Lead–Cooled Breeders and Burners – are the latter Even Necessary?

Kamil Tuček*, Johan Carlsson and Hartmut Wider
Joint Research Center of the European Commission
Institute for Energy, Postbus 2, NL-1755 ZG Petten, The Netherlands

Abstract

This paper compares neutronics, transuranic burning capabilities and safety aspects of lead-cooled self-breeders and burners employing uranium- and thorium-based fuels. Both fast reactors are optimized with respect to minor actinide (MA) transmutation performance in the start-up cores. The Monte Carlo code MCB is used for the neutronic and burn-up analyses; accidental behavior is studied by EAC-2 and STAR-CD codes.

We show that lead-cooled fast reactors (LFRs) can be used both as breeders and burners of transuranics from spent LWR fuel and that minor actinides are incinerated in self-breeder cores nearly as effectively as in dedicated critical burners. In optimized 600 MW_e LFR self-breeders about 100 kg of MAs can be transmuted per year. This corresponds to an annual production of minor actinides in two EPRs. We demonstrate that the same reactor (self-breeder) can be used for breeding only or for breeding combined with MA burning, depending on the core load composition.

Regarding safety, LFRs feature favorable characteristics in coping with investigated accident initiators (unprotected Loss-of-Flow and Loss-of-Heat Sink). The reasons are good natural circulation behavior together with the high boiling point of the lead coolant.

KEYWORDS: Lead cooled fast reactor, self-breeder, burner, moderator, hydrides, minor actinide burning

1. Introduction

Nuclear Power seems to be at the beginning of a renaissance; partially because of energy and resource supply concerns but also due to worries about the climate change. Fast reactors could be necessary relatively soon, particularly if the nuclear power increases by a factor of four by 2050 as is the median prediction of Special Report on the Emission Scenarios of Intergovernmental Panel on Climate Change (SRES/IPCC)[1]. To utilize uranium efficiently, we would need to reprocess most of LWR spent fuel and about 1/3 of the world reactor fleet would have to be fast reactors by 2040 [2]. Lead cooled fast reactors (LFRs) are very attractive fast systems since they appear to be very safe, potentially the most economical fast systems, and sustainable since they have a fast spectrum, which enables them to breed and burn transuranics (TRUs). GANEX or UREX+ reprocessing technologies can be used for increased proliferation resistance.

The nuclear waste question is a major public concern. Nevertheless, to transmute all

* Corresponding author, Tel. +31 224 565 465, Fax. +31 224 565 621, E-mail: kamil.tucek@jrc.nl

transuranics, including plutonium, as fast as possible is questionable from a perspective of sustainability. Plutonium can be seen as a long-term asset, promoting a rapid expansion of fast (self-) breeders and transition to fast reactor schemes. However, the burning of the minor actinides (MAs) from the spent fuel would certainly make the nuclear power more attractive to the wider public. This notion is clearly demonstrated in a recent Eurobarometer poll on radioactive waste, where 38% of the opponents to nuclear power responded that they would become favorable towards it, if the issue of the radioactive waste was solved [3].

2. Method

2.1 Design concepts

In this study, we compare the neutronic and burn-up performance of an LFR self-breeder using $(U,TRU)O_2$ mixed oxide fuel with an LFR burner employing inert matrix CERMET fuel, $(U,TRU)O_2$ – ^{92}Mo. Characteristics of these systems are then compared to that of a $(U,Pu)O_2$-fuelled LFR self-breeder and to that of an LFR using thorium-based mixed oxide fuels – $(Th,TRU)O_2$. To facilitate high minor actinide consumption rates, core designs accommodate substantial amount of minor actinides in the start-up fuel (4-10%).

Based on the European Lead-Cooled Fast Reactor (ELSY) project [4], the 600 MW_e power level was chosen as a basis for this study, but an up-rated version of an LFR burner (900 MW_e) was also studied. Pin and pellet design parameters are given in Tab. 1.

