# SAFETY ISSUES AND SAFETY INDICATORS FOR ACCELERATOR DRIVEN TRANSMUTERS WITH DEDICATED OXIDE FUELS

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## Abstract

In order to exploit the full potential of accelerator driven systems (ADSs) for transmuting and incinerating Minor Actinides (MAs), innovative fuels have to be developed. These so-called dedicated fuels are characterized by a high MA content and by the lack of classical fertile materials as U238. Safety investigations of subcritical cores with these advanced dedicated fuels reveal some safety problems, which are discussed in this paper and put into a new perspective. Characteristically, the subcriticality of the core has to balance large positive void and clad reactivity worth potentials and a negligible prompt negative fuel temperature feedback (Doppler). A safety gain in a Pb/Bi cooled ADT (accelerator driven transmuter) is the high boiling point of the coolant. A conceptual problem for assessing the safety potential appears in analyses of large ADTs when the void and clad worths might be higher than the subcriticality margin. Many safety analyses of critical sodium-cooled fast reactors with a positive void worth were performed in the past, giving a guide-line on the size of void that could be handled under transient and accident conditions. Having in mind this experience, an approach is discussed to estimate which positive reactivity potentials might be acceptable in subcritical accelerator driven transmuters. The paper concentrates on the issue of severe transients, driven by internal reactivity potentials. Compliance with the criterion given in the paper does not exclude core-melt accidents, but should exclude rapid accident developments and potential cliff-edge effect behavior. The dependency of the void worth on the ADT size and the calculational uncertainties are discussed. In addition the influence of some kinetics parameters is discussed.

## Introduction

Fuels in a subcritical ADS designed to transmute minor actinides (MAs) and plutonium (Pu) are called ‘dedicated’ fuels, as their composition, their chemical state, and fuel form are optimized for this special purpose. European R&D for ADS fuel /1/ mainly concentrates on oxide fuel forms such as inert matrix mixed oxide or composites in which the oxide actinide phase is mixed with an oxide (CERCER) or a metal matrix (CERMET) /2/. The fuel form (pellet or e.g. VIPAC pin) does not have a direct impact on the issues discussed here, but will be of relevance for phenomena, which may be encountered under severe accident conditions with clad melting and pin disruption. The omission of uranium from the fuel has a significant impact on the fuel properties in various aspects /3/:

1. A dedicated fuel consisting of Am and Cm will have a lower melting point and lower thermal conductivity than $(U,Pu)O_2$ fuel. To cope with the mentioned deterioration of thermal-physical conditions, mainly composites like CERCER or CERMET will be the choice for transmuter fuels /4/. In addition, actinide redistribution during irradiation (e.g. $AmO_2$), radiation impact on the matrix, increased cladding corrosion, higher fission gas release and pressure build-up due to helium formation (resulting from alpha-decay) have to be taken into account. Helium production could have a decisive influence on pin failure mechanisms and is a potential source for initiating a core-voiding transient.

2. The utilization of these fuels with high Minor Actinide (MA) content will lead to a deterioration of the safety parameters of the core. Besides the almost complete absence of negative Doppler feedback and the minimization of $\beta$-effective, the reactivity potentials of the steel (clad), of the coolant void and of the fuel are significant in these cores. Operation of such reactors seems only feasible in the subcritical mode, as realized in an ADT. Another typical feature, which significantly increases the safety potential, is the high boiling point of the coolant for the heavy liquid metal (HLM) cooled concept.

In order to assess the safety impact of the reactivity potentials one has to take into account opposing and competing safety parameters:

- the subcriticality of the core,
- the high boiling point of the coolant,
- the clad worth potential,
- the coolant void potential,
- the He-release potential,
- the small negative prompt Doppler feedback,
- axial/radial thermal structural expansion, and
- the reduced kinetics parameters.

The impact of the fuel types on the severe accident phenomenology has been discussed before /4/, and it would mainly be related to the fuel reactivity potential. The current paper instead, concentrates on the earlier phases of the potential transients and on how the large reactivity of coolant void and clad removal, versus the subcriticality and the high boiling point of the coolant, could be reconciled in a reasonable safety strategy. The key issue is how to handle the safety issue, when the core void becomes larger than the subcriticality margin. Should such cores and fuels automatically be excluded from the safety point of view? Or could such conditions be tolerated to some extent?

This paper means to be a starting point for the discussion on these safety issues. For the ADT designs to be investigated in the EUROTRANS 6th FP Project of the EU /5/, these issues will be of extreme importance. A discussion of these questions has not taken place up to now e.g. for the PDS-XADS /6/ (5th FP of the EU), as the small MOX fuelled ADSs that were analyzed had very favorable safety parameters i.e.: an overall negative core void, and a large negative Doppler. Moreover, for this design a very benign behavior is predicted, even under severe core melt conditions /7/.

