Benchmark on Dynamic PRA with Simplified Decay Heat Removal System Model of Sodium Fast Reactor
Part1 (Benchmark Analysis Condition and Thermodynamic Model Results)

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Abstract: The specific characteristics of a sodium fast reactor (SFR), such as its great thermal inertia and the fact that sodium circuits present risks of irreversible and temperature-sensitive failures, should be considered in the probabilistic analysis. The probabilistic safety study for SFRs cannot be limited to the relatively short mission times considered in light water reactor probabilistic risk assessments (PRAs), since long time is necessary to reach safe and stable state where the decay heat is adequately dissipated by thermal radiation and conduction. In this kind of time frame, the possibility of repair of damaged equipment, and the variation of system success criteria with decreasing decay heat generation need to be considered if an overly conservative analysis is to be avoided. Dynamic PRA approaches have been developed to extend the conventional PRA to longer mission times and to cover the aforementioned phenomena.

To benchmark the different dynamic PRA methodologies developed by Japan and France, based on a simplified version of the Advanced Sodium Technological Reactor (ASTRID) decay heat removal system (DHRS), both results are compared. Several case studies are carried out to verify results sensitivity to system features and probabilistic parameters. In addition, the thermohydraulic models and static PRA results are also compared as validation. We first compared the dynamic thermohydraulic model using defined test cases. The sodium temperature time evolution after reactor shutdown was calculated by the different thermohydraulic codes, considering defined system failure timing.

This paper introduces the benchmark analysis condition and the results of the thermohydraulic model for the study cases. As a result of the comparison, it was confirmed that the Japanese and French thermohydraulic analysis results have good agreement. This comparison result ensures that there is no significant difference between Japanese and French dynamic PRA approaches on the coupled thermohydraulic codes.

Keywords: dynamic PRA, decay heat removal system, sodium fast reactor, fast breeder reactor

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1. INTRODUCTION

A sodium fast reactor (SFR) has specific characteristics, since liquid sodium is used as a reactor coolant. Due to the thermal properties of sodium, the primary coolant has great thermal inertia and the sodium circuits present risks of irreversible and temperature-sensitive failures. Considering the characteristics of SFRs, mission time of decay heat removal system (DHRS) is generally set longer than that considered in light water reactor probabilistic risk assessments (PRAs) when developing SFR PRA models. A relatively long time is required for SFRs to reach safe and stable state where the decay heat is adequately dissipated by the thermal radiation and conduction. In long mission time, if the decay heat attenuation and the possibility of repair of damaged equipment are neglected, the analysis could be overly conservative. To avoid such an overly conservative analysis, dynamic PRA approaches have been developed to extend the conventional PRA to longer periods of time and to cover the aforementioned phenomena [1].

In the conventional PRA approach based on event tree (ET)/fault tree (FT), the events after occurrence of the initiating event and the order in which each event occurs are determined in advance. Because of the fixed timing and sequence of events, conventional PRA has to be conservative regarding the time dependence of success criteria. On the other hand, in the dynamic PRA approach, the physical model which simulates the plant thermo-hydraulic response after the occurrence of the accident is coupled with the probabilistic model. Treating the failure probability of the components and the operator action as time-dependent uncertainty parameters, Dynamic PRA enables to assess the risk more realistically by taking into consideration the time-dependent evolution of the accident [2-3].

With the aim of applying the dynamic PRA approach to SFRs, a dynamic PRA benchmark has been implemented in Japan and France. To benchmark the different dynamic PRA methodologies developed by Japan and France, both results are compared based on a simplified version of the Advanced Sodium Technological Reactor (ASTRID) DHRS [4]. Several case studies are carried out to verify results sensitivity to system features and probabilistic parameters. In addition, the thermohydraulic models and static PRA results are also compared as validation.

This paper presents the benchmark analysis conditions and the results of the thermohydraulic model benchmark for the study cases. In this benchmark, the thermohydraulic model coupled with dynamic model had been first compared, in order to ensure that there is no difference in the coupled physical models when benchmarking different dynamic PRA methodologies. The comparison of the results of the dynamic PRA models with those of the static PRA model are described in Part 2 of this paper subtitled “DPRA problem description and benchmark results” [5].

