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Probabilistic Evaluation of the Post Disassembly Energetics of a Hypothetical Core Disruptive Accident in a Sodium-Cooled SMR by using a Phenomenological Relationship Diagram

Fabrizio Gabrielli[a,*], Michael Flad[a], Simone Gianfelici[a], Rui Li[a], Vladimir Kriventsev[a,b], Werner Maschek[a], Claudia Matzerath Boccaccini[a], Barbara Vezzoni[a], Andrei Rineiski[a]

[a]*Karlsruhe Institute of Technology (KIT), Institute for Nuclear and Energy Technologies (IKET), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*

[b]*Current address: International Atomic Energy Agency (IAEA), Department of Nuclear Energy, Vienna International Center, PO Box 100, 1400 Vienna, Austria*

Abstract

An innovative probabilistic approach based on the Phenomenological Relations Diagram is developed to perform risk analyses of Hypothetical Core Disruptive Accidents in Sodium Fast Reactors (SFRs). The novel method is applied to evaluate the probability distribution of the thermal-to-mechanical energy conversion ratio in an ULOF/Post-Disassembly Expansion Phase scenario in a small- to medium- size SFR. The results provide a comprehensive picture of the fuel energy distribution in the system.

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Keywords: Sodium Fast Reactors; Nuclear Reactor Safety; Risk Analyses; Expansion Phase; Severe Accidents

1. Introduction

Analyses of Hypothetical Core Disruptive Accidents (HCDA) in Sodium Fast Reactors (SFR) always played a fundamental role in the SFR safety assessment [1-3]. Nowadays, the Integrated Safety Assessment Methodology

* Corresponding author. Tel.: +49-721-608-22491; fax: +49-721-608-23824.
E-mail address: fabrizio.gabrielli@kit.edu

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(ISAM) is employed for the Gen-IV systems to enhance the SFR safety compared with the former concepts with the final goal to achieve a robust architecture to prevent accidents and to demonstrate that their consequences do not violate safety criteria [4].

The work potential of the sodium vapor expansion in sodium pool above the core is one of the key parameters in the analyses of HCDAs. Since SFRs with MOX fuel are not in their most reactive configuration, fuel re-compaction phenomena, due to coherent material motion in the core, may lead to recriticality events with consequent upward discharge of hot fuel/steel high-pressure mixture. Significant amount of sodium vapor may be rapidly produced due to the Fuel-Coolant Interaction (FCI) between Na and fully or partially molten fuel/steel mixture discharged from the core as a consequence of a power excursion. The sodium vapor displaces and accelerates the surrounding liquid sodium and, as result, significant energy may be released as a mechanical load to the internal structures and to the vessel. This HCDA phase is often referred as Post-Disassembly Expansion Phase, PDE [5].

Large computer codes have been developed to analyze the HCDAs progression. In particular, the SIMMER codes [6, 7] are considered nowadays as reference tools for such studies since they allow analyzing mechanistically accident scenarios from their initiation till PDE. On the other hand, the identification and evaluation of the key phenomena and events paths enhancing or mitigating the work potential in such conditions does need a huge amount of simulations, since a wide range of initial conditions and modelling options have to be considered.

Having this in mind, a probabilistic approach is presented in the paper in order to perform a quantitative risk analysis of the work potential during an Unprotected Loss of Flow, ULOF, (ULOF/PDE) in a small- to medium-sized (SMR) SFR (power up to 300 MWe). The method is based on the assessment of the Phenomenological Relationship Diagram (PRD) which was originally investigated at Sandia National Laboratory in the U.S. in the '70s for performing the level-2 Probabilistic Safety Assessment (PSA) of the Clinch River Breeder Reactor (CRBR) [8]. In this approach, complex and non-linear phenomena, i.e. Fuel-Coolant Interaction (FCI), are considered as a combination of dominant factors in a diagrammatic scheme of the flow of the possible events. The corresponding governing phenomena from the top event (event of interest) to the lower governing (elementary) events are identified.

