Quantitative Evaluation of the Post Disassembly Energetics of a Hypothetical Core Disruptive Accident in a Sodium Cooled Fast Reactor

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Abstract. Analyses of Hypothetical Core Disruptive Accidents (HCDAs) play a fundamental role in the safety assessment of Sodium Fast Reactors (SFRs). The accident sequence is typically subdivided into different phases according to dominant phenomena. The phase dealing with an upward discharge of the pressurized hot fuel/steel mixture from the core region is referred as the Post-Disassembly Expansion (PDE) phase. It is characterized by massive sodium vaporization due to Fuel-Coolant Interaction (FCI) in the upper sodium pool, which displaces and accelerates the surrounding liquid sodium resulting in potential significant loads on internal structures and vessel. The present paper - based on KIT simulations with the SIMMER code including dedicated parametric studies - identifies and evaluated the main PDE phenomena and event paths enhancing or mitigating the mechanical work potential.

Key Words: Severe Accidents, SIMMER Code, SFR, Post-Disassembly Expansion

1. Introduction

Analyses of Hypothetical Core Disruptive Accidents (HCDAs) in Sodium Fast Reactors (SFRs) play a fundamental role in the SFR safety assessment [1-4]. Traditionally in analysing HCDAs, the accident is broken down into different phases distinguished by a set of several physical key processes/phenomena. The classical subdivision for an Unprotected Loss of Flow (ULOF)[1] accident is shown in *FIG. 1-a.* It includes the Initiation Phase (IP), Transition Phase (TP), Post-Disassembly Expansion (PDE) phase, Post-Accident Heat Removal (PAHR) phase, and containment loading phase [1,5].

The postulated scenario for an ULOF accident considers the loss of primary pumps flow accompanied by the failure of the available shut-down systems. The coolant flow reduction leads to sodium temperature increase up to the vaporization level. In case of a positive sodium void effect, a power excursion may happen and initiate the core degradation [6-8].

The subsequent core damage propagation from the sub-assembly (SA) level to the whole core scale is considered within the TP. Therein, the formation of a large molten pool may lead to re-compaction phenomena generating secondary power excursions via recriticality events with a high energy release deposited in the fuel. The following temperature and pressure increase in the core zone may lead to its energetic disassembly [9-10]. Under these conditions, the hot liquid mixture (fuel and steel) may be discharged into the upper sodium pool. The PDE process involves phenomena like the motion of the molten core materials towards the remaining structures, the thermal Fuel-Coolant Interaction (FCI) in the upper sodium pool and the formation of a large bubble that may compress the cover gas or accelerate the coolant slug high enough to challenge the stability of the lid of the pressure vessel (*FIG. 1-b*). Another scenario route - that can be facilitated by specific devices enabling fast and sufficient fuel discharge from the core - would end in the PAHR phase without significant energetics.

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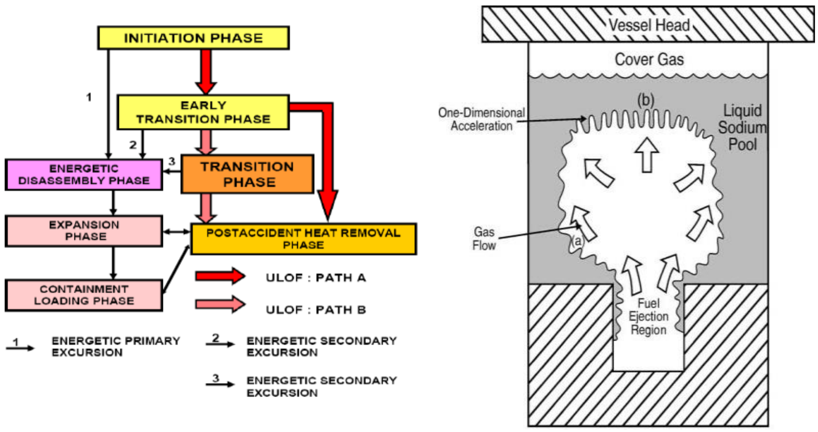
[1] In most fast reactor projects of the past, the ULOF transient has been considered as the key Beyond Design Basis Accident (BDBA).