2. BENCHMARK ANALYSIS CONDITION

The probabilistic benchmark analysis considering repair of damaged equipment and common cause failure (CCF) has been implemented for a simplified version of ASTRID DHRS. A scenario is assumed in which an automatic reactor shutdown occurs at time 0 h, followed by decay heat removal by two types of DHRS described below. As an initial state, a forced convection state by primary pumps at rated output is assumed. This section introduces the descriptions of the systems being analyzed and the benchmark analysis conditions. The descriptions of the dynamic models, the repair conditions and the codes are included in the Part 2 paper [5].

2.1. Description of the DHRS and Their Support Systems

2.1.1. In-vessel DHRS with Forced Convection (S1)

The S1 system with forced convection allows the evacuation of the decay heat. Its schematic diagram is given in Figure 1.

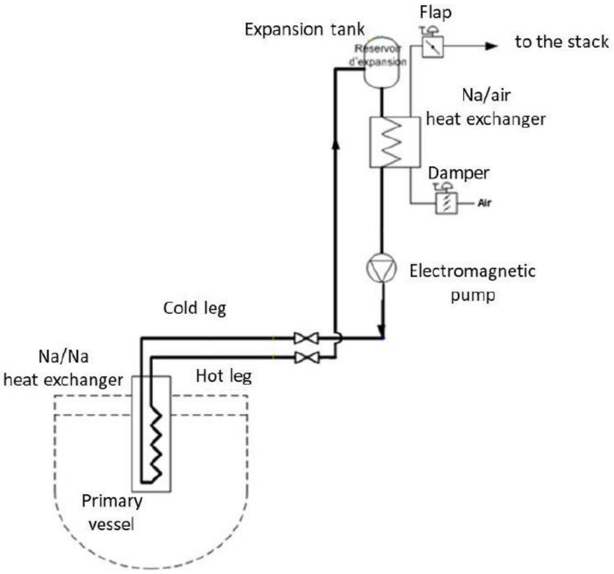

Figure 1. Schematic representation of the S1 system

The S1 system is composed of two trains, each of which alone can dissipate enough residual power so as not to exceed the primary sodium average temperature limit criterion of 650℃ at reactor shutdown (i.e. 2 × 100% at time 0 h). The main assumptions for the operation of the S1 system are as follows:

- The S1 trains operate in forced convection. This forced convection is provided by the electro-magnetic circulating pumps.
- It is supposed that the efficiency of S1 trains is independent of the primary convection regime: their operation is not affected by a loss of the primary pumping.
- When the reactor is at power, the S1 trains are in a partial heat extraction mode: circulating pumps in operation, dampers and flaps closed.
- Freezing of sodium in the Na/Air exchangers is considered impossible as long as the S1 circulating pump is in operation. In case of failure of the S1 circulating pump, freezing is considered to be associated with the refusal to close the flaps (or its unintended opening) OR with the refusal to close (or the unintended opening) of the anti-freeze valve (by signal or valve failure).
- The freezing of sodium in the S1 trains (including at the Na/Air exchanger) is considered irreversible.

2.1.2. DHRS through the Main Vessel (S2)

The S2 system allows the residual power to be dissipated by forced convection and radiation through the main vessel. Its principle diagram is given in Figure 2.