The present study develops further the 'classical' PRD approach [9, 10] and does represent the first application of such methodology to ULOF/PDE analysis. Usually, the mathematical models of the physical phenomena are explicitly defined in the PRD for combining the elementary quantities, i.e. temperature, pressure. The method is not well adapted to conditions where complex and strongly interconnected physical phenomena occur. For such scenarios, a mechanistic, integrative approach looks more reliable. Therefore in our PRD the mechanistic nature of the ULOF/PDE scenario is evaluated and 'integrated' in a probabilistic framework. In our approach the fuel internal energy is the elementary event affecting the top event (mechanical work potential). In this way masses, temperatures, and pressures are directly taken into account. Energy Transfer Factors (TF) are introduced to quantify the effect of the different phenomena on the fuel internal energy by employing a large set of parametric mechanistic studies performed by means of the SIMMER-III code. The Probability Distribution Functions (PDF) of the fuel internal energy after the power excursion and of the TFs are evaluated and combined according to the PRD tree via branching points. The PDFs are then propagated in the PRD tree by performing Monte Carlo calculations by means of the @RISK tool [11]. As a result, the PDFs of the fuel energy, mechanical work, and of the thermal-to-mechanical energy conversion ratio are evaluated.

2. The Accident Progression

Traditionally in analyzing HCDAs, the accident evolution is broken down into different phases distinguished by a set of several physical key processes which evolve during accident progression. Classically, the phases in which a CDA for an ULOF accident can be divided are: initiation phase (IP), transition phase (TP), PDE, post-accident heat removal (PAHR) phase, and containment loading phase [12]. In most fast reactor projects of the past, the ULOF transient has been considered as the key Beyond Design Basis Accident (BDBA). The loss of primary pump flow accompanied by the failure of the available shut-down systems is the postulated sequence for an ULOF. Coolant flow reduction after some seconds leads to the sodium temperature increase up to the saturation level (boiling onset). Dependent on the positive sodium void effect, a CDA with a primary core power excursion is initiated and generalized core degradation occurs. After the primary excursion, a medium or large scale molten pool may be formed (TP) and then, re-compaction phenomena may generate secondary power excursions (recriticality events) leading to energetic disassembly [13, 14] and expansion phases of the fuel/steel pool or sodium vapor bubble. Hot liquid components are discharged into the above sodium pool where part of the coolant is rapidly vaporized due to FCI finally leading to a significant mechanical energy release from the displacement of the surrounding liquid coolant. Structural risks may then follow from the accelerated sodium slug hitting the vessel head (sodium hammer) and from the pressure increase of cover gas.

In view of the evaluation of the mechanical energy release after HCDA induced by ULOF in a SMR fast reactor, the energetics condition of the fuel pool at the end of the TP does ideally represent the bottom event of the PDE. Having this in mind, we have analyzed the results of the mechanistic analyses performed in the past by means of the SIMMER codes [6, 7] for several reactors covering the range from mid- to large size: SNR-300 [15], CRBR [2], Superphénix (SPX) [16], and CP-European Sodium Fast Reactor (ESFR) [17]. On the basis of the data and our own experience, the probability distribution of the peak temperatures in a fuel pool after the power excursion in Table 1 has been assessed.

Table 1. Probability distribution of the peak temperatures in the fuel pool from recriticality events

	<4000 K	4000 K – 5000 K	5000 K – 6000 K	6000 K – 8000 K
Probability (%)	40	50	9	1

3. The @RISK model of the PRD of the ULOF/PDE

The PRD @RISK model for the work potential evaluation of the ULOF/PDE is shown in Fig. 1. The model has been introduced in [18] and here an extended description of the approach is provided. As mentioned, in the PRD methodology, the different phenomena involved in the phenomenon to be quantified are taken into account starting from the top event (mechanical work) to the lower (energy of the pool immediately after the power excursion) event. The physical phenomena affecting the top event are therefore broken down into a combination of dominant factors.