The present paper aims at identifying and evaluating main phenomena and event paths enhancing or mitigating the mechanical work potential during the PDE. Therefore, a large number of parametric analyses, including different initial conditions and modelling options, have been conducted at KIT with the SIMMER code [11-12] for an SFR case. The study is based on more than 100 SIMMER simulations, with only a limited part being summarized here. It allows together with past mechanistic simulations for different SFR types/sizes, to get a better understanding of dominant effects during the PDE, thus providing clues for the development of future SFR designs. The results obtained by the parametric study have been also employed in the framework of a probabilistic evaluation of the work potential of an ULOF-induced PDE in a sodium-cooled small- to medium-sized reactor (ca. 300 MWe) via the adoption of the Phenomenological Relationship Diagram (PRD) method [13,14].



(a) (b)

FIG. 1. a) Typical phase diagram for core disruptive accidents (ULOF transient) [1], b) Principle sketch of expansion phase [15].

2. Expansion Phase Phenomena and Evaluation Methods

Hot fuel droplets and particles ejected into the upper sodium pool lead to FCI phenomena with sodium vaporization and pressure build-up. During this phase, a change of the working fluid (from fuel to sodium) takes place by the formation of the growing bubble consisting of a two-phase mixture of fuel, steel, and dominantly coolant components, that rapidly expands with high dynamics of vortices inside and at the rippled bubble/coolant interface. Instabilities at the interface are provoking the sodium entrainment with a potential either to enhance vaporization or to reduce the bubble volume through condensation [16]. The expanding bubble accelerates the surrounding sodium towards the cover gas (CG) region (*FIG. 1-b*). If the kinetic energy is sufficiently high, the sodium slug hits the vessel lid with an impact pressure value potentially challenging the vessel integrity.

In the past, various measures of the mechanical work potential have been developed to assess the damage that might occur from a given excursion. The simplest method of estimating the mechanical work potential on the structures is given by the use of a so called conversion ratio, i.e. the efficiency of the process.

Bethe and Tait [2] were the first who developed a method to cope with disassembly transients and to provide an evaluation of the fission energy produced. Since the considered excursions were quite severe (hundreds of dollars per seconds) the resulting core pressures became very large. Therefore, the first approach was to compare the accident energetic to the damage potential of trinitrotoluene (TNT) [17].

Later Hicks and Menzies considered sodium as a possible working fluid in their model [18]. This quite simple model has been practically abandoned because of the extremely conservative assumptions [19]. To improve the model, one has to consider and evaluate probabilities of two phenomena: the steam explosion and the low energy FCI.

The modified approach was to consider the expansion of reactor materials (fuel) along an isentropic path for determining the work potentially done during this process. This work potential is set equal to the change in fuel internal energy from a compressed state to an expanded state (e.g. expanding to the available cover gas volume or to the environmental pressure) without taking into account any kinetic process that may be involved. Similar procedures have been applied for coolant and gas [23].

The idealized representation of the expanding core materials [18, 20, 21] has been later replaced by a more realistic approach based on mechanistic calculations. This was one of the principal results of the SIMMER code development [11-12]. Firstly, the important exchange processes of mass, momentum, and energy during the discharge process via the upper core and above core structures, and secondly, the subsequent exchange processes in the upper sodium pool were taken into account. The so-calculated mechanical work potential (Eq. 1) is then composed by the two dominant components: 1) the sodium slug kinetic energy (E_{kin}) and 2) the compression work on the cover gas (W_{compr}). The efficiency of the process, namely the conversion ratio, is defined as the ratio of the maximum mechanical work potential to the initial internal energy accumulated in the core material after several excursions.

$$W_{Mec}(t) = W_{compr}(t) + E_{kin}(t) \qquad E_{kin}(t) = M_{Na}\frac{v_{Na}^2}{2} \qquad W_{compr}(t) = -\int_i^f (pdV)_{CG} \qquad (1)$$

The peak values of the kinetic energy and mechanical work potential can be used for assessments of short-term and local structure loads, pointing to the risk of material rupture failure. Long-term loads (CG pressurization) may evoke a structural failure at much lower energy levels, caused by creeping. The SIMMER code family [11,12] thus advanced the understanding of the phenomena pertinent to the transition phase and in the following expansion phase [15,22,23,24]. The SIMMER code has been extensively validated in the past as indicated in Table I. Further validation was supported by the LIFUS experiments [24].

TABLE I: List of test problems for SIMMER-III validation [24, 25]

Experiment related to fuel-coolant interactions (FCI)	
Experiments	Description
THINA	FCI experiment with molten alumina and sodium
FARO	FARO LWR scoping experiment for study the pre-mixing phase of the steam explosion
THERMOS	Large FARO experiment with molten fuel and sodium
KROTOS	To study the propagation phase of steam explosion
PREMIX	Alumina-jet pouting into water pool
QUEOS	Dropping of high temperature solid balls into water pool
	Experiment related to coolant-coolant interactions (CCI)
LIFUS	SGTR experiments – water-lead interaction
Experiment related to material expansion dynamics	
SGI	PDE with nitrogen or steam bubble in water
OMEGA	As SGI but larger in scale
CARAVELL E	Expansion/condensation behavior pf large steam bubble in water
VECTORS	High-speed single-/two-phase flows through a simulated Upper Core structure (UCS) to study energy mitigation

3. SIMMER-III Expansion Phase Model of a Medium Size SFR

A mechanistic approach requires analyses of a full vessel reactor model with realistic flow paths to properly consider complex melt-, structure- and coolant-interactions with its various momentum exchange processes, heat and mass transfer and phase change effects. With increasing the degree of details, a more precise description of numerous dissipative effects is expected with a distinct impact on the conversion ratio. In a mechanistic approach all phenomena are interlinked and the final effect depends on the combinations of many parameters. To try to identify more clearly the impact of some specific parameters, a simplified SIMMER model for a medium size SFR has been developed and used in the parametric study.

The expansion phase is considered as a pure fluid-dynamic event with important phenomena mainly happening outside the core; therefore, it requires a fine spatial resolution of the upper sodium pool and cover gas regions. In the study, ~50% more cells have been concentrated in these regions compared to typical ULOF cases. In order to promote the upward discharge path other modelling options have been implemented:

1) The fuel pool is isolated from the lower axial blanket (LAB) and from the radial blanket (RB) by virtual walls preventing thermal interaction and promoting an upward fuel discharge.
2) The core zone is modelled as fully voided zone with liquid fuel only. Steel is considered to be kept in frozen plugs.
3) The upper axial blanket (UAB) is modelled for voided conditions with intact and with degraded geometry, respectively. The structure is immobile and set to a temperature of 1250 K. It can be thermally eroded during the discharge process.
4) The instrumented zone representing control rod drivelines, instrumentation equipment, jacket tubes etc. is taken into account in the SIMMER model in order to induce a suitable flow resistance for the discharge path.
5) A "large-scale bubble model" [26-28] has been adopted.

The model has been subdivided into several zones of interest for allowing a better understanding of phenomena happening during the expansion phase. This subdivision is consistent with the one used for quantifying the phenomenological relationship diagram (PRD) [13,14].

4. SFR Cases Set-up and Evaluation of Results (parametric study) / Comparative Values

For the study a parametric approach has been chosen, covering a very large range of temperatures and other conditions. The cases have been grouped into three main families (see Table II) depending on a parametrically chosen average fuel temperature in the core zone.

Table II lists also the parameters and the range considered for the expansion phase evaluations [13, 14]. To assess the validity of the SIMMER code modelling for extreme conditions also cases with an unrealistically high fuel temperature were investigated. In the mechanistic simulations average melt temperatures up to of 4000 K were reached. Some phenomena which would appear above such extreme conditions (C-family, see next chapter) are beyond the modelling capability of the SIMMER code.

5. Results of Simulations for the SFR Model with SIMMER-III

The cases considered for the three initial fuel temperature families typically proceed with their individual time-scales. To analyse the impact of degraded upper structures, two major cases (with and without upper core structures, UCS) are considered in the paper. In both cases, the core pool contains only the fuel. To underline the effect of a mixed fuel/steel pool a third case was investigated as well.

5.1. Case 01: with UCS

Cases with fully existing SA outlet structures were considered. Depending on the initial fuel temperature and driving pressure levels, different amounts of fuel arrive at the sodium plenum, indicating the strong impact of the UCS on the discharge efficiency. With raising temperatures, the event proceeds more violently and rapidly. Low temperature cases show very low mechanical work values compared to those of high temperature cases. For A and B temperature cases (see *FIG. 2-a/b*) the peak of the mechanical energy potential is characterized by the slow progression of compression work of the CG, while for very high temperature cases C (see *FIG. 2-c*) the contribution to the peak is dominated by sodium kinetic energy due to the rapid slug movement up to hitting the lid.