**Reactivity Potentials**

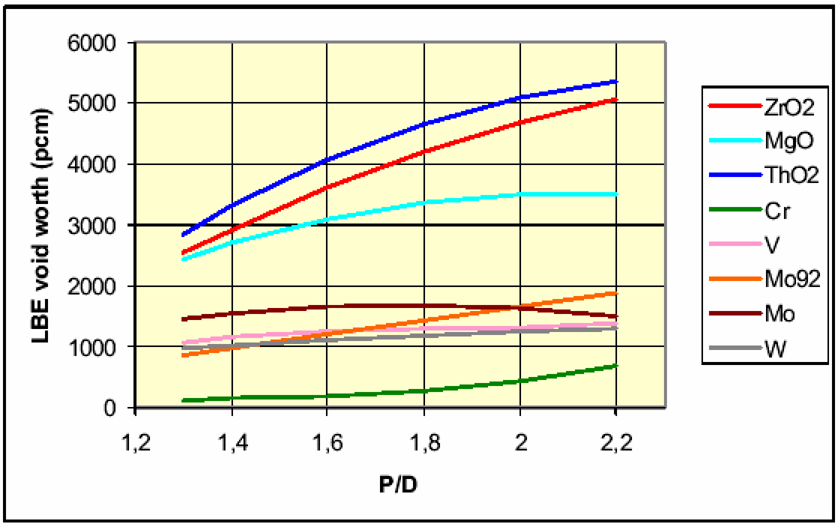
Basically in the early accident phases two reactivity potentials are decisive for reactivity changes: the coolant density/void worth and the clad worth potentials. In later accident phases, after fuel mobilization, the fuel worth will play the decisive role by its greater magnitude, compared to all other reactivity potentials. It should be noted that the activation of the individual potentials might depend on the accident initiator. Finally, it should not be forgotten, that feedback effects are reduced in subcritical systems with external source, at least as long as the reactor operates far away from the criticality limit /8/.

***Void-Worth Potential***

The key question is, whether the core void or the maximum positive void, have to be smaller than the subcriticality margin of the ADT. This problem became obvious after the analyses made for the 800 MWth ADT, analyses conducted in the course of the FUTURE project /2/. In Figure 1, typical void values for various fuels and core parameters in a simplified ADT design are given. It should be kept in mind that the subcriticality limit chosen for these cores is 3000 pcm (k-effective = 0.97).

For p/d ratios larger than 1.6 (with a 5 mm pin diameter and a Pu/Am ratio of 40:60) the CERCER fuel void is generally larger than the subcriticality limit. This poses some restrictions on the design options. For CERMETS the void worth is lower because of the more neutronically transparent fuel and because this fuels allows for a smaller core size at same power level. But there do exist drawbacks: chromium for instance must be excluded because of fabrication reasons, and another candidate, tungsten, is a too strong neutron absorber. The only metallic matrix currently under closer investigation is molibdenum-92.

Figure 1. **Comparative study of void worth for single zone ADT cores and various fuels calculated for the FUTURE program /2/** (Figure taken from /4/).

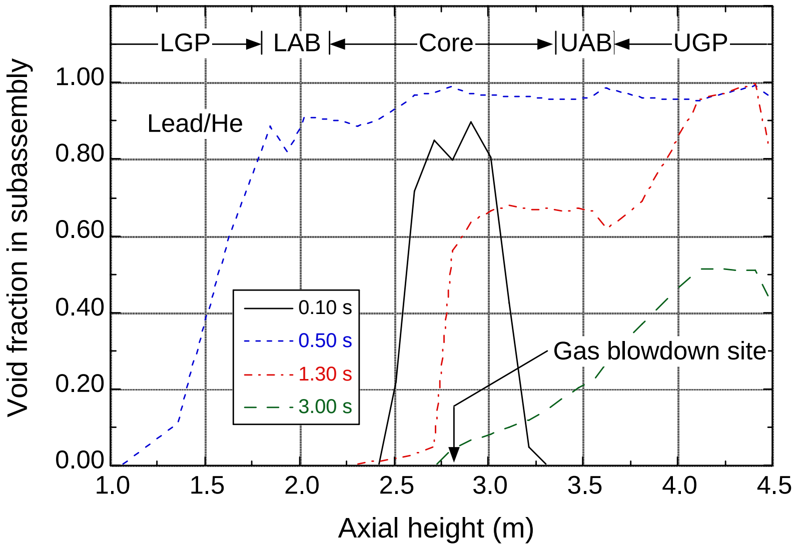



Voiding in the core could happen via massive pin failures and the release of fission gas and helium from the plena of the fuel pins. Another source of voiding could be coolant boiling, but it could only occur in the later phases of a severe accident /9/, and they are of little importance in the current discussion. Other causes for voiding might be e.g. the ingress of oil from secondary side. Furthermore, besides the voiding under pin-breach conditions, there are other aspects of the problem that have to be taken into account, above all the strong positive feedback caused by coolant heat-up during a transient.

As mentioned, a compensating prompt Doppler feedback is missing, and furthermore the axial expansion behaviour (dominated by either the fuel, or the clad, under gap closure conditions) is not well known for these innovative fuels. The radial expansion feedback from bowing, and possibly grid plate expansion, is not discussed here either, since the detailed design, which would be necessary to assess these effects, is not yet available.

Both overpower and undercooling transients may trigger pin failures. However, the scenario and consequences might be different: for overpower transients gas release will occur through breached cladding, for undercooling transients the clad could be massively removed leading to unclad pin-stubs. Nevertheless, the void-worth potential is usually activated first. Depending on the position of the failure, the maximum void worth may be the key parameter and not the full core-void. In Figure 2 the simulation of a helium-blow-down process and core voiding after pin failure in a Pb/Bi environment is simulated with the SIMMER-III code /10, 11/.

Figure 2. **Helium gas blow-down simulation with SIMMER-III**




The ideal operating condition for an ADT would be a subcriticality margin larger than the available reactivity potentials, under all conditions. This might impose strong restrictions on reactor size and design, on the fuel characteristics, and on the accelerator performance. Moreover, the subcriticality limit has to take into account several boundary conditions stemming from the burn-up swing and the shape of the power distribution. Looking at this issue from a critical reactor point of view, the outlined 'requirement' is very limiting, as for all sodium cooled fast reactors of a certain power class, a positive void and clad removal reactivity worth do exist and are commonly accepted.

In Table 1, void values, Doppler constants, and kinetic parameters for several critical reactors are displayed /12/. The typical scenario for e.g. an unprotected loss of flow (ULOF) in a critical sodium cooled fast reactor, would be that several competing reactivity effects limit the reactivity addition coming from the reduction of the coolant density and the voiding. The axial fuel expansion and the Doppler feedback usually balance the sodium density effect.

Sodium boiling starts in the high power regions of the core at the upper core end, successively, the boiling front proceeds downwards. This phenomenon triggers a sharp power increase, which is anyway limited by axial fuel expansion and the Doppler feedback. Furthermore, the reactivity potential associated to this voiding event is not released all at once, since large wet regions in the core are still present. When these void potentials can be activated, fuel mobility has already been achieved, and since the dispersing fuel has a much higher reactivity worth than the coolant, it brings the excursion to an end. In conclusion, though a void potential of approximately 5-7 $ exists in most of the reactors mentioned in Tab.1, this void reactivity cannot be released suddenly and is well compensated by the negative reactivity contributions of other effects. The incoherencies of the acting processes play a significant role in mitigating the positive reactivity potentials. These facts are well accepted and proven by analyses /16, 22, 23, 24/.

It should be noted however, that the scenario described above is a characteristic one, which does not mean it includes all possible evolution patterns. In reactors with special void measures, as the BN-600, or in reactors with an extended pump coast-down, as e.g. the SPX-1, other paths can be followed in the transient development (e.g. impact of Doppler can play a different role). In the EFR for instance, the structural feedback will play the most significant role (e.g. control rod drive line expansion), and Russian studies have also demonstrated the importance of radial core expansion /13/. Nevertheless the above scenario is helpful to describe the potential effects.

Table 1. **Typical reactivity potentials, Doppler constants and kinetic parameters for various critical sodium cooled fast reactors /12, 14/.**

The data for the Pb-cooled DEDI-1 reactor is taken from a study on dedicated critical cores /15/.

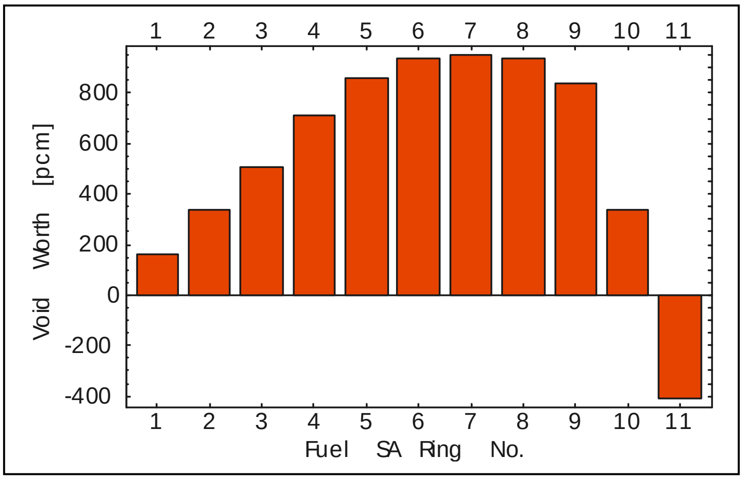
| | | **Monju** | **SNR300** | **CAPRA 4/94** | **EFR CD/91** | **SPX-1** | **CAPRA -2000** | **DEDI-1** |
|---|---|---|---|---|---|---|---|---|
| **Power** | **MWth** | 714 | 760 | 3600 | 3600 | 3047 | 3600 | 150 |
| Coolant worth | pcm | 802 | 770 | 1560 | 2100 | 1990 | 2322 | 1687 |
| Doppler-wet | pcm | -670 | -600 | -455 | -650 | -860 | -723 | 260 |
| (Void/Doppler-wet) | | -1.2 | -1.3 | -3.4 | -3.2 | -2.3 | -3.2 | -6.5 |
| Beta-eff | pcm | 360 | 347 | 324 | 362 | 357 | 345 | 126 |
| Neutron generation time | $10^{-7}$ s | 4.4 | 4.2 | 8.4 | 4.2 | 4.2 | 4.2 | 2.8 |

The important message that can be drawn from Table 1 is that for both the small and the large cores several analyses have demonstrated the safety case even for severe core disruptive accident conditions. In all these cores the ratio of void to Doppler is less than or about three. Only for the lead cooled DEDI-1 core with MA fuel, severe safety problems could be identified. This discussion focuses on the core-void. However maximum positive void could also be taken into account as the relevant measure. A typical radial void distribution in an ADT (however, not representing the maximum positive void) is given in Figure 3.

***Clad/Steel-Worth Potential***

As describer earlier, the clad/steel worth potential could be activated during undercooling transients. While in sodium cooled reactors coolant boiling precedes any clad motion, in a Pb/Bi cooled reactor, the boiling point is at 1943 K, any significant heat up of the coolant could lead to steel melting, before boiling can occur. Consequently, the steel will be dragged away and buoyed by the approximately 30% heavier Pb/Bi. Successively the molten core could freeze out on the colder surfaces of the structures of the downstream regions. The location for the freeze-out affects both the subsequent evolution of the accident, and the core decay heat removal. Essentially, this would represent the scenario without accounting for fission gas and helium release.

Figure 3. **Void worth of individual fuel SA rings for the FUTURE-$ZrO_2$-matrix fuel ADT /2/.**




Under the conditions of a high fission gas and helium inventory in the core, in the reflector and in the plenum regions, and a concurrent damage in the clad, these gases would be immediately blown out. Clad failure might occur at much lower temperatures than melting, under the load conditions of the scenario.

Steel reactivity worth values are usually not available in literature. The main reason is that this parameter does not play 'the' decisive role in critical sodium cooled fast reactors, which are the main reference for these studies. Only for low-void cores, as e.g. the heterogeneous CRBR /16/ clad steel motion precedes fuel motion (no co-disruption), and the steel reactivity plays an important role. However, it is reasonable to infer that the steel worth is a non-negligible quantity for an ADT core, though coolant voiding would generally be more relevant, especially in view of the activation sequence of the reactivity potentials. Under the condition of steel removal, the un-clad fuel stubs would disintegrate and become mobile. At this stage then, the higher reactivity worth of the fuel will dominate the reactivity feedback.

***Fuel Worth Potential***

Fuel has the highest reactivity potential, if activated it dominates over all the other processes, both in case of a positive reactivity addition (e.g. fuel compaction), or of a negative reactivity contribution (e.g. fuel dispersion or expansion). Likewise, the fuel reactivity potential plays a decisive role for the eventual occurrence of recriticalities, in the event of core disruptive accidents.

ADTs contain multiple critical masses; any fuel agglomeration, either upstream, or downstream (depending on the actual fuel and coolant densities and temperatures), could as a result overcome the designed subcriticality of the core. Therefore, to limit the influence for at least some accident classes, one should restrict the bundle size, especially to counteract the effects of blockage accidents, and limit the fuel amount per bundle. Under Pb/Bi cooling conditions, pin disruption will lead to a release of fuel pellet chunks and/or particles into the coolant channel.

No sound analyses have been performed for such scenarios. It is currently unknown how the fuel will redistribute upwards and within the vessel. The often-quoted 'fuel floating theory' seems to be more an expression of unspecified hope than reality. Another scenario to be investigated is the pressure driven fuel stack compaction by plenum gases. The role of helium, its release and the timing of release, the fuel dispersion potential under fuel heating conditions etc. are at the moment not known, and significant theoretical developments and experimental evidence are needed to understand these phenomena. The impact of the late accident phases on the fuel behavior and related problem, especially for the composite fuels CERCER and CERMET, is discussed in /9, 17/.

**Doppler and Axial Expansion Feedbacks**

The Doppler feedback and the axial expansion of the fuel are regulative measures to stabilize the power of the core. In normal operation conditions, small feedback effects are advantageous, and consequently the accelerator would only have to balance long time effects e.g.: burn-up, or to handle the power load requirements. Anyway, feedback effects will be damped as long as a significant subcriticality margin exists. However, a stabilizing negative feedback against the strong coolant density effect might be helpful under certain perturbations and transients.

Since the Doppler is rather small, the axial fuel expansion and radial structural expansion effects will become important. Given the current status of knowledge on: fuels and their interaction with cladding, helium behaviour, dependency on burn-up and transient conditions, and structural behaviour of pins and hexcans, it is at present not possible to assess the structural effects properly. For severe transients leading to core disruption, the small magnitude of the Doppler effect poses a real problem, since, without this prompt negative feedback, only core disassembling could stop any severe power excursion that might occur. Ideas to increase the Doppler, i.e. by inserting special resonance absorbing materials (tungsten) into the core are not very helpful, since they tend to separate from the fuel and become ineffective under the melting conditions of a severe transient.

**Kinetic Quantities**

As can be seen in Tab. 2, $\beta$-effective is small for all MA loaded cores. Under the condition of transients and/or accidents, $\beta$-effective could play a role when the criticality limit is approached and eventually exceeded, e.g. by fuel compaction and a recriticality scenario. In such a severe transient, its small value would lead to an increased accident energetics.

Another important parameter for the transient behaviour is the prompt neutron generation time $\Lambda$. It depends on the fuel/matrix and on the p/d ratio of the reactor /4/. If compared to the values of Tab. 1 for critical fast reactors, no significant differences can be noticed. However, in case of a core disruption and/or fuel melting, the p/d ratio definition loses its meaning. As a matter of fact, a separation of the fuel from the matrix, or a redistribution of the fuel and of the clad steel, may actually lead to a drastic reduction of the neutron generation time as shown in /18/. Furthermore, given the small Doppler of these cores, the influence of neutron generation time on the energy release during a severe accident becomes important, enhancing dramatically the energetics of any excursion /19, 20/. The high boiling HLM coolant might however guarantee some mixing within the disrupted fuel configuration, and therefore prevent the described drastic reduction of the neutron generation time.

**A Recommendation on Treating the Reactivity Potentials in Subcritical Systems**

In the FUTURE project of the 5th FP of the EU an 800 MWth ADT is analyzed with the purpose of evaluating and classifying the behaviour of various innovative fuels. Three main fuels met the requirements of the first screening: two CERCER fuels with a $ZrO_2$, or an MgO matrix, and a CERMET fuel with a Mo-92 matrix. In Tab. 2 the safety related data of these fuels is reported.

The void worth strongly depends on the pin diameter d and the pitch/diameter ratio. In Tab. 2 the values are given for a p/d=1.6 and a pin diameter D= 0.6 cm. The data reported here can be compared to the values given for the critical reactors in Tab. 1. As mentioned before, for sodium cooled critical fast reactors severe accident calculations have been performed, and a successful safety case has been demonstrated. The attention is drawn to the ratio of the void-worth/Doppler, which is about minus three in the large reactor cases. As can be observed, the clad worth values are also higher than the subcriticality margin.

Table 2. **Fuels investigated within the FUTURE project** (taken from /2, 4/).

| **Fuel Matrix** | | **CERCER $ZrO_2$** | **CERCER MgO** | **CERMET Mo-92** |
|---|---|---|---|---|
| Coolant Worth | pcm | 6235 | 4840 | 3548 |
| Clad Worth | pcm | 3497 | 3265 | 3076 |
| Subcriticality margin | pcm | -3000 | -3000 | -3000 |
| Doppler-wet | pcm | 7 | -3 | -34 |
| SI= Void/subcriti-cality margin | | -2.1 | -1.6 | -1.2 |
| Beta-eff | pcm | 190 | 182 | 198 |
| Neutron generation time | $10^{-07}$ s | 5.9 | 4.4 | 3.8 |

The idea is to create a safety indicator (SI) based on the subcriticality level and on the Doppler coefficient (fuel expansion could also be integrated), including the positive reactivity potentials of the void and clad-worth (in pcm):

$$SI \equiv \frac{(\text{core void } + \theta * \text{core clad worth})}{(\text{subcriticality } + \text{ Doppler constant})} \approx -3, \text{ where } \theta \leq 1 \text{ is the effectiveness factor.}$$

If SI is in the range of minus three, or even more negative similarly to critical reactors, one could possibly accept the suggested core design. For the SI values in Tab. 2, the θ factor has been set to zero; firstly to compare these data with the values of Table 1 coherently, and secondly, because of the dominance of void over clad relocation effects.

It is clear that the SI index cannot replace more extended analyses, but it could serve as a starting point for the safety assessment, not forgetting that this parameter evidently depends on fuel burn-up. At least, cores and fuels complying with the SI limit might not be discarded immediately from the discussion. The idea promoted here is based on experience and it is not yet a clear-cut criterion; it definitely needs further discussion, testing and analysis to define the limits more clearly.

The given criterion focuses on the issue of severe transients with the potential of core damage and the exclusion of cliff-edge effects. Compliance with the criterion does not exclude core-melt accidents. An example for a violation of the above 'SI rule' is given in /3/ for a 1200 MWth ADT. The subcriticality margin in this case was only 2000 pcm, with an SI close to four. Indeed the ADT had a potential to run into severe accidents. Currently the ADTs listed in Tab. 2 are investigated under various transient conditions /7, 21/. The results could serve as a test for the proposed safety index. Results both for the high void $ZrO_2$ and the MgO core of the FUTURE Program suggest a much milder behaviour e.g. for the ULOF transient than experienced with the 1200 MWth ADT. Clad temperatures in the ULOF case stay below 1300K.

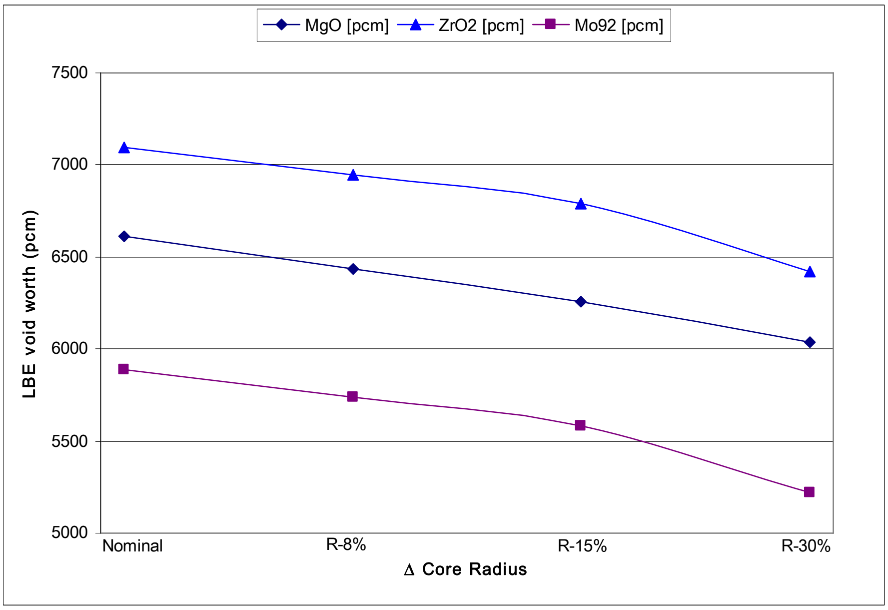
**Void Worth Dependency on Power/Core Size**

Several calculations were performed assuming a full voiding of the active part of the core, as if a large bubble of gas were to form there (e.g. after a major clad failure), leaving the Pb/Bi coolant in place in the reflectors. The likelihood of this scenario is probably not very strong; however its investigation gives important insights on the behavior patterns of the ADT.

The effect on void reactivity worth of smaller cores was studied thoroughly keeping the nominal condition subcriticality margin equal to about 3000pcm and keeping linear power constant, and therefore comparable fuel temperatures (all calculations were performed with SIMMER-III).

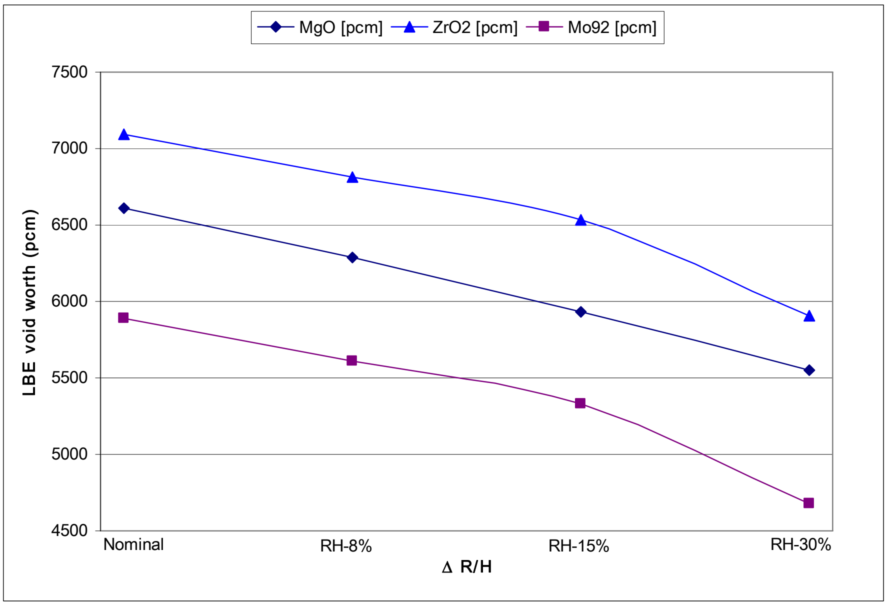
Figure 4 summarizes the effects of a smaller core radius for the three candidate fuels. Since the ADT core is subdivided in three radial regions, the reduction of the core radius was devised to maintain the number of subassemblies of each zone proportional to the initial core arrangement, hence keeping the ratios constant. As a result of this, the core radius was reduced by 8%, 15% and 30%, preserving the central hexagonal symmetry also. The maximum void worth reduction was of about 670 pcm for the $ZrO_2$ and the Mo92 cores, and about 570 pcm for the MgO core. In all cases however, the subcriticality margin is overcome by the total void reactivity worth.

Figure 4. **Void worth of the three candidate cores as a function of core radius.**



Finally, Figure 5 summarizes the influence of a smaller core volume. In this case the radius over height ratio was kept constant; therefore the radius was reduced again by 8%, 15% and 30% and the height accordingly by ~6%, ~10%, and ~18%. As expected, the reduction of the void worth is more significant than in the previous cases and above 1000pcm. Nonetheless this achievement is not enough to guarantee that the core will remain subcritical. Note that the maximum positive void is significantly larger – on the other side no voiding was assumed in the reflectors.

Figure 5. **Void worth of the three candidate cores as a function of core radius/height ratio.**




These analyses show that indeed a reduction of the core dimensions improves the void worth making it less positive; however additional efforts seem to be necessary to reduce the void potential below the assumed subcriticality margin in the chosen design. Measures proposed for fast reactor critical cores, as the positioning of absorbers in the axial core periphery could be discussed. In any case all these results point out the need for a safety criterion like the suggested Safety Indicator.

**Sensitivity of Void Worth Calculations**

During the studies that were conducted on the FUTURE cores, a few sensitive points were identified, which have an influence on the void calculation. The utilized nuclear data basis may be a cause for large deviations both in criticality and void-worth. Differences in the void worth range up to 2500pcm. The nuclear data files compared for this exercise were: JEF 2.2, JEFF 3.0, FZKINR, ENDF 6.8 and JENDL 3.3 (Cm-245 taken from ENDF 6.8). The correspondence between the deterministic and stochastic methods is usually good, ranging around 100pcm. The influence of the heterogeneity treatment seems not to be decisive with deviations less than 100pcm. A strong influence can be caused by the equation of state used for LBE. Due to the very high absolute value of the void worth small differences in the equation of state can lead to significant effects.

## Conclusions

The investigations performed on ADTs with various fuels and Pb/Bi cooling within the FUTURE 5th FP of the EU, made it obvious that some of the cores of interest have a strong positive void reactivity worth, as a matter of fact, higher than the subcriticality limit. This leaves open two options:

1. Discard such core designs (with parameters as core size, p/d ratio, Pu/MA ratio etc.) from further consideration, and hence acknowledging only ADT designs where the subcriticality margin is larger than the void and the steel worth potentials.

2. To be less restrictive and formulate a criterion which would include ADT designs where the void and clad worth may be larger than the built-in subcriticality. A safety indicator SI is then devised, which should stay below a certain limit during the core burn-up. The criterion is mainly intended to check for severe accident potentials.

The second approach gives credit to the subcriticality and the high boiling point of the Pb/Bi coolant. The criterion cannot replace thorough and extensive analyses, but it can be used to discriminate between designs worth of further consideration and designs prone for energetics phenomena under accident conditions.

From the safety parameter point of view, the Mo-92 fuel would be the optimal choice. Moreover, the reduction of power/core size is another way to restrict the void values. Additional measures are recommended to limit the release of the gas from the plenum under the condition of a pin breach, which could be done with internal orifices. In addition, ideas proposed for critical fast reactors, such as introducing absorber layers above the core, could help to reduce the void effect.

## REFERENCES


[1] R.J.M. Konings (ed.) *Advanced Fuel Cycles for Accelerator-Driven Systems: Fuel Fabrication and Reprocessing,* EUR 19928 EN, ITU (2001)

[2] FUTURE, FUels for Transmutation of TransURanium Elements, Contract FIKI-CT-2001-00148, 5th Framework Programme EU, (2001)P.

[3] W. Maschek, A. Rineiski, M. Flad, K. Morita, P.Coste, *Analysis of Severe Accident Scenarios and Proposals for Safety Improvements for Accelerator Driven System Transmuters with Dedicated Fuel*, Nuclear Technology, Vol 141, 2, 2003.

[4] S. Pillon, J. Wallenius, P. Smith, W. Maschek, The European FUTURE programme, GLOBAL 2003, New Orleans, La., November 16-20, 2003.

[5] Proposal of IP EUROTRANS, 6th FP of the EU ,(2004).

[6] PDS-XADS Preliminary Design Studies of an Experimental Accelerator Driven System, EU Contract No.FIKW-CT-2001-00179 (2001).