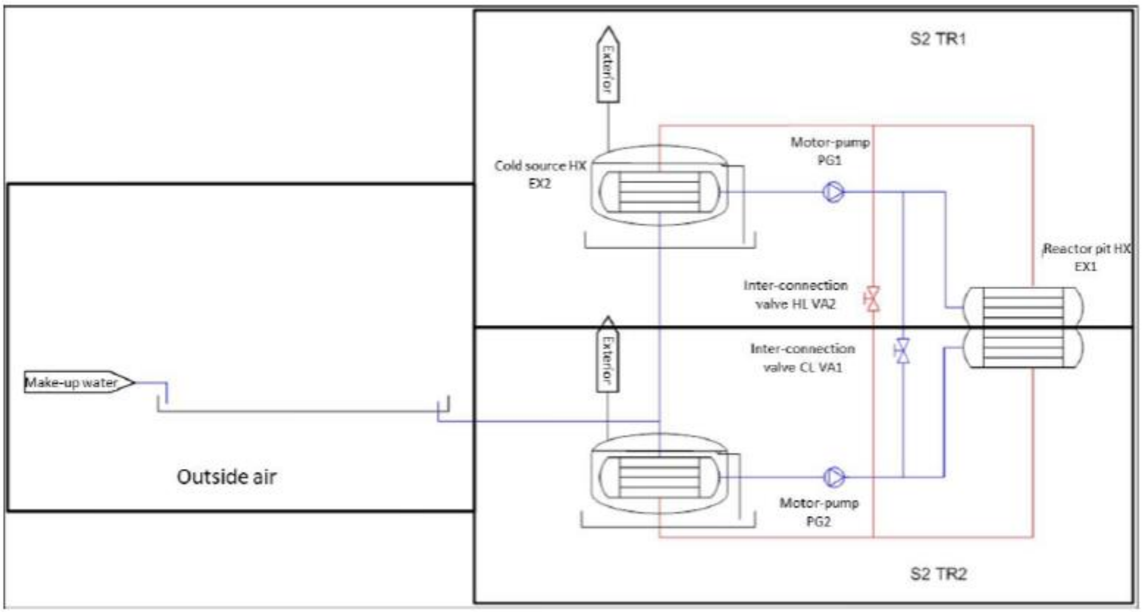

Figure 2. Schematic representation of the S2 system

The S2 system is composed of two trains, partially redundant (shared cooling unit). Two S2 trains evacuate sufficient residual power so as not to exceed the limit criterion for the average primary sodium temperature of 650°C after 30 hours of operation of a single S1 train after reactor shutdown (see Section 2.2). The S2 trains are in operation whenever the reactor is on power.

2.1.3. Support Systems

In this study, S1 and S2 systems are supposed to be supported by electrical systems, air conditioning systems, and instrumentation and control system. The main components of the electrical divisions are the electrical panels, the batteries (2 hrs. autonomy) and the diesel generator (recharged as required). The air conditioning systems are used to condition the electrical rooms and the room containing the S1 pumps. For the simplified case, the instrumentation and control systems can be represented in 4 sub-functions: an instrumentation part, a “specific” processing part, a “non-specific” processing part and a transmission part.

2.2. Description of the Accidental Sequence

The accidental sequence to be modelled corresponds to a “generic” initiating event, such as a reactor trip, representing any IE whose occurrence does not lead to an DHR system unavailability.

Regarding the criteria for the success of the DHR function, the DHR mission is considered successful when the primary sodium average temperature limit criterion of 650℃ has not been exceeded for the duration of the mission. The reference duration of the mission ("mission time") is 1000 h. This duration has not been chosen with regard to actual safety studies, but as to maximize the effect of the dynamic part of the PRA (i.e. the impact of repair and the physical model). Two criteria for the success of the DHR mission are considered:

- A "deterministic" criterion or a minimum requirement in terms of number of available DHR systems as a function of time after scram (i.e. minimum number of systems allowing not to exceed the 650℃ criterion over a given period):
  - in the period [0, t1(30 h)]: at least 1 train S1;
  - in the period [t1, t2(102 h)]: at least 1 train S1 or 2 trains S2;
  - in the period [t2, t3(mission duration)]: at least 1 S1 train or 1 S2 train.
- A "dynamic" criterion on the average temperature of the primary sodium, which must remain below 650℃ throughout the mission.

In this study, static PRA uses the deterministic criterion, which does not correctly consider the dynamic aspect of Na thermal inertia, whereas dynamic PRA uses the dynamic criterion. Therefore, the evaluation results of dynamic PRA should be relatively realistic. For instance, in the case of a S1 system failure late in the first time slot, it is considered fatal in deterministic criterion, but might not be so in dynamic criterion.