TABLE II: SIMMER parametrical cases considered

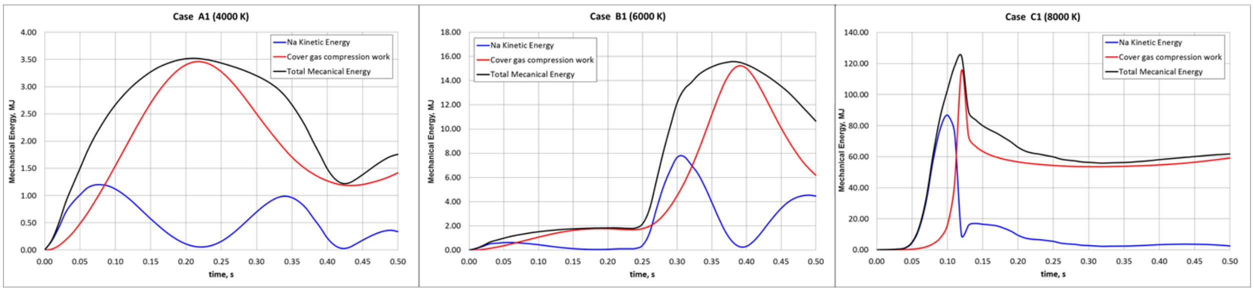
Families	**A-family**	**B-family**	**C-family**
Average fuel T (K)	4000	6000	8000
Average fuel internal energy (MJ)	9577	14955	19311
Parameters	**Range investigated**		
Different initial fuel mass	50-100% of the initial fuel mass		
Initial fission gas pressure	3 – 60 MPa		
Steel content of melt pool	10-100% of the initial steel mass		
Temperature peaking of fuel	Different distributions		
Mass distribution of melt in the pool	Different pool arrangements (flat, triangular, …)		
Interaction with lower axial blanket/radial blanket	yes/no		
Interaction with sodium films in sub-channels	yes/no		
Melt-structure interaction	Different options ($T_{structures}$, P_{UAB}, HTC, …)		
Degree of thermal erosion of UAB	0-50-100%, partially open at dif. radial positions		

The large discrepancy in the mechanical energy potential (*FIG. 3-a*) results from the different discharge rates of the melted material ejected into the hot sodium pool. After a short time the mechanical energy dissipates to thermal energy. As indicated in *FIG. 3-b*, high temperature cases (indicated as C01) show a very large initial average pressure in the core that rapidly decreases to a long term “equilibrium” value. This high pressure is the driving force for the material ejection. The discharge rate from the core zone is shown in *FIG. 4-a*. For low temperature cases, the initial fuel mass remains mainly in the core zone (80%) while for medium (*FIG. 4-b*) and high (*FIG. 4-c*) temperature cases the initial fuel mass is moved to a large extent to the upper sodium pool increasing the potential for a large FCI in this zone. A relative fuel mass larger than one results from additional blanket material melted during the discharge. As follows from *FIG. 4*, the dynamic of the discharge is highly temperature/pressure dependent. Thus with a temperature increase and the following higher discharge rate the fuel content also increases in the expanding bubble, thus defining also the source term for leakages from the vessel.

5.2. Case 05: without UCS

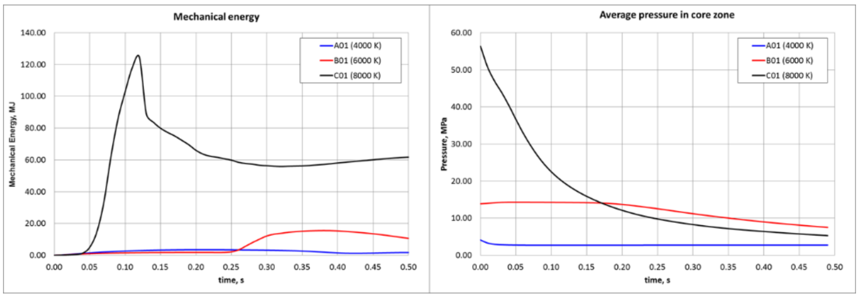
Family 05 deals with a completely ruptured core. Concerns are that after a failure of several wrapper walls the coherence of remaining intact sub-assemblies cannot be further maintained by the clamping system. This case corresponds to a large cross-section available for melt discharge. A parametric modelling of the discharge flow paths is required as suitable

SIMMER-III models are presently not available for load-based structure failure and large-scale structure movement.



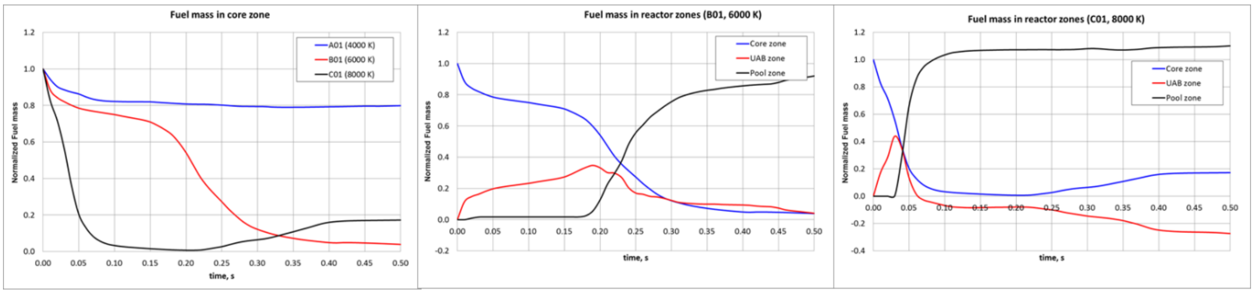
(a) (b) (c)

FIG. 2. Cases with UCS: evolution of Na kinetic energy, cover gas compression work and total mechanical energy depending of the fuel average initial temperature



(a) (b)

FIG. 3. Cases with UCS: a) comparison of the total mechanical energy and b) average pressure evolution in core zone for different fuel temperatures

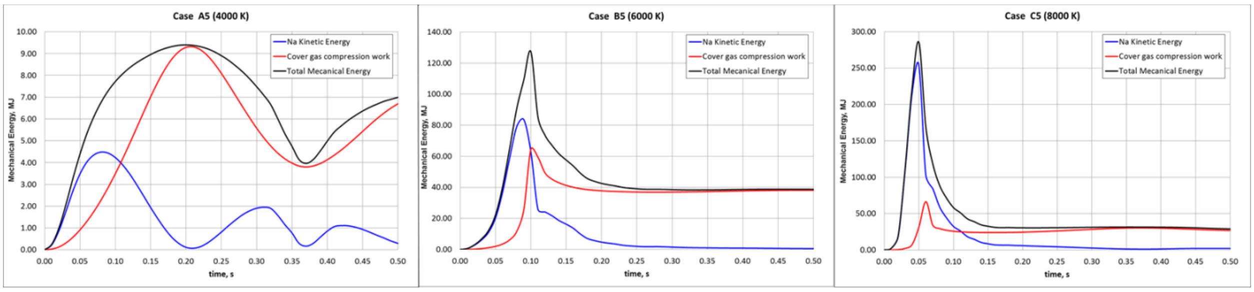


(a) (b) (c)

FIG. 4. Cases with UCS - fuel mass evolution: a) in core zone depending on the fuel temperature, b) medium temperature case (B01) and c) high temperature case (C01)

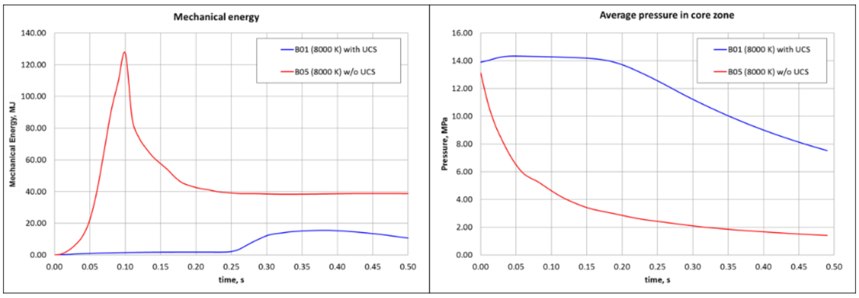
FIG. 5 shows a comparison between the three fuel temperature families. Also in this case, with raised temperatures, the event proceeds more violently and rapidly. As shown in *FIG. 5-a*, the low temperature case is not strongly affected by the presence of the UCS, to be compared with *FIG. 2-a*. For medium/high temperature cases (see *FIG. 5-b/c*), the mechanical energy behaviour significantly changes compared to the case with UCS (*FIG. 6-a*). The large flow resistance of UCS on the discharge rate is also visible in *FIG. 6-b* in which the average core pressure is compared for medium temperature cases.

