are adopted in the NDHX. The height difference between the centers of the two heat exchangers is 3 m. The air cooling tower forms a U-shaped air flow channel with a 3 m to 6 m adjustable height. A natural or desirable air flow can be acquired by adjusting the fan and the air damper under the air cooling tower. An expansion tank is set to adjust the pressure of the loop.

Three coupled natural circulation/convection loops complete the heat removal. Heat is transferred from the electric heater to the DHX through natural circulation of the molten salt in the pool. The molten salt inside the loop is heated in the DHX and becomes lighter. The heated molten salt flows upward to the NDHX where it is cooled by the natural air flow. Then, the cooled molten salt becomes denser and heavier and flows back to the DHX. There are no active components set in the loop except some valves for molten salt loading and unloading. The circulations rely completely on buoyancy.

## 3. Methodology

Efforts were made all over the world to develop a methodology for reliability assessment of the passive systems. However, no consensus on a common approach has been established so far (IAEA, 2014). The earliest attempt was known as reliability evaluation of passive safety system (REPAS), which was developed cooperatively by ENEA, the University of Pisa, the Polytechnic of Milan and the University of Rome in Italy (Jadari et al., 2003). Then the REPAS was developed within the frame work of a project called Reliability Methods for Passive Safety Functions (RMPS), performed under the auspices of the European 5th Framework Programme (Marques et al., 2006). The RMPS is based on the propagation of the uncertainties considering the deviations of those physical and geometric parameters which can lead to a failure of the system through calculations of T-H models. The RMPS or similar approaches are now widely used in the reliability study of passive safety systems. The latest approach is called the RMPS +, an improved version of RMPS developed by CNEA, Argentina (IAEA, 2014). The most two different places are the introduction of Performance Indicator which is used to determine whether the failure criteria are achieved and the addition of iterative calculations for the increase of the precision of the reliability results.

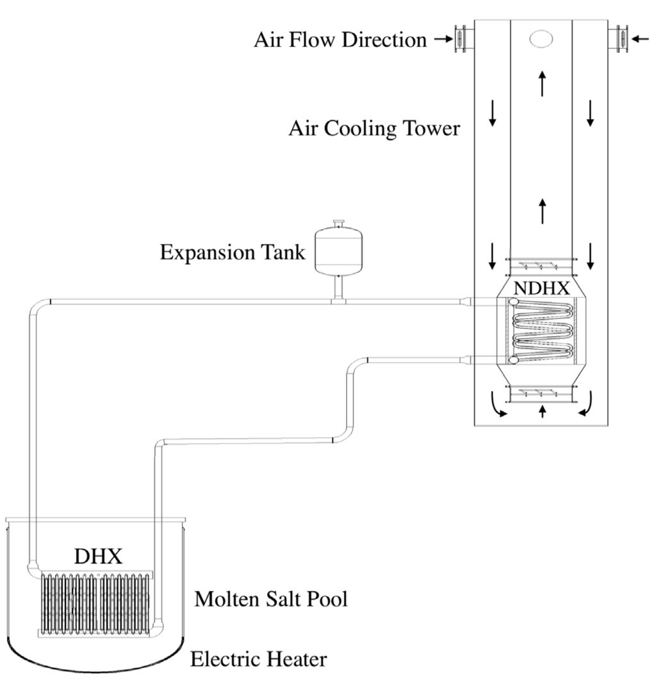


**Fig. 1.** Schematic of the NNCL.

In this paper, procedures for the evaluation of functional reliability of passive systems characterized by natural circulation are as shown in Fig. 2 and detailed as follows:

1) Identification of the system is to obtain information on the behavior of a passive system, and to identify the failure zones and conditions. One or more output parameters are focused as observables, which should reflect the 'distance' between the system success and failure.
2) Due to lack of operation or experimental data, the analysis must rely on numerical modelling. And considering a passive system is sensitive to various small deviations, Best-Estimate code is chosen for system modelling.
3) All the uncertainties influencing the system performance should be picked out as the input uncertainty parameters. A probability distribution function (PDF) is assigned for each input parameter by data statistics or expert judgement. The PDF quantifies the state of knowledge and express the reliable and available information about a parameter.
4) Simple random sampling method is used to acquire the association of sampling of the input uncertainty parameters. The number of runs performed, considering the confidence level, is determined by the Wilks' formula.
5) Direct propagation of the sample associations is performed through the Best-Estimate code. The observable samples are obtained by multiple executions.
6) Calculation of functional reliability. The system is considered failed if one or more of the failure criteria are met. The functional failure probability can be calculated with the failure case amount.
7) A systematic sensitivity analysis process helps to give a ranking of input parameters. This information provides guidance as to where to improve the state of knowledge or the design of a new system.

Among these steps, there are two major improvements compared with the RMPS: