Fast reactor systems in the German P&T and related studies

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Abstract. After the planned shutdown of German nuclear power plants in 2022, more than 10 thousand tons of spent nuclear fuel will be accumulated in Germany. Transmutation of trans-uranium elements (TRUs) into fission products in nuclear reactors may facilitate appreciably the spent fuel storage. Options for transmutation of German TRUs in the European and German frameworks are studied at KIT. Accelerator driven systems and fast reactor designs proposed for EU and international projects offer the basis for these studies. Transmutation and safety performances of several designs have been investigated at KIT and reported in the paper.

Key Words: Transmutation, fast reactors, accelerator driven systems, reactor safety

1. Introduction

It is planned that all German light water reactors (LWRs) will be shut-down by 2022. Then more than 10 thousand tons of the LWR spent nuclear fuel (SNF) should be managed for a long time. Extraction (partitioning) of trans-uranium elements (TRUs) from LWR SNF and their transmutation into fission products (FPs) under neutron irradiation in special nuclear reactors (transmuters), may reduce appreciably the amount of TRUs to be finally stored and therefore lessen risks associated with their storage. Irradiation of a TRU-bearing fuel in a transmuter does not eliminate all TRUs in the fuel due to a limited irradiation time. Therefore partitioning and transmutation (P&T) includes also recycling of transmuter spent fuel.

A study on P&T options was done in Germany in 2012-2014 [1]. In one type of scenarios, oriented to the German framework, the objective is to burn almost all TRUs from German SNF starting at some time after phase-out. In alternative scenarios for the EU framework the main attention in the short term is to burn MAs accumulated in Germany and other countries phasing out of nuclear; while in the long term it is on MA management in countries producing nuclear energy in the future: in order to limit the MA amount in the fuel cycle. A conservative assumption accepted in [1] is that German SNF will contain in 2075 ca. 137 tons of Pu and ca. 38 tons of Minor Actinides (MAs) apart from already vitrified waste, which contains relatively small amounts of FPs and MAs.

These investigations have been extended by studies performed at KIT more recently; some of these studies are reviewed in the following. In particular ASTRID-like and ESFR-like sodium fast reactor (SFR) models were investigated as reported in the following.

2. Earlier studies on P&T

P&T studies are under way at KIT for a long time. Important efforts in the 1990s were related to KIT contributions to the EU CAPRA/CADRA SFR projects [2]. For these projects, a conventional 3600 MW (thermal power is given hereafter) European fast reactor design was modified for a higher TRU content. The core incorporated special “diluents”, i.e. subassemblies and pins containing no actinides, but materials such as steel and aluminium oxide. The diluents make the sodium void effect less positive, a favourable feature for safety. They also make possible higher fuel enrichments and facilitate molten material discharge from the core under hypothetical accident conditions, thus helping to prevent re-criticalities after core melting. Higher TRU fuel enrichments in CAPRA/CADRA cores decrease the TRU conversion ratios to values well below unity, thus making the transmutation possible. It was shown that the proposed CAPRA/CADRA cores could be potentially used for TRU management, while safety, economics, and other issues should be proven in more detail.

In early 2000s more attention in EU was focused on subcritical accelerator driven systems (ADS), in particular on those with uranium-free fuel, i.e. with the zero TRU conversion ratio, such as EFIT [3]. In European fuel cycle studies, plutonium (Pu) is considered as fuel, not waste, in view of plans to use it in fast reactors in countries which rely on nuclear energy production in the long term; therefore only minor actinides (MAs) should be burned. The 400 MW EFIT core contains fertile-free inert matrix fuel (IMF). The inert matrix is magnesium oxide or molybdenum (optionally enriched by Mo-92) metal. TRUs are added to this matrix. The EFIT MA burner fuel contains similar amounts of Pu and MAs; the MAs are burned under irradiation, while the Pu mass is almost constant due to breeding of Pu from MAs. Even if Pu is not depleted appreciably, it should be present in the ADS fuel initially; otherwise the criticality level is too low. The EFIT power is quite small compared to that of CAPRA, being limited in particular by the beam power and by the criticality level imposed due to safety reasons. To improve the EFIT transmutation performance per reactor unit, designs with higher power, from 600 to 800 MW were proposed at KIT for the Mo-92-based IMF [4], while accepting a higher k-eff value at nominal conditions. Due to a limited effort in investigation of these designs, we consider the 400 MW EFIT systems as the basis ADS option in the following. In EFIT, the MA incineration rate is about 42 kg/TWh.

As alternatives to ADS, critical molten salt fast reactors (MSFRs) attracted interest in the 2000s in EU. KIT contributed in particular to studies of the 2400 MW MOSART design [5] and of a conceptually similar (i.e. without graphite moderator in the core) European MSFR design. Note that safety parameters of reactors with solid fuel strongly deteriorate in case of a high MA content; this makes impossible their operation in the critical mode. On the other hand, MSFR safety parameters are almost insensitive to the TRU isotopic vector: the major reactivity feedback in MSFR is due to thermal salt expansion. This feedback is negative in MSFRs independently of the fuel isotopic composition. KIT contributions to MSFR design studies include optimization of the molten salt flow pattern in the core at nominal conditions, transient analyses in support of safety studies, decay heat removal under accident conditions, etc. MSFRs can potentially incinerate all TRUs from LWR SNF. Similarly to ADS, MSFR transmuters are promising options; but the ADS and MSFR technologies are less mature than those for sodium fast reactors (SFRs).

In late 2000s and 2010s, SFRs attracted attention again in EU. New SFR designs were proposed, such as ESFR and ASTRID. KIT performs safety studies of these reactors in the EU framework, investigates their potential for burning TRUs and studies possible design modification to improve their safety and transmutation performance. Design modifications were also proposed at KIT for EFIT systems, initially aimed on MA burning only; these modified EFIT-like transmuters are considered for burning all TRUs of the German SNF.

3. ESFR-like and EFIT-like transmuters

The 3600 MW ESFR core contains 225 fuel subassemblies (SAs) in the inner core and 288 ones in the outer core, the SA pitch being ca. 21 cm [6]. The core contains also DSDs (Diverse Shutdown Devices) and CSDs (Control and Shutdown Devices), see Fig. 1a. The initial “working horse” (WH) design with a fissile core height of 1 m is characterized by a higher, compared to earlier European designs, fuel volume fraction in the core due to thicker fuel pins with the outer pellet/clad diameter of 9.43/10.73 mm. This makes possible a near-unity conversion ratio without fertile blankets and reduces the sodium and steel volume fractions, thus reducing the reactivity effects related to sodium and steel relocation from the core in case of a hypothetical accident. Though the coolant void effect is reduced in ESFR compared to earlier large EU SFR designs, it is definitely positive in ESFR WH, being about 3$ at the beginning of life (BOL) and about 1.5$ higher at the end of equilibrium cycle (EOEC). 1$ in ESFR WH is about 400 pcm at BOL. To reduce the sodium void effect and improve the reactor safety performance, an optimized ESFR design was developed.

An effective measure in reducing the void effect is the introduction of a sodium plenum above the core, the plenum being topped by an absorber material layer, in addition a fertile blanket being put below the core. In this optimized design referred as ESFR CONF2 [7], the sodium leakage is increased, in particular under voided conditions, therefore the void effect is reduced to about 1$ at BOL. A hypothetical severe accident is not excluded in the low void SFR, it may happen e.g. after an unprotected loss of coolant flow (ULOF), but the power variations at the coolant boiling onset are milder. Therefore, more time after ULOF initiation is needed to achieve a massive steel/fuel melting in a low void SFR core. After the core melting, re-criticality events with a potentially high mechanical energy release may occur: due to steel/fuel separation and due to sloshing events in the molten pool. As shown in the following, introduction of an absorber, such as boron carbide, may not be sufficient to prevent such events. In order to avoid re-criticalities one may have to facilitate early relocation of molten materials out of the core region.

An ESFR configuration with 18 “empty” SAs in the inner core was proposed at KIT; compared to the original ESFR layout (see Fig. 1a) it includes 18 special elements (see Fig. 1b), which replace 18 fuel inner core SA. These elements contain only sodium inside the wrapper, which is the same as the fuel SA wrapper. These elements may provide extra paths - in addition to control rod guide tubes - for molten fuel discharge from the core under accident conditions. In the configuration shown in Fig 1b, one may also see 18 fuel SAs added to the outer core: to compensate their reduction in the inner one. Calculations show that this modification reduces slightly, by less than 0.5$, the void effect in fuel SAs due to higher sodium content in the voided core. Voiding of these 18 elements under accident conditions would introduce a strong negative effect of ca. -2.5$: due to a neutron leakage increase. The results of transient simulations, in which penetration of molten fuel into these 18 elements is studied, are sensitive to assumptions on intra-gap sodium temperature and flow rate. Using of similar elements, but fully or partly without wrapper in the core axial region is now considered at KIT.

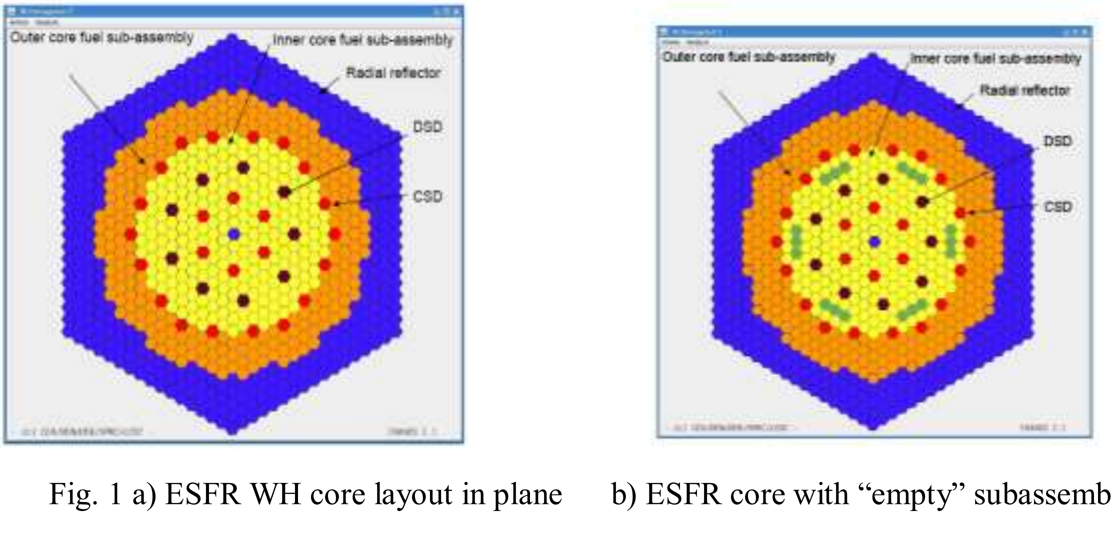


Fig. 1 a) ESFR WH core layout in plane b) ESFR core with “empty” subassemblies

For establishing a ESFR-like transmuter design, an option of adding of 3.5 wt% Am into the fuel and 4.0 wt% in the blanket of CONF2 was studied at KIT. This would increase the void effect to ca. 2.5$ at BOL. To make the void effect smaller, we considered a reduction of the core height and power by 20%. This brings the void effect to ca. 0$/1$ at BOL/EOEC. In Fig. 2, criticality variations during reactor operation are shown for this low height (80 cm) core and normal height (100 cm) cores under assumption of no refuelling during the fuel SA residence time (5 cycles of 410 effective power days, efpd). Note that the criticality is almost constant vs. time for this core, the BOEC/EOEC criticality values corresponding to the values at 820/1330 efpd, the difference between these values being less than 1$.

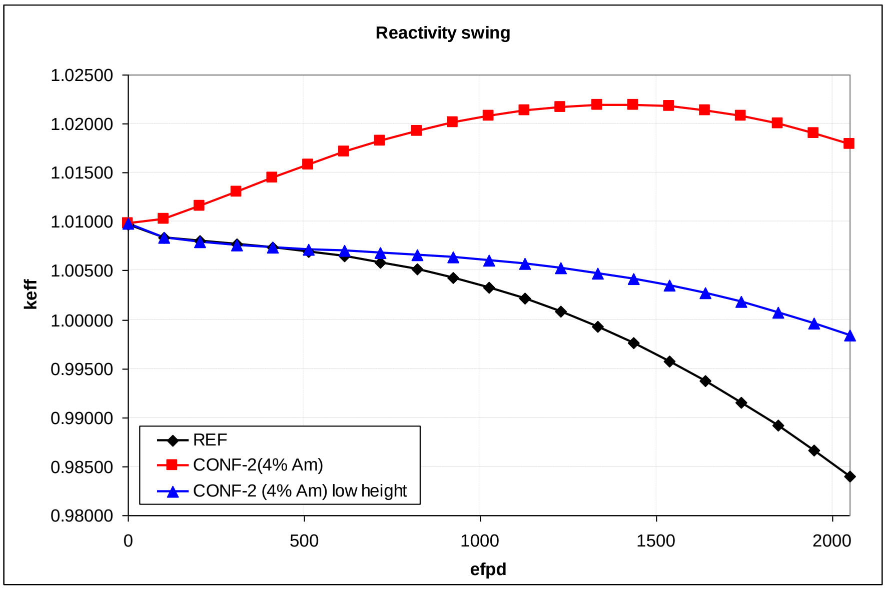


Fig. 2 Criticality under irradiation in ESFR WH (REF) and optimized configurations with Am

An ESFR-like transmuter with 80 cm core height, 2880 MW power and a near-zero void effect can be considered as a MA-burner if e.g. 3.5 wt% Am is added to the core, while the blanket height and isotopic content may have to be optimized further to reduce Pu production if needed. The MA burning rate in the core is ca. 4 kg/TWh, see Table I. This rate is about 10 times smaller than that for EFIT. Note, however that studies for EFIT were done for fresh fuel containing also Cm. Using of such MA-bearing fuel strongly reduces Cm production compared to the case of no Cm in the fresh fuel. If Cm was not present in the EFIT fresh fuel or present in the ESFR-like one, the MA burning rates per reactor unit of the 400 MW EFIT and 2880 MW ESFR-like transmuter would be comparable.

	CONF2, 4%Am		CONF2, 4%Am, low height (80 cm)	
	Core	Reactor	Core	Reactor
Pu	2.13	7.59	-0.04	7.14
Am	-6.78	-8.24	-6.33	-8.24
Cm	2.07	2.46	2.00	2.50

Table I. Mass balance at EOL in ESFR-like transmuters (kg/TWh)

Neither EFIT, nor ESFR-like transmuters are aimed at Pu burning. However, an EFIT-like system with higher Pu/MA fractions in the fuel can be considered for burning Pu and MAs together. One option is an EFIT-like system with 20% of MAs (the rest being Pu) in the TRU component of IMF with Mo (natural) metal matrix. Such system can be employed for incineration of all TRUs of the German LWR SNF. The Pu burning rate of this system is ca. 35 kg/TWh, the MA one is ca. 9 kg/TWh.

4. ASTRID-like transmuters

ASTRID-like transmuters are based on the 1500 MW ASTRID core [8], which is studied in EU and international frameworks. ASTRID contains 177 fuel SAs in the inner core and 114 fuel SAs in the outer core. The inner and outer core fissile heights are 80 cm and 90 cm, respectively, including the internal axial fertile blanket of 20 cm in the inner core. The SA pitch is ca. 17.5 cm. The height of the lower axial blanket is 30 cm. The ASTRID-like transmuters proposed for the German P&T study are based on the same SA layout in plane, while the inner and outer core heights are reduced to 50 and 70 cm, respectively, i.e. by about 20%. In the ASTRID-like core, the internal fertile blanket is not present and the height of the lower axial blanket is 2 cm. The power level has been reduced similarly to the fissile core height reduction, by 20%, i.e. to 1200 MW. Two “extreme” fuel options are considered for the ASTRID-like design: with MA contents of 5% (TRU burner) and 34% (MA burner) in the TRU component of the fuel. The sodium void effect is ca. -3.4$/-2.6$ at BOL/EOEC in the TRU burner and -0.3$/-0.6$ in the MA burner [9]. The TRU-burner transmutation rates are ca. 14 kg/TWh and 0 kg/TWh for Pu and MAs, respectively. In the MA burner they are ca. 4 kg/TWh and 15 kg/TWh. While considering a particular fuel cycle scenario, intermediate MA contents in the fuel can be chosen at particular times to optimize the fuel cycle, e.g. a TRU burner with 10% of MAs and a MA burner with 25% of MAs are possible options. The transmutation performances of ASTRID-like systems per reactor unit are similar to those of EFIT/EFIT-like systems, while the power production in ASTRID-like systems is 3 times higher.

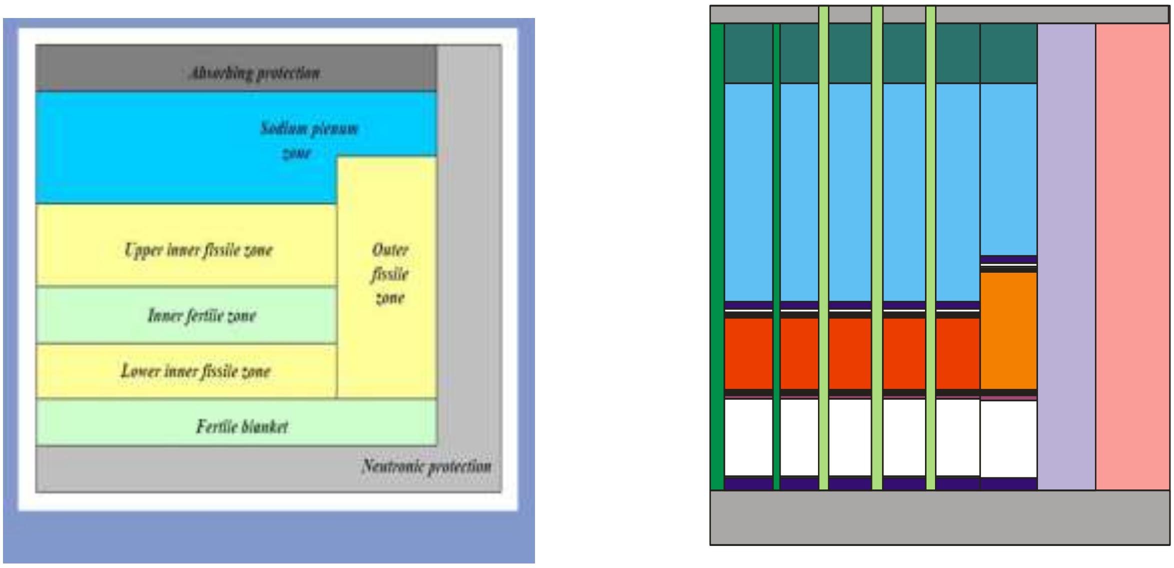


Fig. 3 a) ASTRID core b) ASTRID-like transmuter core

5. Transmutation studies in the EU and German frameworks

All system types considered in this paper, in particular 400 MW EFIT MA burners, 2880 ESFR-like MA burners, and 1200 MW ASTRID-like MA burners, can be potentially employed in the EU framework, while operating either in subcritical mode (EFIT) or with the void effect near or below zero (ESFR-like and ASTRID-like systems). Their transmutation performance per reactor unit is similar, the smallest energy production being by EFIT systems, the largest by ESFR-like MA burners. In fuel cycle scenarios, they can be employed first for incineration of MAs in countries phasing out of nuclear and then for keeping MA inventory stable in countries which continue with nuclear energy production. For incineration of the German MA inventory, one option is to employ 6 to 7 systems for operation during 30 to 40 years. If it is planned to employ them afterwards for management of MAs produced in other countries, they can be located in these countries.

If both Pu and MAs should be burned, 400 MW EFIT-like and 1200 MW ASTRID-like TRU burners can be considered. For burning almost all German TRUs (the full incineration is not possible as the last irradiated transmuter cores will contain some TRUs, also fuel reprocessing losses should be considered), 7 to 8 systems in average should be employed for ca. 150 years. More details, including results of fuel cycle simulations can be found in [10]. A summary of transmuter designs is given in Table II.

System	Core power (MW)	Coolant void effect, $	MA/PU burning rate, kg/TWh
EFIT MA burner, EFIT-like TRU burner	400	Near or below the sub-criticality margin of ca. 10$	42/0, 9/35
ASTRID-like MA burner, ASTRID-like TRU burner	1200	Below 0, ca. -3$	14/0, 4/15
ESFR-like MA burner	2880	Near or below 1$	4/0

Table II. Main parameters of MA and TRU burners

6. Introduction of absorber material into ESFR during a severe accident

The remaining part of the paper is related to ESFR WH safety analyses. Compared to other SFR systems considered in the paper, the sodium void coefficient in ESFR WH is relatively high; therefore safety analyses for this system may offer a kind of enveloping case. Past safety analyses for ESFR WH are reported in particular in [11]. A rather energetic power excursion is observed in these analyses soon after the sodium boiling onset, which is caused by ULOF. But a major challenge for the reactor vessel integrity is due to subsequent re-criticality events, which are caused by molten steel and fuel separation and sloshing events in the molten material pool. For stopping cyclic re-criticalities, an introduction of absorber material into the core was considered and simulated at KIT.

The absorber was assumed to be inserted in the core just after the first ULOF-induced power excursion. The ULOF simulations were done at KIT firstly with the SAS-SFR code (that is similar in many respects to the SAS4A code) and then continued with the SIMMER-III code [12]. The SIMMER calculations started when a can-wall failure occurred. It happened at 6.8 s after the Na boiling onset, which induced a power excursion with the peak power of 350 to 400 P0, P0 being the nominal power. At the SAS-SIMMER coupling time, referred at t=0 hereafter, the reactivity is slightly negative, ca. -0.27$, the power is ca. 2.5 P0. At this time, a large part of the fuel is already molten or broken into particles, see Fig. 4. The SIMMER calculation model covers the full vessel, but only the core region is shown in Fig. 4a, where L1, L2, L3 stands for liquid fuel, liquid steel, and liquid Na respectively, while L4 represents fuel particles.

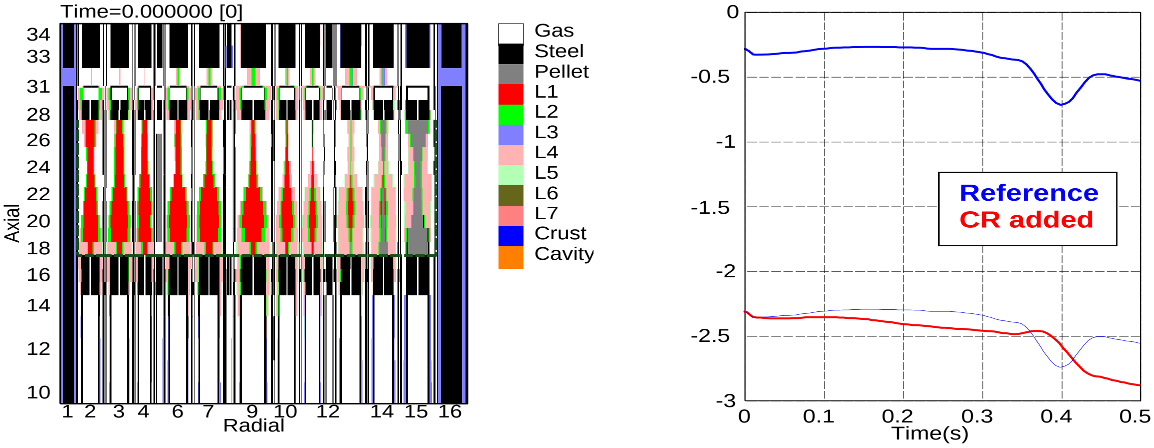
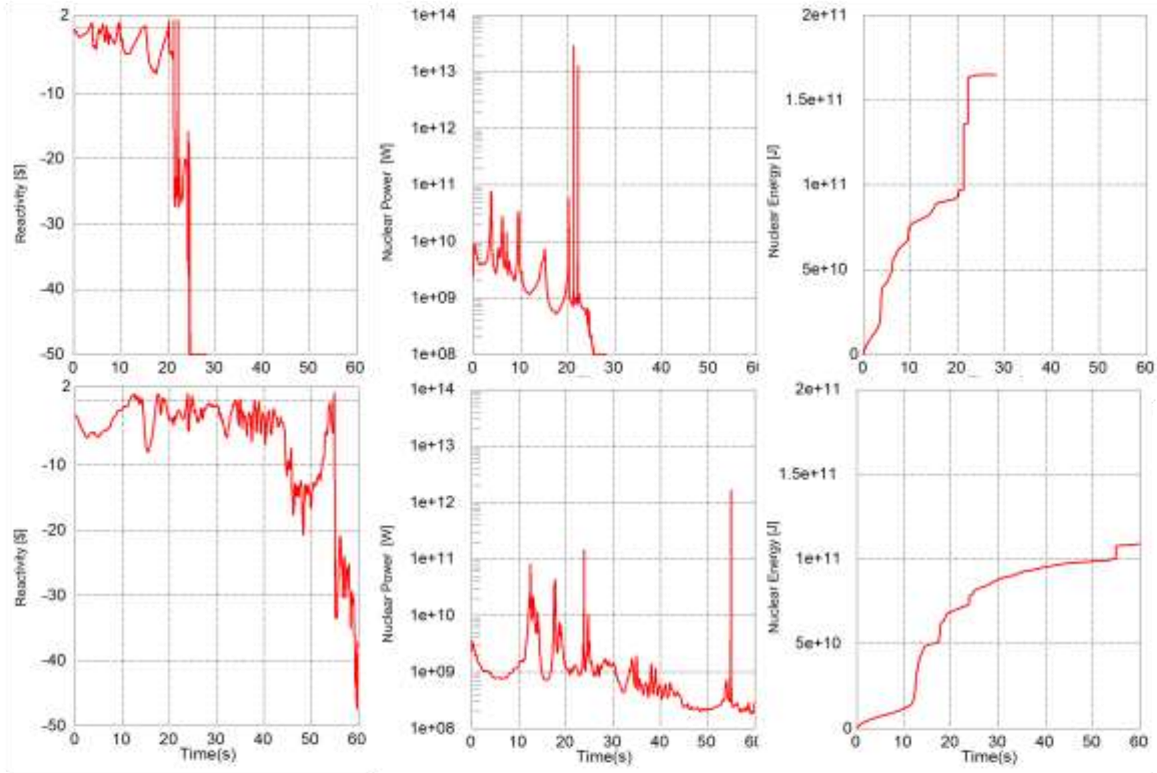


Fig. 4 a) ESFR WH core at t=0, b) Reactivity trace shortly after t=0



Reactivity without (above) and with introduction of absorber

Power

Nuclear energy

Fig. 5. Reactivity, power and nuclear energy release in the closed pool

At t=0, a prompt introduction of the B4C absorber material from the Control Rod (CR) in Ring 5 is assumed. This reduces the reactivity by ca. 2$. For a short time after t=0 the reactivity variations with and without the absorber of CR are similar, see Fig. 4b; the reactivity variations being determined mainly by material movement in the core under subcritical conditions, with decay heat being the major heat source.

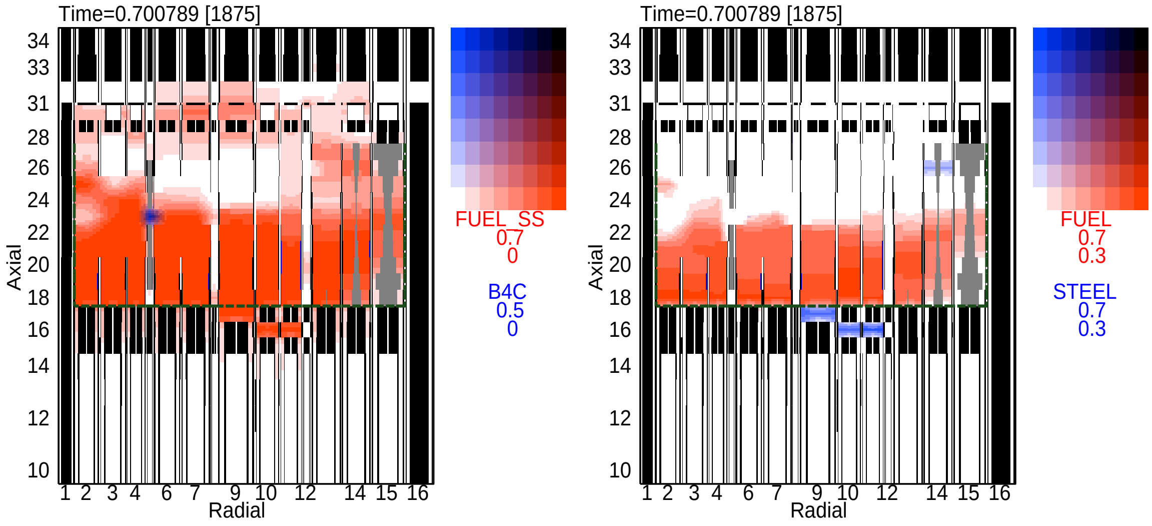


Fig. 6 a) B4C/Fuel Redistribution at ca. 0.7 s b) Steel/Fuel Redistribution at ca. 0.7 s

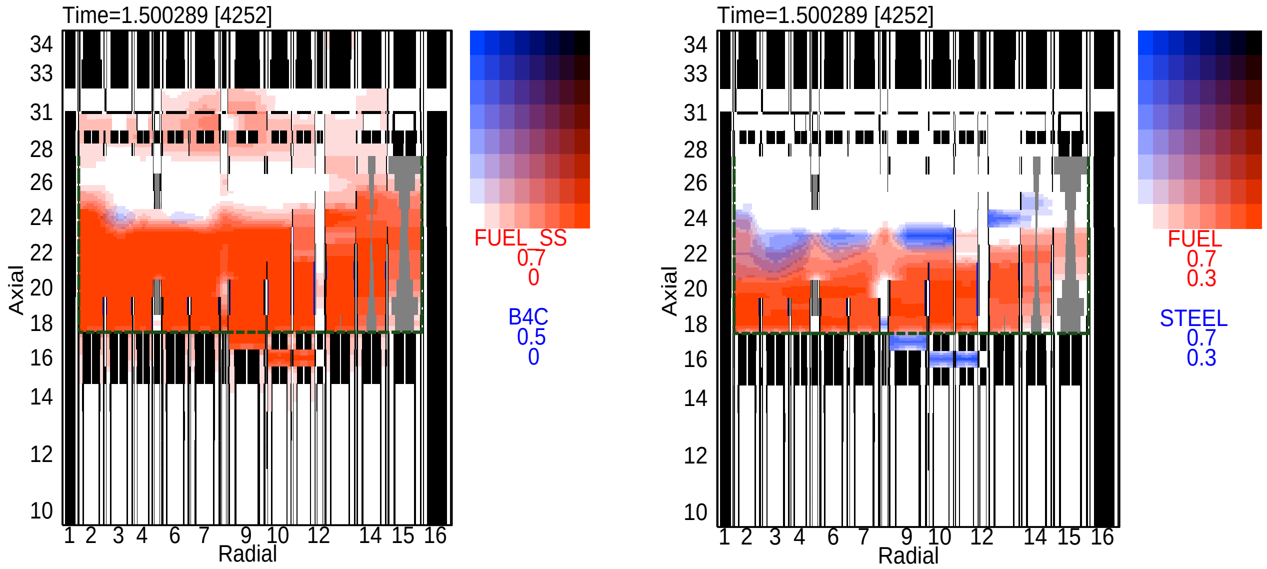


Fig. 7 a) B4C/Fuel Redistribution at ca. 1.5s b) Steel/Fuel Redistribution at ca. 1.5 s

For better understanding and covering a wider range of transient phenomena, the calculations were done (1) by assuming that the core was isolated from the right and from below (closed pool) and (2) without this assumption. The isolation assumption is mainly to exclude the effect of FCI (fuel-coolant interaction) on the transient progression. The results of calculations are illustrated in Fig. 5 for the closed pool without absorber (top row) and with absorber from CR (bottom row). The distributions of absorber, fuel and steel in the closed pool after absorber introduction are given in Figs. 6 -8.

At 0.7 s (Fig. 6) the can-walls still exist to a large extent, while the structure around B4C fails, B4C particle being released. At 1.5 s (Fig. 7) B4C particles float to the top of the pool; the density driven fuel/steel separation is going on, formation of steel/B4C eutectic being not simulated.

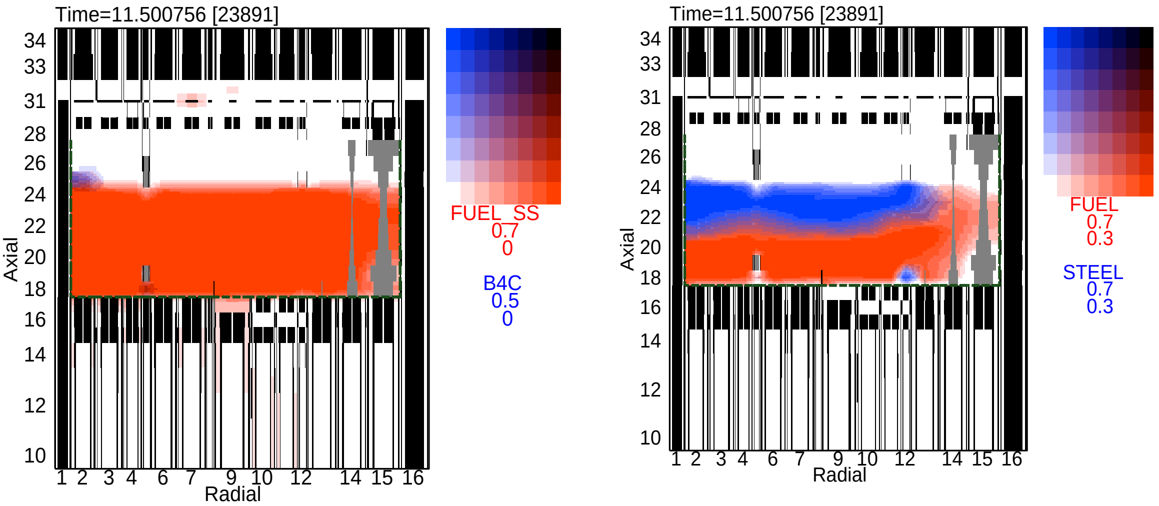


Fig. 8 a) B4C/Fuel Redistribution at ca. 11.5 s b) Steel/Fuel Redistribution at ca. 11.5 s

At 11.5 s a re-criticality is reached (Fig. 8). One may observe a pronounced fuel/steel layering, where steel acts as a neutron reflector layer.

At 13.5 s vaporization of small amounts of liquid steel causes sloshing core behaviour and a further re-criticality event. Thus, introduction of the B4C absorber in the core may reduce its criticality level for a limited time, but then re-criticalities may occur as the light absorber floats up and the stratification between absorber, steel and fuel introduces a positive reactivity. In case of the open pool, the calculations were stopped earlier, but the preliminary conclusions are similar.

7. Conclusions

For management of spent nuclear fuel several fast reactors types can be used. ADS and MSFR systems are attractive in view of possible high MA content in the ADS fuel and negative thermal expansion reactivity feedbacks in MSFR. However, more effort on ADS and MSFR technology development is needed before ADS and MSFR industrial employment.

The SFR systems proposed in Europe recently can be fit to different P&T scenario options. For their employment as transmuters, their fuel composition should include more TRUs, including MAs. The EFIT/EFIT-like and ASTRID-like systems offer similar transmutation rates per reactor unit for both German-oriented scenario’s aiming at burning of all TRUs and for EU ones aiming at MA burning. Also ESFR-like systems can be employed as MA burners with a comparable to EFIT and ASTRID-like system transmutation performance per unit.

To keep the safety parameters of SFR transmuters with higher MA content in the proper range, e.g. to keep the sodium void effect near or below zero, design modifications of ASTRID and ESFR were proposed. In the paper, two types of design modifications are considered: (1) reduction of the core height and power to bring the sodium void effect to a near zero or negative value, this also increases the TRU transmutation rate and (2) incorporation of special elements instead for fuel subassemblies for early molten fuel discharge in case of hypothetical accident.

The transient analyses show that alternative safety measures, e.g. introduction of absorber such as boron carbide, may not prevent re-criticalities after massive core melting, while introduction of absorbers with a higher material density has not yet been studied in detail. The obtained results are preliminary. Further studies are needed to investigate safety performance of fast reactor systems with transmutation capabilities.

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