As expected, the absence of UCS has a significant impact on the fuel mass unloaded from the core and discharged into the sodium plenum (*FIG. 7*). Even for the low temperature case with its limited driving pressure two thirds of the fuel can be reloaded from the core (*FIG. 7-a*), compared to only 20% for the case with existing structure (*FIG. 4-a*). For the high temperature case, the evaluated kinetic energy is three times higher and the overall mechanical work potential is double compared to the values of the case with UCS. The mechanical energy peak is anticipated in time with 0.06 s instead of 0.12 s. In case of weakened and failing upper structures the amount of fuel accumulated in the upper vessel region thus significantly increases.



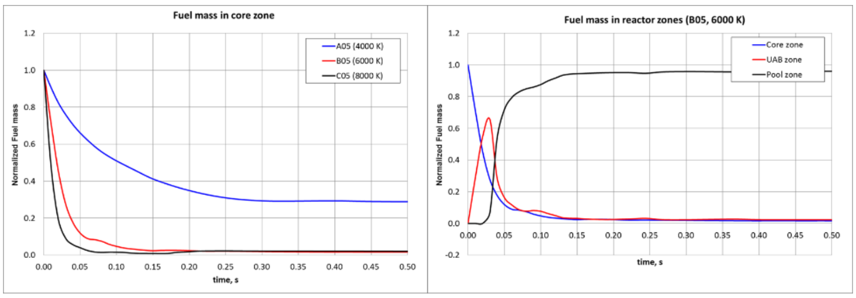
(a) (b) (c)

FIG. 5. Cases without UCS: evolution of Na kinetic energy, cover gas compression work and total mechanical energy depending of the fuel average initial temperature



(a) (b)

FIG. 6. Effect of UCS: a) total mechanical energy and b) average pressure evolution in core zone

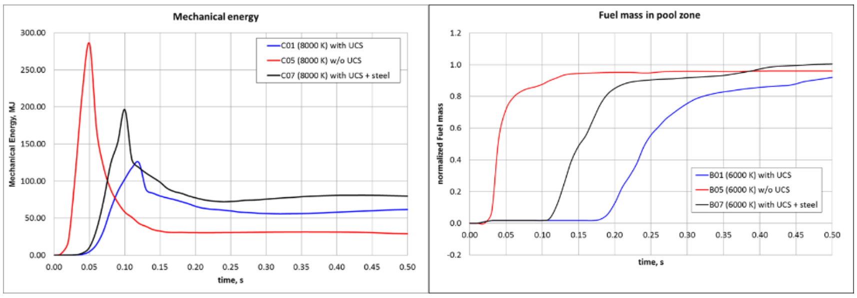


(a) (b)

FIG. 7. Cases without UCS - fuel mass evolution: a) in core zone depending on the fuel temperature, b) medium temperature case (B05) toward reactor zones

5.3. Case 07: With UCS, core pool composed by fuel and steel

As a further example, a case (referred as 07) with 20% liquid steel homogeneously mixed to the fuel pool and intact UCS is discussed. According to *FIG. 8-a*, the presence of a small amount of steel increased the peak mechanical energy by ca. 60 % compared to case 01. It is explained by a higher driving pressure due to the additional steel vapour pressure during the first 0.07 s (period of time just before the peak) resulting in a higher discharge rate (*FIG. 8-b*). Other cases, with larger steel content, have shown a mitigating effect due to the reduction of the average temperature of the molten pool.