Having this in mind, the PRD @RISK model does consist of three sub-PRDs which group the key phenomena occurring during the hot fuel/steel discharge from the core, sub-PRD (1), to the sodium pool, sub-PRD (3), up to the top event. The PDF of the fuel internal energy of the pool immediately after the power excursion (E_0) is propagated in the PRD by applying the PDFs of different sets of energy Transfer Factors (TFs), A_t, B_k, C_m, and D_n, which are combined via branching points.

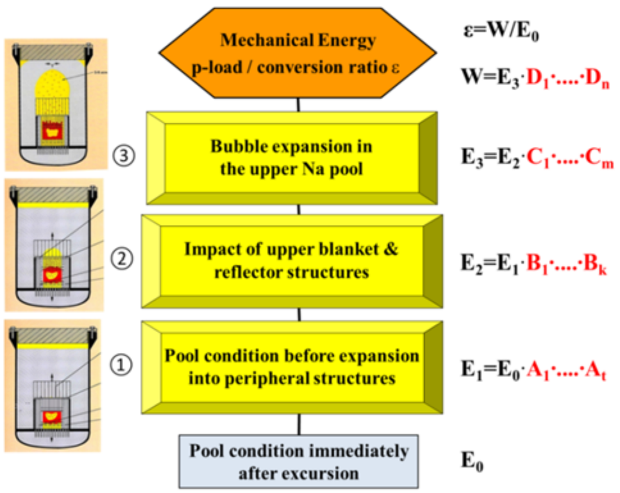

Fig. 1. The @RISK model of the PRD of the ULOF/PDE for the sodium-cooled SMR [18].

The A_t energy TFs values take into account the decrease of the initial fuel internal energy due to expansion into peripheral structures: the effect of the presence of the stainless steel, the energy loss by radiation, and the mass losses in the blankets are considered. Their application to E_0 does allow evaluating the fuel internal energy after expansion inside the core region (E_1).

The B_k factors take into account the fuel internal energy transfer into the upper core structure considering the momentum and heat exchange with Upper Axial Blanket (UAB) structures. The thermal reaction of the liquid fuel with sodium films, the energy loss by radiation, and the fission gas release from the plenum are also considered. Once applied to E_1, the internal energy of the fuel entering in the UAB (E_2) is evaluated.

The application of the C_m TFs to E_2 allows evaluating the effect of the hot fuel/cold sodium interaction in the Na pool (E_3), comprising the actual conversion of (fuel) thermal to mechanical energy. The C_m TFs take into account the heat, mass, and momentum transfer phenomena, the effect of stainless steel, and the energy loss by radiation. Part of E_3 is converted in mechanical work.

The D_n energy TFs are applied to E_3 to evaluate the change of the working fluid (fuel to sodium): the energy transferred to the liquid sodium and then to the sodium vapor is evaluated. Note that the @RISK MC analysis does provide the PDFs of E_1, E_2, and E_3. Finally PDFs of the mechanical work, W, and of the conversion ratio, ε, are evaluated.

In order to provide an example of the PRD method, the sub-PRD 2 and the sub-PRD 1 are shown in Fig. 2 and Fig. 3, respectively. The PDF of the B_k energy TFs in Fig.2 take into account the effect of the interaction between the fuel/steel mixture and the structures of the UAB on the fuel release from the core. A decision gate in introduced to define the condition on the fuel internal energy in the UAB (E_1 computed from the sub-PRD 1, Fig. 3) according to which the UAB may experience a partial or total removal. If the load is larger than the tensile strength of the SS 316, sub-assembly rupture occurs and additional openings for fuel discharge are available. For our investigations, the North American Stainless Steel data [19] have been considered in conjunction with the SIMMER Equation Of State (EOS) data [6, 7]. Results provide the indication that the sub-assembly rupture due to the acting forces is not imperative for T_{fuel}=4000 K. For T_{fuel}=6000 K and T_{fuel}=8000 K additional holes may be likely created. We therefore did assume that holes opening occur when the mean value of the internal fuel energy of the fuel pool ($E_{1,mean}$) is larger than 15000 ± 2σ MJ. The PDF of E_2 is evaluated by applying the PDF of the B_k energy TFs to the PDF of E_1, which is computed in the sub-PRD 1 (Fig. 3). The PDF of the A_t energy TFs take into account the effect of fuel/SS energy exchange (A_1, considering mixing losses) and of the material expansion in the blanket (A_3 and A_4). The A_2 factors account for the energy loss by radiation. An additional sub-PRD is then assessed where a mathematical formulation of the phenomenon can be provided since a well-defined model is available. The PDF of E_1 is evaluated by applying the PDF of the A_t energy TFs to the PDF of E_0.