[7] X.-N. Chen, T. Suzuki, A. Rineiski, C. Matzerath Boccaccini, W. Maschek, P. Smith, Source and Reactivity Perturbations in Acc. Driven Systems with Conventional MOX and Advanced Fertile Free Fuels, PHYSOR 2004, Chicago, USA, April 25-29, (2004).

[8] W. Maschek, A. Rineiski, K. Morita, M. Flad, Inherent and Passive Safety Measures in Accelerator Driven Safety Systems: A Safety Strategy for ADS, Int. Conf. On 'Back-End of the Fuel Cycle: From Research to Solutions' GLOBAL 2001, Paris, France, Sept. 9-13, 2001.

[9] W. Maschek, T. Suzuki, X.-N. Chen, Mg. Mori, C. Matzerath-Boccaccini, M. Flad, K. Morita, *Behavior of transmuter fuels of accelerator driven systems under severe accident conditions.* GENES3/ANP2003, Kyoto, Japan (2003).

[10] K. Morita, A. Rineiski, E. Kiefhaber, W. Maschek, M. Flad, G. Rimpault, P. Coste, S. Pigny, Sa. Kondo, Y. Tobita, S. Fujita, Mechanistic SIMMER-III Analyses for Severe Transients in Accelerator Driver Systems, ICONE-9, Nice (April 2001).

[11] W. Maschek, A. Rineiski, K. Morita, E. Kiefhaber, G. Buckel, M. Flad, P. Coste, S. Pigny, G. Rimpault, J. Louvet, T. Cadiou, S. Kondo, Y. Tobita, T. Suzuki, H. Yamano, S. Fujita, SIMMER-III, a Code for Analyzing Transients and Accidents in ADS, AccApp'00, Washington D.C., USA (2000).

[12] 3IAEA Fast Reactor Data Base, IAEA-TECDOC-866 (1996).

[13] I. Krivitski, M. Vorotyntsev, V. Pyshin, L. Korobeinikova, Safety Analysis of FR Core with U-Free Fuel for Actinide Transmut., Nucl. Techn., 143,3, 281 (2003).

[14] A. Vasile, G. Vanbenepe, J.C. Lefevre, K. Hesketh, W. Maschek, Ch. DE Raedt, D. Haas, The CAPRA-CADRA Program, ICONE-8, Baltimore, USA, (2000).

[15] J. Tommasi, S. Massara : LMFR Dedicated Cores for Transmutation, Critical versus Subcritical Comparison, GLOBAL'99, Jackson Hole, USA (1999).

[16] T.G. Theofanous, Cr.R. Bell, An Assessment of the CRBR Core Disruptive Accident Energetics, NUREG/CR-3224 (1984).

[17] W. Maschek, A. Rineiski, T. Suzuki, Mg. Mori, X. Chen, M. Flad, Safety Aspects of Oxide Fuels for Transmutation and Utilization in Accelerator Driven Systems, Journal of Nuclear Materials 320, 147-155, 2003.

[18] W. Maschek, D. Thiem, P. Lo Pinto, Core Disruptive Accident Analyses for Advanced CAPRA Cores, ICONE-4, New Orleans, USA (1996).

[19] A.E. Waltar, A.B. Reynolds, Fast Breeder Reactors, Pergamon Press, New York, (1981).

[20] W. Maschek, D. Thiem, Energetics Potentials of Core Disruptive Accidents in Fast Reactors with Transmutation/Burning Capabilities, ARS '94 Int. Top. Mtg. Advanced Reactor Safety, April 1994, Pittsburgh, USA (1994).

[21] J. Wallenius, M. Eriksson, Design of LBE cooled sub-critical minor actinide burners as function of fuel form and composition, GLOBAL 2003, New Orleans, USA, (2003).

[22] P. Royl, G. Kussmaul, J. Cahalan, R. Wigeland, G. Friedl, J. Moreau, M. Perks, Influence of Metal and Oxide Fuel Behavior on the ULOF Accident 3500 MW Heterogeneous LMR Cores and Comparison with Other Large Cores, Proc. of the 1990 Int. Fast Reactor Safety Meeting, Snowbird, USA (1990) .

[23] D. Struwe, W. Pfrang , Analysis Results of Unprotected Transients in SNR-300 Applying the CABRI-Validated SAS3D Code Version CASAS-87, Proc. of the 1990 Int. Fast Reactor Safety Meeting, Snowbird, USA (1990) .

[24] H. Endo, S. Takahashi, M. Ishida, T. Hoshi, A Study of the Initiating Phase Scenario of Unprotected Loss-of-Flow in a 600 MWe MOX Homogeneous Core, IAEA, IWGFR/89, O-arai, Japan (1994).

## Acknowledgements

This work was partly funded by the EU Contract FIKI-CT-2001-00148, 5th Framework Programme FUTURE.