(a) (b)

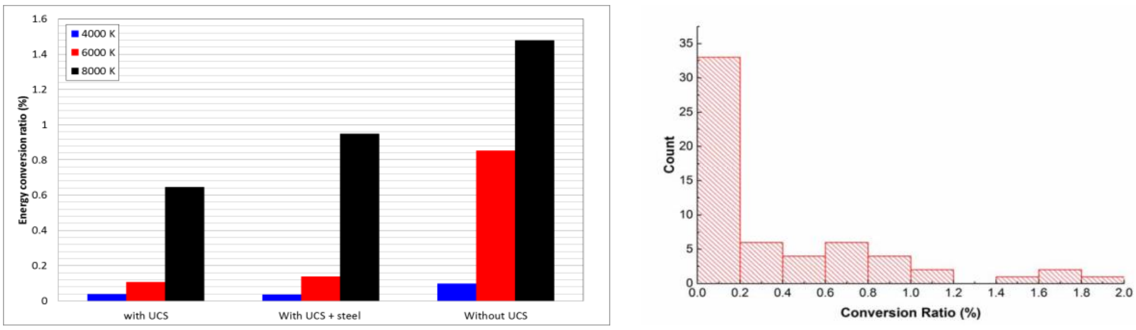
FIG. 2. Effect of UCS and steel: a) comparison of the total mechanical energy (C-family) and b) medium temperature cases mass evolution in the upper sodium pool

6. Assessment of results

The parametric results of the study have to be connected with realistic fuel temperatures experienced during the transition phase of a ULOF accident. Both mechanistic SIMMER analyses and some information from past investigations provide this data base. The reactors cover a range from midsize to large reactors as SNR-300, CRBR and EFR, SPX, CP-ESFR and others. Various transients from accident initiators like ULOF, Unprotected Top Over Power (UTOP), Total Instantaneous Blockage (TIB) and also Unprotected Loss of Heat Sink (ULOHS) have been investigated for these reactors. The fuel maximum temperatures in these analyses for the transition phase are from 3200 to maximum 5000 K, with a peaking of results below 4000 K as also indicated 'Risikoorientierte Analyse zum SNR-300' [29]. In ref. [29], the peak temperatures from recriticality events are correlated with probabilities provided by the expert answers. Combining all the studies, Table III can be built.

TABLE III: Proposed distribution of temperature levels from recriticality events

Peak temperature intervals [K] and probabilities in %			
< 4000	4000-5000	5000-6000	6000-8000
40	50	9	1



(a) (b)

FIG. 9. a) Effect of UCS and steel on the energy conversion ratio depending of the fuel average initial temperature, b) Overview of the overall parametric study results

The outcome of this evaluation is important for the assessment of the PRD for the expansion phase. More details of the probabilistic evaluations can be found in ref. 13-14.

In *FIG. 9-a* the results of the investigation related to the effect of UCS and steel on the energy conversion ratio as function of the fuel average initial temperature are displayed. An overview of the overall results obtained by the parametric case considered is shown in *FIG. 9-b*. The energy conversion ratio is calculated for all the cases. The average value is below 0.2%, in good agreement also with the probabilistic study performed in [13-14].

7. Conclusions

The present study has allowed identifying and evaluating important phenomena and event paths enhancing or mitigating the mechanical work potential during the PDE. The results obtained from the parametric study together with past mechanistic simulations for different reactor types have provided a solid database employed at KIT in the framework of a probabilistic evaluation of the work potential of an ULOF/PDE in a sodium-cooled small- to medium-sized reactor (power up to 300 MWe) via the adoption of the PRD method [13-14].
In general, the initial fuel temperature has a strong non-linear impact on the mechanical work. The existence of intact UCS strongly affects the discharge rate into the upper sodium pool and the mechanical work resulting from expansion and thermal interaction with surrounding coolant. For low temperature cases the structure proved to be a barrier difficult to pass. .
Steel is assumed to be present in a mechanistic simulation, therefore, dedicated cases, in which different amounts of liquid steel homogenously mixed with the fuel, have been analysed. Depending on the existence of upper structures, different liquid steel fractions lead to a diverse effect. With structure, impeding the discharge, the mixing of the melt constituents becomes important resulting in a reduced mixture temperature. Therefore, a mitigation effect was observed for large steel fractions (larger than 50%) and an augmenting one for small steel contents as for the case presented in the paper (20% of steel).

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