The generic event tree is built for a mission time, with a breakdown into three periods corresponding to the previously defined success criteria. It includes three "function events" representing the failure of the DHR mission over these three periods. It is therefore sufficient for the DHR mission to fail in one of the three periods to consider that an unacceptable consequence for reactor safety, associated with the exceeding of the primary TNa criterion = 650℃, has been reached. The annual frequency of occurrence associated with the generic initiating event is taken as 1.

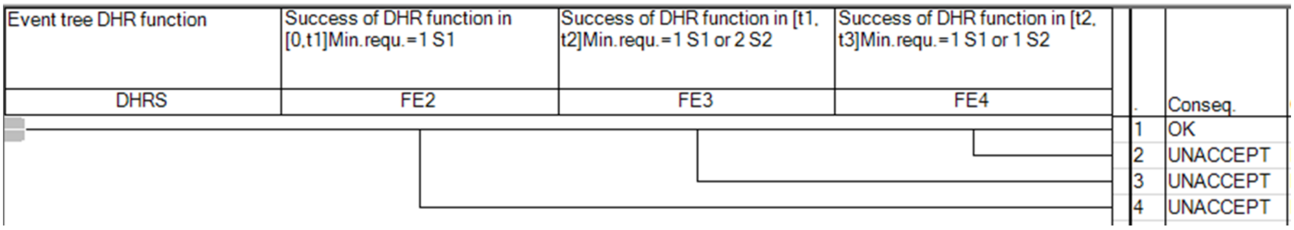

Figure 3. Generic event tree for loss of the DHR function

2.3. Definition of the Simplified Case

The simple study case, based on a simplified SFR concept, is intended to comprise the main aspects that motivate the use of dynamic PRA approaches. Thus, the simplified model takes into consideration and allow for:

- coupling to a thermohydraulic calculation code, in order to carry out calculations of average primary sodium temperatures (TNa) and to verify compliance with the decoupling criterion $T_{Na} < 650℃$;
- unavailability/dependencies related to the initiating events;
- individual failures in operation and on demand;
- simultaneous common cause failures in operation and on demand;
- dependencies between systems or components (taking into account at least one common failure mode between systems S1 and S2 which makes them inoperative at the same time);
- unavailability for pre-initiator maintenance (preventive or corrective);
- repair times by category of component failure modes (easily repairable, difficult to repair or irreparable);
- conditional repairs (with a criterion on the temperature of the circuits for intervention and a criterion on the number of maintenance agents required).
- malfunctions due to inadvertent operation of I&C;

2.4. Power Balance Equation

Taking into account the power created by the primary pumps and the mean thermal inertia of the system, the power balance on the sodium in the primary vessel with S1 and S2 in operation is:

$$I_{moy} \times \frac{dT_{moy}}{dt} = \left(P_{res} + P_{pp}\right) - \left(P_{S1} + P_{S2}\right) \tag{1}$$

Where,

I_{moy} = mean thermal inertia of the system, in MJ/°C
T_{moy} = average temperature of the primary sodium, in °C
P_{res} = residual power (decay heat), in MW
P_{pp} = heat generated by the primary pumps, in MW
P_{S1} = heat removed by the system S1, in MW
P_{S2} = heat removed by the system S2, in MW

No heat release from the pipes or via the reactor slab is taken into account. The limit criterion being considered for the loss of the DHR function, leading possibly to a loss of integrity of the primary structures of the core support, is $T_{moy} \geq 650°C$.

3. BENCHMARK ANALYSIS PLAN

The benchmark has been proceeded in three phases:

I) Comparison of the implementations of the dynamic thermohydraulic model using defined test cases,
II) Comparison of the results of static and dynamic models and cross-comparison of the different dynamic methods,
III) Sensitivity study on two calculation parameters (mission time and S2 system performance).

It is noted that the third phase has not been implemented yet and is not covered in this paper.

3.1. Comparison of the Implementations of the Dynamic Thermohydraulic Model Using Defined Test Cases

The physical model used in this study is based on the power balance described in equation (1). The comparison of the results of the mean primary sodium temperature (T_{moy}) calculations from the coupled physical models is carried out to ensure that there is little difference in the coupled physical models when benchmarking different dynamic PRA methodologies. The calculations of the average primary sodium temperature are performed considering 2 trains of S1 and 2 trains of S2 and with or without repairs over a period of 1000h. Repairs are treated in a deterministic way (i.e. it is considered that when a system fails, it is repaired within the time defined, according to the type of failure). The recovery completion times were assumed to be consistent with the following mean down times (MDTs) :

- 24 hours for easily repairable failures
- 30 days for not-easily repairable failures of S1
- 100 hours for not-easily repairable failures of S2

The test case scenarios are described in Table 1 below.

Table 1. Description of test cases for temperature evolution calculations

Calculation cases	System lost at T0 = 0h	Systems lost at T1 = 400h	Systems lost at T2 = 700h
N°1	1 S1 lost on demand at T0 on not-easily repairable failure	1 S1 lost in operation at T1 on easily repairable failure	1 S2 lost in operation at T2 on easily repairable failure
N°1a (without repair)	1 S1 lost on demand at T0	1 S1 lost in operation at T1	1 S2 lost in operation at T2
N°2	1 S2 lost at T0 on easily repairable failure	1 S1 lost in operation at T1 on irreparable failure	1 S2 lost in operation at T2 on not-easily repairable failure
N°2a (without repair)	1 S2 lost at T0	1 S1 lost in operation at T1	1 S2 lost in operation at T2 not-easily repairable failure
N°3	2 S2 lost at T0 on easily repairable failure	1 S1 lost in operation at T1 on easily repairable failure	1 S1 lost in operation at T2 on irreparable failure
N°3a (without repair)	2 S2 lost at T0	1 S1 lost in operation at T1	1 S1 lost in operation at T2
N°4	2 S2 lost at T0 on easily repairable failure	2 S1 lost in operation at T1 on easily repairable faults	-
N°4a (without repair)	2 S2 lost at T0	2 S1 lost in operation at T1	-

3.2. Comparison of the Results of Static and Dynamic Models and Cross-comparison of the Different Dynamic Methods

The comparison of the results of the dynamic models with those of the static model is carried out to make it possible to verify that the dynamic models provide:

- the same failure sequences describing the accidental sequences as the static model (same success criteria, same system mission times);
- the same dominant accidental sequences and results of the same order of magnitude as those of the static model in the absence of repairs.

The main objective of the dynamic model cross-comparison is to compare the probabilities of loss of the DHR function over the given mission time. In order to analyze possible discrepancies between the results obtained, it is necessary to identify the failure/repair sequences describing the dominant sequences. Finally, an additional objective is to assess the performance of each method on a realistic calculation by comparing the time required to perform each calculation using the different models.

The reference calculations are described in Table 2 below. The results of these cases are included in Part 2 paper [5].

Table 2. Description of the reference calculations for the static/dynamic comparison

Calculation cases	Types of calculations	Modelled systems	CCF, repairs	Mission time
N°5	Static/Dynamic	2 S1, 2 S2	Without CCF, without repair	1000 h
N°6	Static/Dynamic	2 S1, 2 S2	With CCF, without repair	1000 h
N°7	Dynamics	2 S1, 2 S2	With CCF, with repairs	1000 h

4. THERMOHYDRAULIC MODEL RESULTS

The comparisons of the results of physical model benchmark described in Section 3.1 are shown in Figure 4 through 11. Figure 4 through 11 show that the primary sodium average temperatures fluctuate according to the time of each system loss and repair as defined in Table 1. As shown in the results of Case No.1a to 4a, at the beginning of the transient with high decay heat, one train of S1 is sufficient and S2 is unnecessary from the viewpoint of avoidance of exceeding the primary sodium average temperature limit criterion of 650°C. At the later term of the transient with low decay heat, such as exceeding 400 h, if either S1 or S2 has an intact train, the primary sodium average temperature does not exceed the limit criterion. According to these insights, we can see that the results of Case No.1a to 4a are consistent with the deterministic success criterion described in

Section 3.2. Furthermore, when compared with Case No.3a/4a and Case No.3/4, the primary sodium average temperature exceeds the limit criteria in the case without considering repair, on the other hand, it does not exceed the limit criterion with considering repair.