Table 1: Design parameters of self-breeder and burner concept cores considered in this study. For the self-breeder, number of SAs and linear power correspond to a $(U,Pu)O_2$-fuelled unmoderated core. In the case of the system optimized to burn MAs (“MA incinerator”), these figures refer to a $UZrH_{1.6}$ moderated core. Pin and pellet design parameters of the latter are also chosen for LFRs using thorium-based mixed oxide fuel.

Parameter	Burner	Self-breeder / MA incinerator
Power (MW_e)	600 / 900	600
Pellet outer radius (mm)	3.3	5.0
Clad inner radius (mm)	3.4	5.1
Clad outer radius (mm)	4.55	6.25
Pellet hole radius (mm)	--	-- / 1.5
Pitch-to-diameter ratio (P/D)	1.5	1.5 / 1.6
S/A outer flat-to-flat (cm)	20.10	22.10 / 23.60
Pins per S/A	217	127
Length of upper plenum (cm)	100	100
Length of lower plenum (cm)	10	10
Active pin length (cm)	100	200
Number of sub-assemblies	625	391 / 293
Averaged linear power (kW/m)	11.5 / 17.3	14.4 / 21.0

For the burner core, the concept of a high-leakage, pancake-like core was chosen. Such core configuration is advantageous as it limits the positive coolant reactivity coefficient/void worth by allowing more neutrons to leak out from the core during coolant heat-up/voiding. Active pin length is 100 cm and the core has the same pin and pellet design as the BREST reactor [5].

For the LFR self-breeder, a more compact core geometry is chosen, offering a better neutron economy. Active pin length is 200 cm as proposed for the STAR-LM LFR design [6]. Pin and pellet dimensions are larger than for the LFR burner as dictated by requirements to retain stability of pin column in a lead coolant environment.

Two pin lattices, with pitch-to-diameter ratios of 1.5 and 1.6, are studied for self-breeders. The former is applied in $(U,Pu)O_2$-fuelled system while the latter is used in designs that are optimized to incinerate MAs ("MA incinerators") in start-up cores. There, a 3-mm diameter central hole is also incorporated in the pellet in order to limit peak fuel temperatures. The P/D =1.6 and hollow pellet geometry design options are also chosen for an LFR employing thorium-based mixed oxide fuel. The reason of different P/Ds used is an effort to improve neutron economy and coolant temperature reactivity coefficient in self-breeders employing $(U,Pu)O_2$ fuel.

Average coolant outlet temperature of 753 K and an 80 K axial gradient in the core are based on the aforementioned ELSY design. The average coolant outlet temperature is comfortably below the limit of 870 K, guaranteeing the stability of protective oxide layers on the cladding and structures at nominal operation conditions.

To give an indicative inter-comparison of burn-up performance of all systems, a fuel cycle length of 330 days with 35 days refueling period was tentatively chosen.

A homogeneous introduction of MAs into the reactor cores leads to a significant deterioration of the coolant temperature and Doppler reactivity coefficients. Tailoring of the neutron spectra by including moderators can diminish the spectral gradient, which accompanies coolant heat-up/voiding. The inclusion of moderators also means that more neutrons scatter down to the region of pronounced resonances, which improves the Doppler feedback.

In this study, we have considered incorporation of hydrides as in-core moderators, but their relatively low decomposition temperature (e.g., 1090 K for CaH_2 in a H_2 atmosphere) excludes their use in the fuel directly. Thus, they should be located in dedicated pins within a sub-assembly. Such an approach is currently tested in the Phénix reactor in the frame of the ECRIX experiment [7]. Besides CaH_2, we also investigated BeO, $UZrH_{1.6}$, and $ThZrH_{1.6}$ as moderating materials.

2.2 Computational model

The Monte Carlo code MCB [8] was used in our neutronic and burn-up analyses. The MCB is a versatile code integrating MCNP4C transport with an in-flight calculation of reaction rates and nuclear density evolution. In all simulations, 1-σ statistical deviations in k_{eff} were under 10 pcm. Coolant temperature reactivity coefficients correspond to a change in k_{eff} due to a heat-up of coolant in the active core only. The composition of the actinide vector is that of spent LWR UOX fuel, which has a burn-up of 41 GWd/t_{HM} and is assumed to have undergone 30 years of cooling. MA fraction in the TRU vector is then 18%. Depleted uranium (0.3% ^{235}U) is used in the current study.

Safety analyses were performed with the European Accident Code-2 (EAC-2) [9] and the Computational Fluid Dynamics STAR-CD [10] code. The accidents considered were unprotected

Loss-of-Flow (ULOF) and Loss-of-Heat Sink (ULOHS). During the initial phase of the Loss-of-Flow (LOF) accident, the flow rate is varied according to Eq. 1.

$$\frac{G(t)}{G_0} = \frac{1}{1 + t / t_c} \ , \qquad (1)$$

where $G(t)$ and G_0 are coolant flow rates at time t and t=0, respectively, t_c is equal to 6 s.

3. Results

3.1 Neutronic and burn-up performance

In order to achieve significant consumption of plutonium and minor actinides in burner type of cores, the fertile material (^{238}U) in the fuel should be at least partially replaced. In this study, we chose (Actinide-) AnO_2 – ^{92}Mo CERMET fuel, which is currently being developed at the JRC-ITU in Karlsruhe in the frame of the EUROTRANS project. The volume fraction of ^{92}Mo in the fuel was kept at 50% assuring the fuel fabricability and thermal stability during irradiation. TRU fraction in these fuels should be rather high, 40-50%, in order to reach considerable TRU consumption. Corresponding MA fraction in the fuel is then 7-9%.

The requirement of a high TRU fraction is not imposed in Th-fuelled systems and high consumption can be reached even for modest TRU enrichments of about 30%.

Self-breeder reactors should feature low burn-up reactivity swing, ideally bellow 1 $ between outages, to limit the consequences of (unprotected) reactivity-induced accidents. A requirement of zero breeding gain effectively sets a limit for a maximum Pu fraction in the core fuel to 16-18%, depending on the presence of MAs and particular core configuration.

3.1.1 Systems employing U-based fuels

The neutronic and burn-up characteristics of LFR self-breeder and burner core concepts are summarized in Tab. 2.

Table 2: Neutronic and burn-up parameters of the 600 MW_e LFR self-breeders and burners. Doppler and coolant temperature reactivity feedbacks correspond to the increase of fuel and coolant temperatures by 100 K.

System configuration/ Fuel	Moderator	Nr. of moder. pins per S/A	Nr. of S/As	Actinide mass at BOL (t_{HM})	Averaged TRU enrichm. (%)	Doppler Δk_D (pcm)	Coolant Δk_c (pcm)	Actinide burn-up (%FIMA per year)	Burn-up swing Δk per year ($)
Self-breeder $(U,Pu)O_2$	--	--	391	64.60	16.3	-77	63	0.7	0.0
Self-breeder $(U,TRU)O_2$	$UZrH_{1.6}$	6	391	61.92	22.6	-91	62	0.8	-0.5
MA incinerator $(U,TRU)O_2$	$UZrH_{1.6}$	11	293	41.89	30.4*	-86	58	1.1	-2.8
	BeO	18	391	48.15	27.5	-72	66	1.0	-1.3
Burner AnO_2–^{92}Mo	BeO	19	625	17.07	50.0	-50	38	2.7	-11.7

* MA fraction in the TRU vector was increased to 20%

A superior moderating effect provided by hydrides is clearly manifested for $(U,TRU)O_2$-fuelled MA incinerating self-breeder cores. Use of hydrides facilitates both better coolant temperature and Doppler reactivity coefficients, the latter remaining about 50% higher than the coolant temperature reactivity feedback. The hydrides increase Doppler by moderating neutrons into the range of large actinide resonances and decrease coolant temperature feedback by diminishing the spectral gradient during coolant heat-up. On the other hand, the BeO moderated core features a lower burn-up reactivity swing than its $UZrH_{1.6}$ moderated counterpart, thanks to a better breeding and larger actinide mass at BOL.

The LFR burner using inert matrix fuel has both lower Doppler and coolant temperature reactivity feedbacks. The former is due to the heavy presence of MAs in the burner fuel (9%), while the latter can be ascribed to the choice of high-leakage, pancake-like geometry.

In the $(U,Pu)O_2$-fuelled self-breeder core configuration, the Doppler still remains higher than the coolant temperature coefficient even though no moderators were used. Both reactivity swing and breeding become worse when 4% of minor actinides are admixed into the self-breeder fuel. In this case, however, six moderator pins per sub-assembly were used to improve reactivity coefficients.

The relatively large TRU masses can be considered as “parking” larger amounts of TRUs into the reactor cores.

Table 3: Amount of annually consumed transuranics in LFR self-breeders and burners. The figures correspond to the start-up cycle. In the spent fuel, all ^{242}Cm was assumed to decay to ^{238}Pu.

System	Power (MW_e)	Averaged TRU enrichment (%)	Pu transmuted (kg/y)	MA transmuted (kg/y)
Self-breeder $(U,Pu)O_2$	600	16.3	-47	-31
Self-breeder $(U,TRU)O_2$	600	22.6	-19	71
MA incinerator $(U,TRU)O_2$ with $UZrH_{1.6}$ moderator	600	30.4	68	97
Burner $(U,TRU)O_2$–^{92}Mo with BeO moderator	600	50.0	215	88
	900		315	134

Our calculations also indicate that in the start-up mode an LFR self-breeder burns nearly as many MAs as a dedicated LFR burner of the same power (Tab. 3). In the optimized 600 MW_e MA incinerator, the consumption rate of MAs is as high as 97 kg per year. The burner core also consumes additionally a large amount of plutonium, which is in contrast to a self-breeder that compensates its burned plutonium by newly bred one. MA incinerating cores also consume some plutonium at the start-up cycles, but provide an advantage of lower actinide inventories and higher burn-up than self-breeder cores.

All in all, TRU consumption in an up-rated 900 MW_e LFR equals to 449 kg, which corresponds to an annual TRU production in a 1.6 GW_e EPR. Note that due to the self-production of plutonium the destruction rate of MAs in the fuel is in fact higher than what would correspond to their share in the initial load.

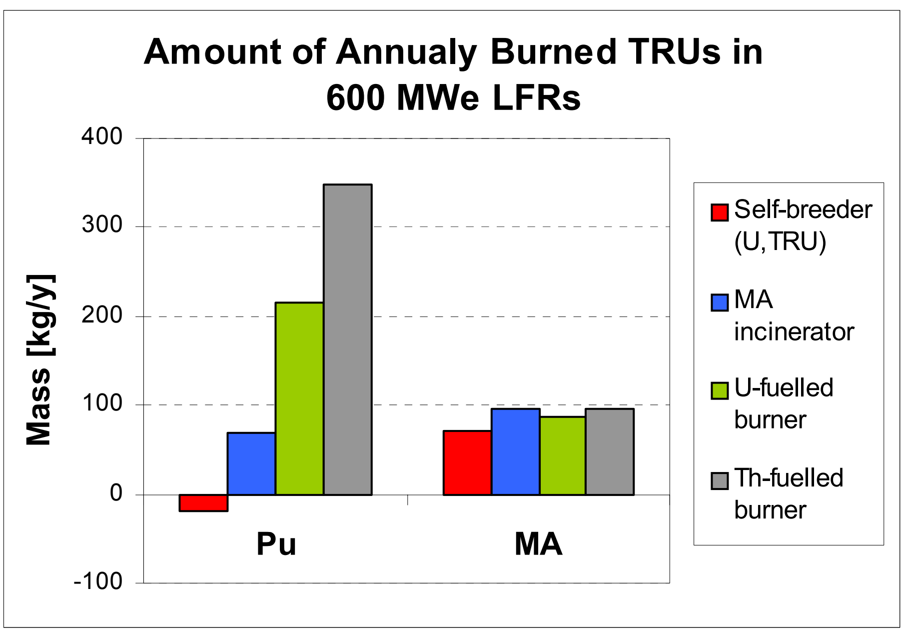
3.1.2 Systems employing Th-based fuels

Another type of burner/breeder is an LFR using thorium-based mixed oxide fuels – $(Th,TRU)O_2$. The plutonium and MA burning capability of such a system is very good since there is very limited self-generation of transuranics from thorium. These systems also breed ^{233}U, which could be used for example as fuel in LWRs. These aspects favor the sustainability. Two types of moderator materials were investigated in this study, $ThZrH_{1.6}$ and CaH_2 (Tab. 4).

Table 4: Neutronic and burn-up characteristics of LFR cores with $(Th,TRU)O_2$ fuel. Doppler and coolant temperature reactivity feedbacks correspond to the increase of fuel and coolant temperatures by 100 K. Power of both systems is 600 MW_e. All ^{242}Cm was assumed to decay to ^{238}Pu in the spent fuel. The fuel cycle performance values correspond to the 1st year of the start-up mode.

Moderator	$ThZrH_{1.6}$	CaH_2
Average TRU fraction in the fuel (%)	30	29.5
Number of moderator pins per S/A	16	16
Number of S/As	263	263
m_{act} at BOL (t_{HM})	36.29	36.29
Doppler Δk (pcm)	-113	-127
Coolant Δk (pcm)	45	44
Burn-up swing during 1st year ($)	-0.4	0.0
Actinide burn-up (%FIMA/y)	1.3	1.3
TRU burn-up (%FIMA/y)	4.0	4.0
Pu transmuted (kg/y)	348	347
MA transmuted (kg/y)	96	94
^{233}U produced (kg/y)	246	256

Figure 1: Amount of annually consumed transuranics in 600 MW_e LFRs employing uranium- and thorium-based fuels. The figures correspond to the start-up cycle. In the spent fuel, all ^{242}Cm was assumed to decay to ^{238}Pu.



Th-fuelled core with CaH_2 consume about 348 kg of plutonium, 96 kg of MAs and produce 246 kg of ^{233}U. The plutonium consumption is significantly higher than in equal powered U-fuelled LFR burner (Fig. 1). Hydride moderators again effectively reduce the spectral hardening during coolant voiding/heat-up and increase neutron scattering into the region of large resonances. The CaH_2 moderated system features somewhat lower burn-up reactivity swing due to the better breeding. However, the swing remains under 1 $ per year for both Th-based systems. In contrast to this low burn-up swing, the uranium-based burner with inert ^{92}Mo matrix fuel has a high burn-up swing of 11.7 $/year.

3.2 Safety performance

Regarding safety, lead has several advantages over other liquid metal coolants. The boiling point is 2023 K, which makes the risk for coolant boiling and subsequent large core voiding rather hypothetical. Also, the volumetric heat capacity of lead (ρc_p) is high (e.g., 1.4 times larger than that of sodium) and lead features a low chemical activity with water and water vapor excluding the possibility for fires or explosions. Lead has a melting point of 601 K, which may require the implementation of redundant electrical heaters to avoid problems of freezing and blockages in fresh cores.

Corrosion resistance of structural materials (ferritic/martensitic steels) up to 820 K was mastered in Russia through controlling oxygen content in lead. FeAl surface coating (GESA) enhances corrosion resistance of the material further, at least up to 870 K, and similar temperatures seem to be possible also for ODS steels. However, in the future, higher coolant outlet temperatures may be allowable if innovative structural materials (e.g., SiC/SiC) prove to perform satisfactorily. Nowadays, the coolant operational interval of LFRs is effectively limited to about 680-860/870 K.

Figure 2: Temperature evolution during a ULOF accident for three LFR cores – (U, TRU)O_2 fuelled 600 MW_e MA incinerating self-breeder employing $UZrH_{1.6}$ moderator pins and 600 & 900 MW_e burner cores – no feedbacks are considered. With the multi-channel thermal hydraulics / point kinetics code EAC-2 the power decreased to 80% of the nominal power.

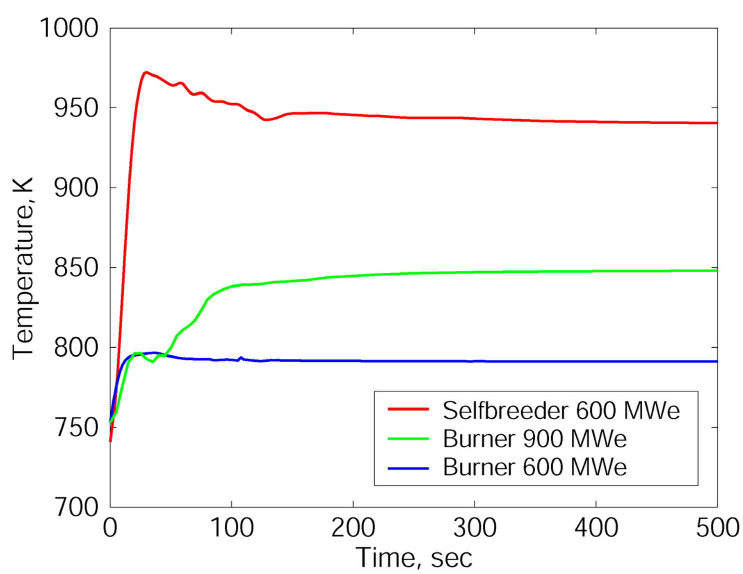
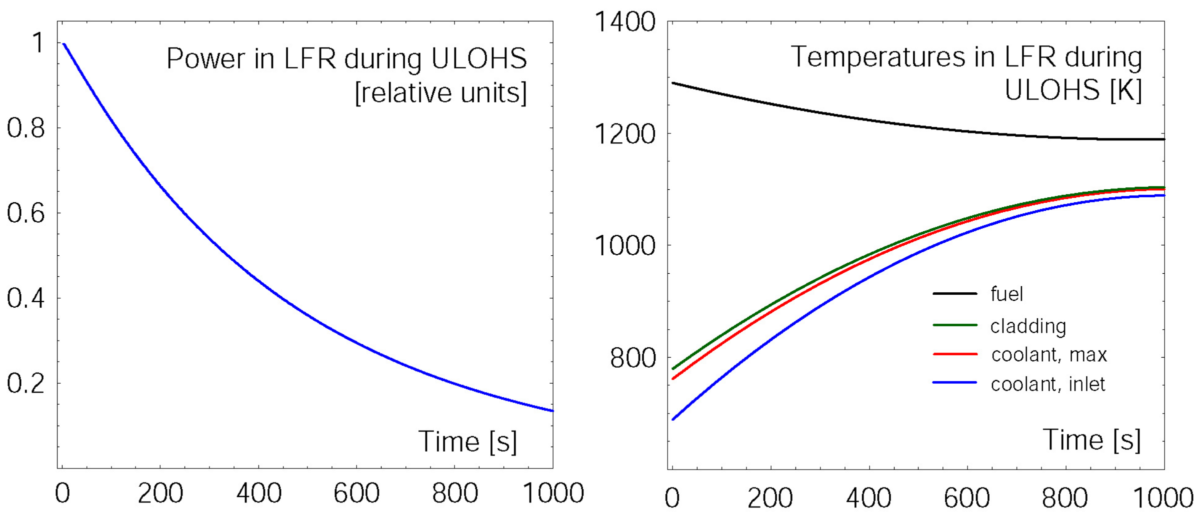


Fig. 2 shows the behavior of a 600 MW_e LFR MA incinerating self-breeder (2 m core height) and 600 MW_e & 900 MW_e burners (1 m core height) in an unprotected Loss-of-Flow accident. In the simulations, the inlet coolant temperature was kept constant at 673 K. Thanks to the very good natural circulation behavior of lead, all systems comfortably stay below the limit for fast creep of the reactor vessel (~ 1170 K). The 1170 K figure corresponds to SS-316 steels and an 11m tall vessel. Higher values have been quoted for NIMONIC alloys (1250 K) and probably also ODS steels have a higher fast creep limit. The MA incinerator surpasses the corrosion limit of 870 K, but this seems to be acceptable for longer time periods. The self-breeder core outlet temperature stabilizes at 940 K, whereas for the (U,TRU)O_2-fuelled burner of 600 MW_e at 791 K and for the 900 MW_e burner at 848 K.