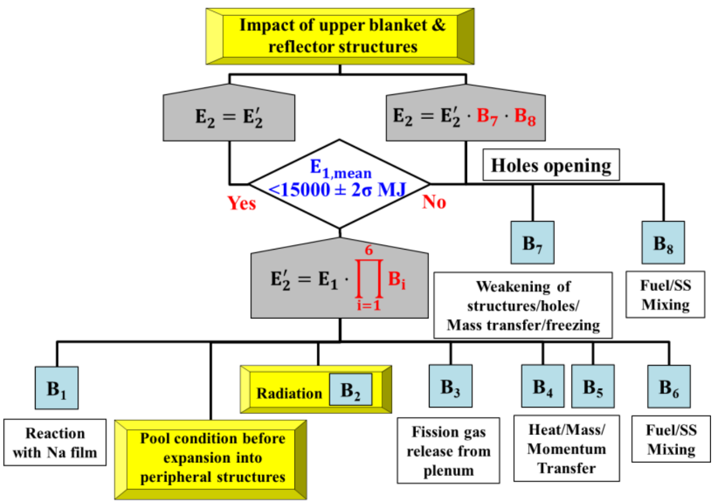

Fig. 2. The @RISK model of the sub-PRD 2.

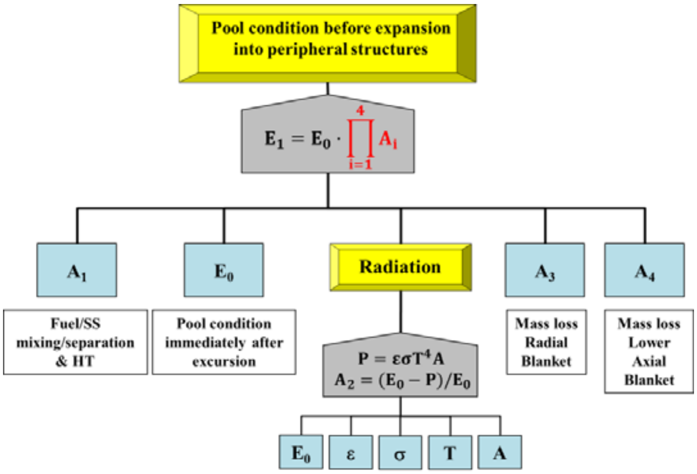

Fig. 3. The @RISK model of the sub-PRD 1 [18].

The PDF of the TFs have been computed on the basis of the results of a large parametric analysis by means of the more than 100 SIMMER-III simulations of PDE for a SMR with an equivalent active core diameter and height less than 1 m. Time- and volume- averaged SIMMER results for masses, temperatures, and pressure of the fuel, steel, and sodium in different phases have been employed. The time integration is performed up to the instant when the cover gas volume is minimum (chosen characteristic time relevant for the sodium kinetic energy evaluation) to provide a proper description of the phenomena affecting the top event during the PDE.

As an example, the procedure for evaluating the PDF of the B_5 energy TFs is described. The B_5 energy TFs account for the internal fuel energy transferred from the core upwards in the UAB due to momentum, heat, and mass transfer phenomena. They are evaluated as ratio of the time- and volume- averaged fuel internal energy in the UAB to the core for the three initial energetic status of the fuel pool (Fig. 4a). As shown in Fig. 4b, the TFs for each energetic family do show a linear dependence on the integration time (dt), in particular for the mid energetic case. The TF is rather constant for the low energetic pool. As a result, the most probable B_5 value for each energetic family will be the average of the corresponding values. The B_5 TFs labelled in green in Fig. 4a are then obtained and the minimum and maximum values are kept as boundaries of the corresponding uniform PDF to be employed in the @RISK analysis.

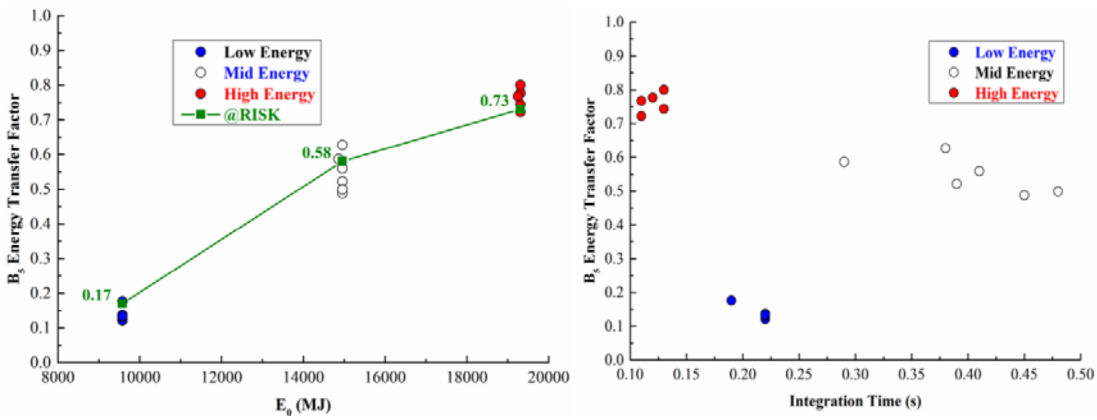

Fig. 4. (a) B_5 energy TFs; (b) B_5 TFs vs. integration time for each energetic status of the fuel pool.

4. Results

The evaluation of the ULOF/PDE PRD has been performed by means of the @RISK tool [11]. For calculations, 1000 Monte-Carlo simulations have been performed with 95% confidence level and 3% convergence tolerance. No criteria have been chosen for discriminating the data in the results, namely 100% of data have been considered.

The PDF of E_0 (fuel internal energy immediately after the power excursion) has been evaluated on the basis of the data in Table 1 and it is shown in Fig 5. A fuel pool with an average temperature of 4000 K, 6000K, and 8000 K has been considered per definition to cover a large range of temperatures. Note the fuel vapor pressure at 3700 K is ~0.1 MPa; below this temperature only the steel vapor pressure and fission gas could work as an effective driver for fuel discharge. Since no appreciable mechanical energy release is expected for cases below 4000 K, the probability distribution above 4000 K has been employed in the @RISK analyses. Taking into account the fuel pool conditions of the SMR model we employ for our study, three different thermal energy ranges have been evaluated: ~ 9500 MJ-12000 MJ, 12000 MJ-15000 MJ, and 15000 MJ-19000 MJ.

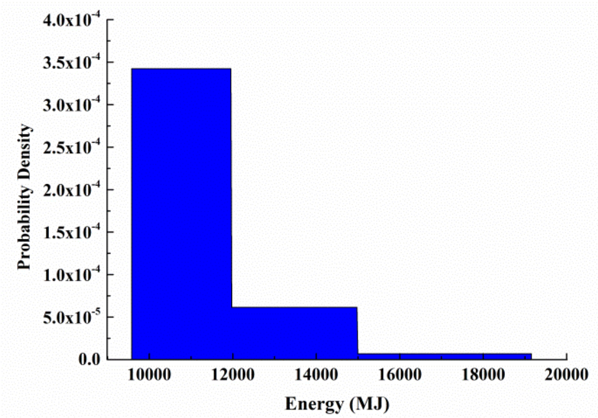

Fig. 5. Probability Distribution Function of E_0.

The PDF and the Cumulative Distribution Function (CDF) of internal energy of the fuel entering in the sodium pool (E_3) is shown in Fig. 6a and 6b, respectively. The mean value is ~1750 MJ, the minimum being ~75 MJ. The CDF shows that that 65% of the results lie in the 150 MJ-1800 MJ energy range, the highest probabilities occurring in the 600 MJ- 1200 MJ.