In addition, since the results of the Japanese and French physical model benchmark have good agreement, it can be said that there is no significant difference between Japanese and French dynamic PRA approaches on the coupled physical models.

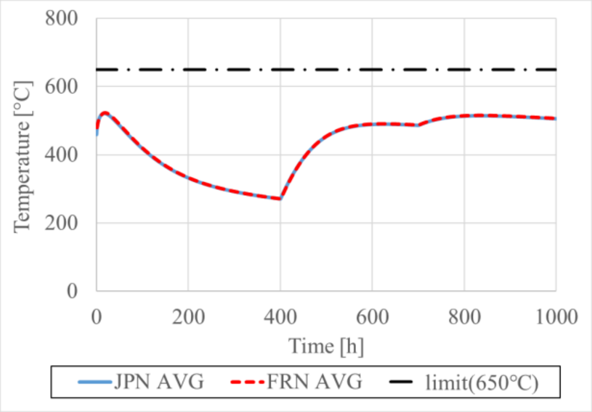

Figure 4. No.1a result (without repair)

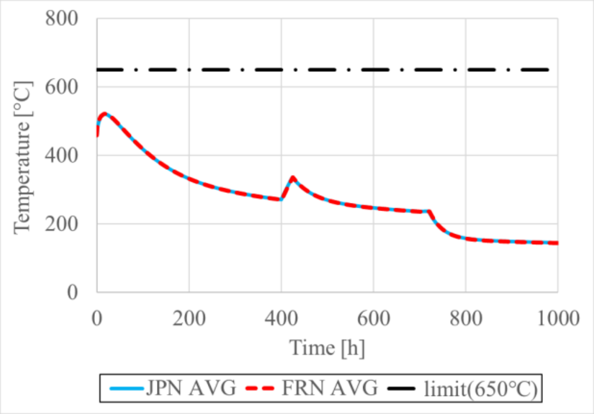

Figure 5. No.1 result (with repair)

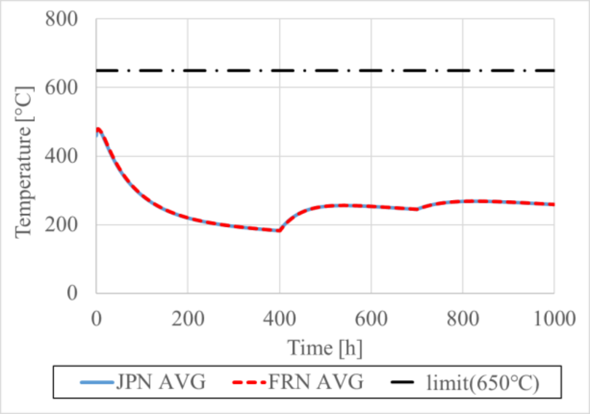

Figure 6. No.2a result (without repair)

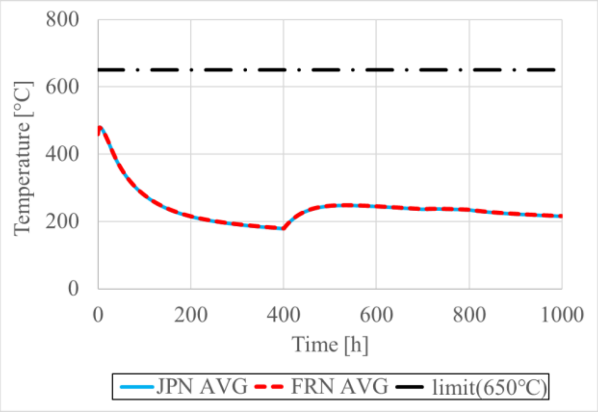

Figure 7. No.2 result (with repair)

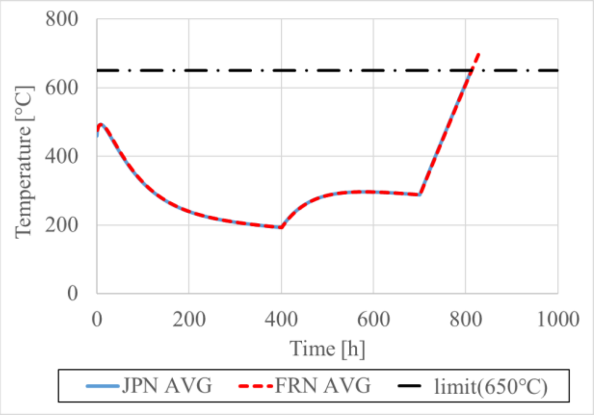

Figure 8. No.3a result (without repair)