Figure 3: Unprotected Loss-of-Heat Sink accident in a 600 MW_e (U, TRU)O_2 MA incinerating self-breeder LFR employing $UZrH_{1.6}$ moderator pins. EAC-2 was used together with STAR-CD that calculated the inlet temperature rise. The lead outlet temperature at 1000 s is 1070 K.



Power and temperatures during an unprotected Loss-of-Heat Sink accident in an LFR (U,TRU)O_2 MA incinerator with $UZrH_{1.6}$ moderator are depicted in Fig. 3. During the accident the pumps are assumed to function normally and heat exchangers cease to remove the heat in 20 seconds. As can be observed, the power slowly decreases to about 15% after 1000 seconds. Temperatures of the coolant and structure then rise to about 1100 K. In EAC-2 calculation, no lower grid-plate radial expansion could be considered and we infer that this feedback would get the power down to a decay heat level during 1000 seconds.

In unprotected reactivity accidents, which for large reactivity insertion could eventually lead to pin failures, a lead coolant facilitates fuel sweep-out due to its large inertia and a low pressurization during fuel-coolant interactions. This phenomenon has actually been observed in one of the Russian Pb/Bi cooled sub-marine reactors [11].

4. Conclusions

In this study, we compared neutronic and safety performance of LFR self-breeders and burners fuelled by uranium- and thorium-based MOX and uranium-based CERMET fuels, respectively. The core designs were optimized to maximize minor actinide consumption rates in the start-up cores.

We demonstrated that LFRs can be used both as breeders and burners of transuranics from spent LWR UOX fuel and that minor actinides are incinerated in self-breeder cores nearly as effectively as in dedicated critical burners. Optimized 600 MW_e self-breeder start-up cores can annually burn up to 100 kg MAs, which corresponds to an annual MA production in about two EPR reactors. Burner reactors feature both very high plutonium and minor actinide consumption rates, but a rapid burning of plutonium would not be a favored option with regard to sustainability. The incineration performance of Th-fuelled systems is superior to those utilizing U-fuel both what concerns consumption of plutonium and minor actinides, but an implementation of Th-fuels will require a successful development of thorium reprocessing technologies. Also, proliferation issues with regard to ^{233}U need to be addressed.

The safety coefficients of self-breeders and burners are degraded due to the hardening of the neutron spectrum by minor actinides homogeneously admixed in the core fuel. Therefore, in-core moderating pins (BeO, CaH_2, $UZrH_{1.6}$ and $ThZrH_{1.6}$) were applied. Hydrides appeared to be the most effective, but their susceptibility to thermal dissociation at elevated/accidental temperatures has to be coped with by some innovative means. This includes the encapsulation of pellets or coating of internal pin surfaces by tungsten or molybdenum, which is currently being investigated.

LFRs showed to be robust regarding the behavior in severe accidents (unprotected Loss-of-Flow, unprotected Loss-of-Heat Sink) and the creep temperature limits of structural materials are not violated. This is due to a good natural circulation behavior of the lead coolant and its high boiling point. Concerning core-melt accidents, lead has a similar density as coolant that favors mixing.

In the scenario of expanding nuclear power, we may therefore envisage having self-breeders both utilizing efficiently uranium and plutonium resources and consuming MAs from the whole reactor park. For this purpose, Th-fuelled systems could also be used if technology has matured enough. On the other hand, dedicated TRU burners should be introduced only if *both* plutonium and minor actinides are to be transmuted fast. We showed that depending on the core load composition the same self-breeder reactor could be used for breeding only or breeding combined with burning of MAs from LWR spent fuel.

For the long-term sustainability we will eventually also need breeders with a considerable breeding ratio. The more compact sodium-cooled reactor (SFR) may have an advantage in this respect.

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