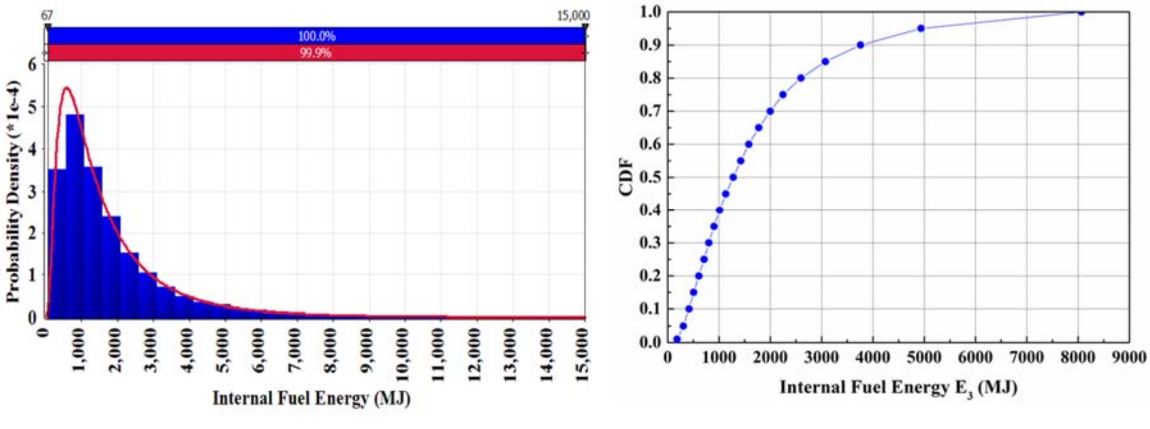

Fig. 6. Internal energy of the fuel entering in the sodium pool (a) PDF; (b) CDF.

The PDF and the CDF of the mechanical work are shown in Fig. 7a and 7b, respectively. The mean value is ~50 MJ and CFD results show that ~80% of the results lie below 75 MJ, the probability density being peaked around 20 MJ.

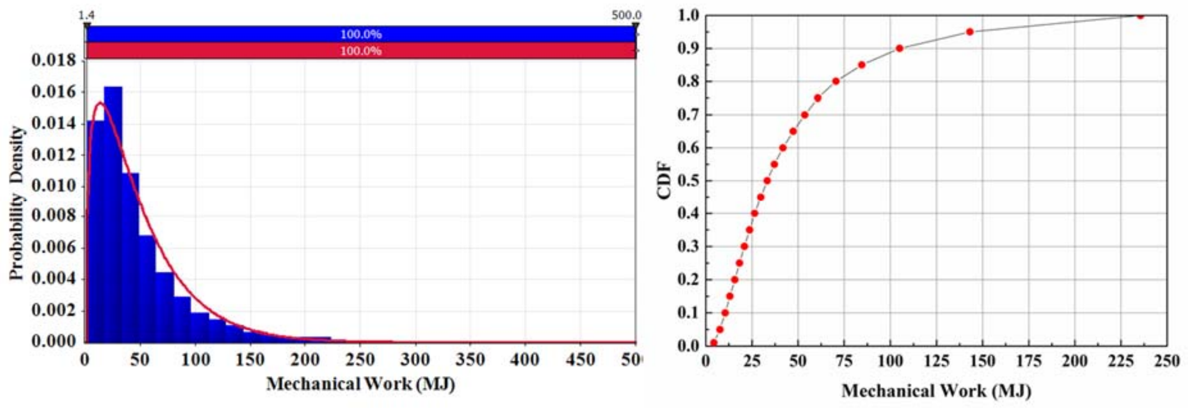

Fig. 7. Mechanical work (a) PDF; (b) CDF.

