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Annals of Nuclear Energy 31 (2004) 1783–1801
annals of NUCLEAR ENERGY
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Technical note

Coolant void worth in fast breeder reactors and accelerator-driven transuranium and minor-actinide burners

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Received 24 December 2003; accepted 8 May 2004

Abstract

Liquid metal coolant void worth have been calculated as a function of fuel composition and core geometry for several model fast breeder reactors and accelerator-driven systems (ADSs). The Monte Carlo transport code MCNP with continuous energy cross-section libraries was used for this study. With respect to the core void worth, lead/bismuth cooled FBRs appear to be inferior to those employing sodium for pitch-to-diameter ratios exceeding 1.4. It is shown that in reactor systems cooled by lead/bismuth eutectic radial steel pin reflector significantly lowers the void worth. The void worth proves to be a strong function of the fuel composition, reactor cores with high content of minor actinides in fuel exhibiting larger void reactivities than systems with plutonium based fuel. Enlarging the lattice pitch in ADS burners operating on Pu rich fuel decreases the void worth while the opposite fact is true for ADSs employing americium based fuels.

1. Introduction

A number of innovative reactor systems for transmutation of plutonium and minor actinides were proposed in last decades (Takizuka et al., 1991; Conti et al., 1995). Fuels utilised in these reactors have low uranium content or are completely U-free, and the

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doi:10.1016/j.anucene.2004.05.005

systems are usually conceived to operate on fast neutron spectrum. The presence of americium leads to a decrease in Doppler reactivity coefficient and delayed neutron fractions, raising significant safety concerns (Wallenius and Eriksson, submitted). It was therefore suggested that sub-critical reactor systems should be implemented in fuel cycles involving recycling of minor actinides. For this purpose, accelerator-spallation (Foster et al., 1974; Murata and Mukaiyama, 1984) and deuterium–tritium fusion neutron sources (Rose et al., 1977; Cheng et al., 1995; Stacey et al., 2002) were both envisioned. Additional reactivity margin is hence provided in sub-critical systems, limiting the influence of reactivity coefficients and allowing steady-state operation of the system. However, it has appeared that such MA-fuelled ADS have a potential for rapid reactivity excursions following loss of coolant from the core, which may lead to fuel failure and core disruption (Maschek et al., 2000; Eriksson et al., 2002).

Therefore, it is necessary to provide a fuel and core design that minimises conceivable reactivity insertions in the standard set of design basis accidents. In this parametric study, we investigate coolant void worth for series of fast breeder and accelerator-driven system (ADS) configurations with aim to identify suitable core and fuel design parameters.

First, we discuss physical mechanisms involved in coolant voiding. Then, we perform scoping studies of Δk_{∞} in two-dimensional pin lattices for several fuel compositions and wide range of pitches. Finally, we investigate the coolant void worth in various types of model critical and ADS transmutation systems, employing nitride and oxide fuel, different types of inert matrices and two types of coolants – lead/bismuth and sodium. Void reactivity is studied as a function of core geometry parameters as e.g. reactor lattice pin pitch and fuel pin design. The optimal pin pitch is then identified for each configuration. Finally, we discuss the implications of our results for ADS core design in general.

2. Voiding mechanism

The occurrence of void in the core can be a result of following events:

- fuel pin rupture, releasing fission gases and helium into the core,
- blow-down of steam from ruptured steam generator,
- coolant boiling,
- blow-down of bubbles from gas injection system (Cinotti and Gherardi, 2002).

We note, that in sodium cooled systems undercooling can result in coolant boiling prior any significant damage to the fuel, clad, or structural material is inflicted. On the other hand, due to the high boiling temperatures of lead and lead/bismuth (Pb: $T_b = 2023$ K; Pb/Bi: $T_b = 1943$ K), coolant boiling in these systems occurs first *after* the integrity of reactor core is lost, rendering such events to the realm of beyond-design basis accident analyses.

The void worth and void reactivity coefficient are the major safety parameters, determining permissive maximum criticality level of the system (k_{eff}).

2.1. Phenomena occurring during the voiding

The physical effects associated with coolant voiding are

- reduction of neutron moderation (spectral hardening), increasing fission probabilities of even neutron number actinides,
- reduction of neutron capture in fuel, coolant, and cladding.

The coolant void worth is the difference in the k-eigenvalue between the flooded and voided state

$$W = \Delta k_{\mathrm{eff}} = k_{\mathrm{eff}}^{\mathrm{void}} - k_{\mathrm{eff}}^{\mathrm{flood}} \tag{1}$$

$$= \overline{\nu}_{\mathrm{void}} L_{\mathrm{f}}^{\mathrm{void}} - \overline{\nu}_{\mathrm{flood}} L_{\mathrm{f}}^{\mathrm{flood}}. \tag{2}$$

where L_{f} is neutron loss to fission in one neutron generation for respective core state – flooded or voided.

In fast neutron systems, the average fission neutron yield can be considered as constant ($\overline{\nu} \equiv \overline{\nu}_{\mathrm{flood}} \simeq \overline{\nu}_{\mathrm{void}}$). Then,

$$W = \overline{\nu}(L_{\mathrm{f}}^{\mathrm{void}} - L_{\mathrm{f}}^{\mathrm{flood}}), \tag{3}$$

from which follows that $W = \overline{\nu}\Delta L_{\mathrm{f}}$.

The neutron balance equation for *one neutron fission generation* in an eigen-state can be written as

$$1 + C_{\mathrm{x}} = L_{\mathrm{c}} + L_{\mathrm{e}} + L_{\mathrm{f}} + L_{\mathrm{x}}, \tag{4}$$

where L_{x} denotes the neutron loss rate in non-fission multiplication reactions, $C_{\mathrm{x}} = \overline{\nu_{\mathrm{x}}} L_{\mathrm{x}}$ is the neutron creation rate in non-fission multiplication reactions, $\overline{\nu_{\mathrm{x}}}$ is the average neutron yield in non-fission multiplication reactions ($\overline{\nu_{\mathrm{x}}} \simeq 2$), L_{e} denotes the loss rate to leakage, L_{c} the loss rate to capture reactions, and L_{f} is the loss rate to fission.

Upon coolant voiding, $\Delta C_{\mathrm{x}} \leqslant 10^{-3}$ in most of the cases yielding $\Delta L_{\mathrm{f}} + \Delta L_{\mathrm{c}} + \Delta L_{\mathrm{e}} \sim 0$. In the infinite pin lattice 2-D model ($L_{\mathrm{e}} = 0$), the coolant void worth can be subsequently decomposed as

$$W = \overline{\nu} \cdot \Delta L_{\mathrm{f}} = -\overline{\nu}(\Delta L_{\mathrm{c,fuel}} + \Delta L_{\mathrm{c,coolant}} + \Delta L_{\mathrm{c,clad}}). \tag{5}$$

where $L_{\mathrm{c,fuel}}$, $L_{\mathrm{c,coolant}}$, and $L_{\mathrm{c,clad}}$ is neutron capture rates to fuel, coolant, and cladding, respectively.

In realistic three dimensional core configurations, the void worth is given by

$$W = -\overline{\nu}(\Delta L_{\mathrm{c,fuel}} + \Delta L_{\mathrm{c,coolant}} + \Delta L_{\mathrm{c,clad}} + \Delta L_{\mathrm{e}} - \Delta G_{\mathrm{x}}), \tag{6}$$

where L_{e} quantifies a rate of neutron leakage from the system, and $G_{\mathrm{x}} = C_{\mathrm{x}} - L_{\mathrm{x}}$ is the neutron gain from non-fission multiplication reactions. The neutron balance equation is evaluated for the whole geometry inclusive reflectors and plena.

2.2. Cross-sections

In order to apprehend the nature of neutron slowing-down process in coolant due to the elastic and inelastic scattering, we define the energy-loss cross-section as

$$\overline{\Sigma_{\Delta E}} \equiv \frac{\Sigma_{\mathrm{el}}\overline{\Delta E_{\mathrm{el}}} + \Sigma_{\mathrm{inel}}\overline{\Delta E_{\mathrm{inel}}}}{E}, \tag{7}$$

where

$$\overline{\Delta E_{\mathrm{el}}} = \frac{1}{2}(1-\alpha)E_{\mathrm{n}}, \quad \alpha = \left(\frac{A-1}{A+1}\right)^2 \tag{8}$$

and

$$\overline{\Delta E_{\mathrm{inel}}} = E_{\mathrm{n}} - \left(\frac{A}{A+1}\right)^2\left[E_{\mathrm{n}} - Q\frac{A+1}{A}\right] \tag{9}$$

is the average energy loss in elastic scattering and inelastic scattering, respectively; Q denotes the excited energy levels of the target nuclei, E_{n} is the neutron energy, and A is the target nucleus mass number.