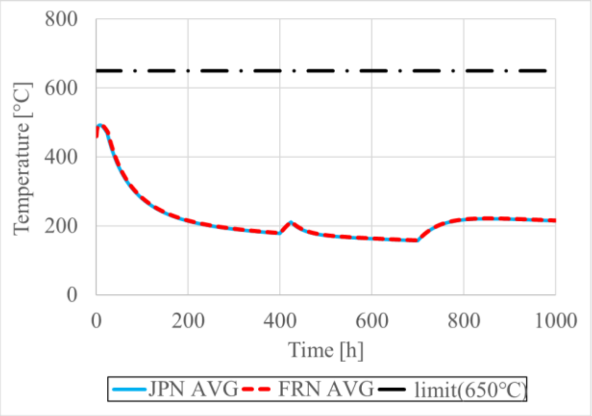

Figure 9. No.3 result (with repair)

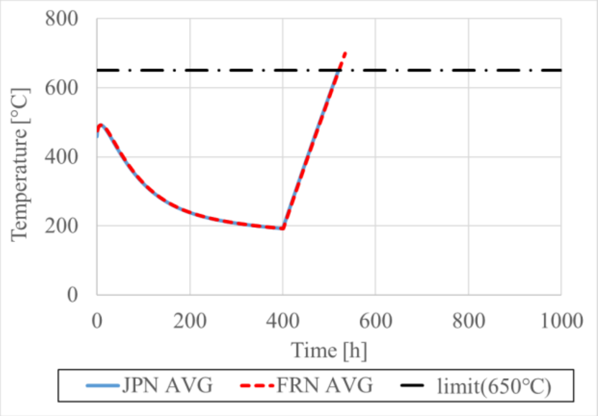

Figure 10. No.4a result (without repair)

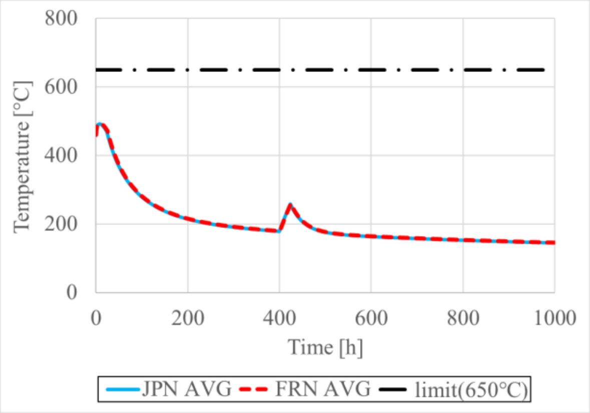

Figure 11. No.4 result (with repair)

5. CONCLUSION

For the purpose of comparing the dynamic PRA approaches, the dynamic PRA model benchmark has been carried out between Japan and France, based on a simplified version of the ASTRID DHRS. In this benchmark, the coupled physical model benchmark was implemented and it was confirmed that there is no significant difference between Japanese and French dynamic PRA approaches on the coupled physical models, since the results of Japan and France have good agreement in all test cases, including those with and without considering repair. It can be said that differences in the physical models are negligible in the dynamic PRA model benchmark described in Section 3.2, whose results are included in Part 2 paper [5].

Acknowledgements

We would like to thank CEA for collaboration on the benchmark and providing support in data input. The authors also greatly appreciate the technical support from JAEA, MFBR and MHINSE. Some analyses in the benchmark have been performed using the RiskSpectrum PSA being developed by RiskSpectrum AB. The paper includes some of the results of the “Technical development program on a common base for fast reactors” and "Technical development program on a fast reactor for demonstration" ensured to JAEA by the Ministry of Economy, Trade and Industry in Japan (METI).

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