The PDF and the CDF of the total thermal-to-mechanical conversion ratio are shown in Fig. 8a and 8b, respectively. The mean value is ~0.43% and ~75% of the results lie in the 0.03 %-0.55 % range, the highest probabilities occurring in the 0.15 %- 0.3% range. By comparison, the CDF of the conversion ratio in the sodium pool (W/E_3) is also shown in Fig. 8b. As expected the conversion ratio in the sodium pool is dominant and ~80% of the results lie in the 1.62 %-3.5 % range.

The most probable ranges of the mechanical work and of the total conversion ratio are in line with the outcomes of the mechanistic investigations performed for fast reactors of similar size [20, 21]. Nevertheless, the application of the PRD methodology by using Monte-Carlo method allows providing a comprehensive picture of the energetics of the ULOF/PDE scenario. As shown in Fig. 7 and 8, the application of the probabilistic approach does produce a distribution of results depending on the initial conditions and on the dominant phenomena in play during the accidental scenario. Therefore, one can analyze not only the most probable results, but also the probability associated to the less probable but most severe accidental conditions.

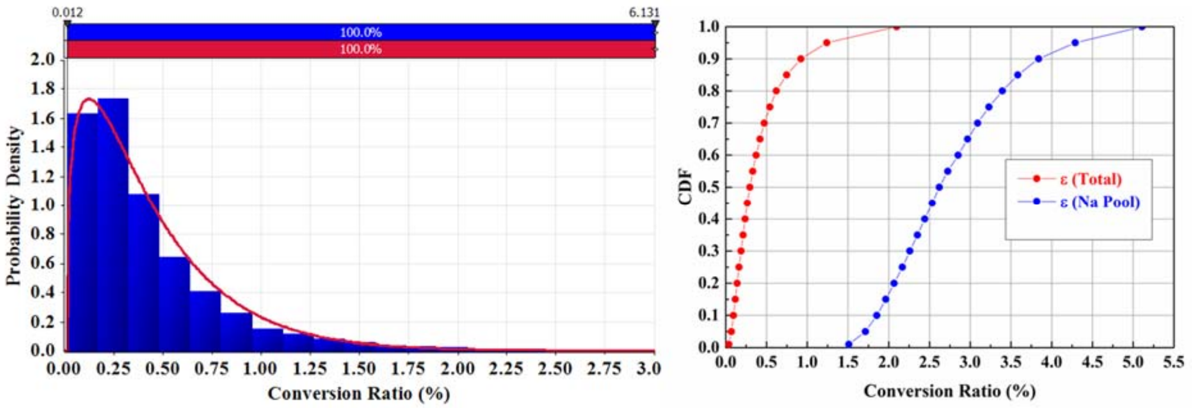

Fig. 8. Thermal-to-mechanical conversion ratio, ε (a) PDF; (b) CDF.

5. Conclusion

A quantitative risk analysis based on the use of the Probabilistic Relationship Diagram (PRD) is performed to evaluate the mechanical work potential during an ULOF/PDE in a small- to medium- size SFR. The study is the first application of the PRD approach to the ULOF/PDE. In the PRD approach, complex physical phenomena are broken down in elementary dominant factors in a diagrammatic scheme representing the flow of the possible accidental path from the top event (the mechanical work) to the bottom event (the energetic condition of the fuel pool). The classical PRD method is based on the assessment of the mathematical models using elementary physical quantities as input variables but it is not well adapted to the PDE analyses, where complex and interconnected phenomena occur. Our PRD concept develops further the former approach by integrating into a probabilistic analysis the mechanistic nature of the ULOF/PDE. The PDF of the fuel internal energy after the power excursion is the elementary event affecting the top event and the PDF of the energy Transfer Factors (TF) of the dominant phenomena are evaluated by means of several SIMMER-III simulations. The probability distributions are combined and propagated in the PRD tree by carrying out Monte Carlo calculations by means with the @RISK tool. The results show that the most probable range of values for the mechanical work (10-20 MJ) and for the thermal-to-mechanical conversion ratio (0.15 %-0.3%) are in agreement with the current status of knowledge. Further, the application of the PRD approach provides a comprehensive picture of the probabilistic distribution of the fuel energy in the SMR system. In this sense, the study does represent a solid basis for the application of such methodologies to the other HCDAs scenarios.

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