The energy-loss cross-section for sodium decomposed into the contributions from elastic and inelastic scattering is displayed in Fig. 1. We observe that for the energy region below 500 keV, neutron slowing down is dominated by elastic collisions, while in-between 0.7 and 2 MeV inelastic scattering becomes about equally effective.

In Fig. 2, the same comparison is made for natural lead. We note that energy-loss cross-section due to the elastic scattering is significantly smaller than for sodium in whole energy range investigated. However, due to the presence of several thresholds for inelastic scattering in the energy interval from 0.57 to 2 MeV, the energy loss in inelastic scattering is notably larger than for sodium. The neutron spectrum of lead and lead/bismuth cooled reactors will be thus somewhat suppressed for energies above 1 MeV comparing with Na-cooled systems having the same geometry, see Fig. 3. For sodium, the magnitude of neutron spectrum relative to lead/bismuth is

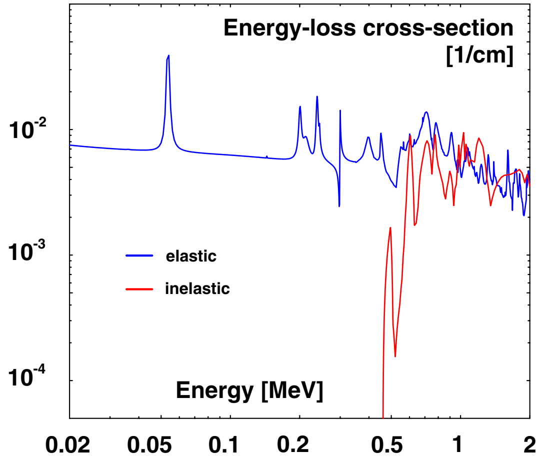

Fig. 1. Energy-loss cross-section for ^{23}Na. Data from JEF2.2 library were used. Macroscopic scattering cross-sections were taken at $T = 600$ K.

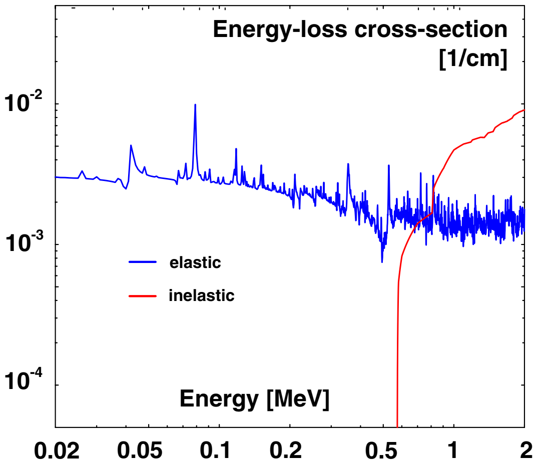

Fig. 2. Energy-loss cross-section for natural lead. Cross-section data were taken from ENDFB/VI-8 cross-section library. Σ_{el} and Σ_{inel} at $T = 600$ K were used.

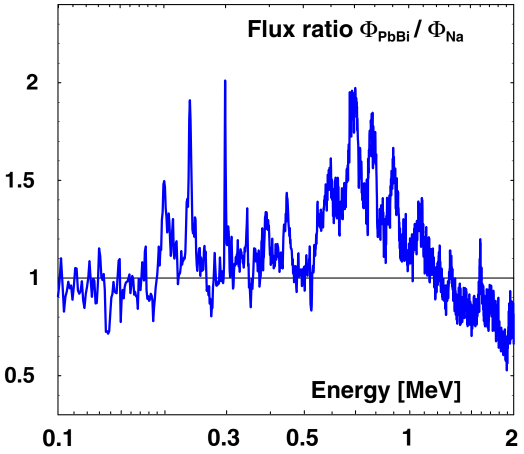

Fig. 3. The neutron spectrum of lead–bismuth cooled system relative to that cooled by sodium with the same geometry and fuel composition.

suppressed in the energy region of 0.7–1.5 MeV where contributions to the neutron slowing down from elastic and inelastic scattering reactions merely equal.

We further note that within the range of energies considered the ^{206}Pb features a number of threshold levels, while the threshold for inelastic scattering of the doubly magic isotope ^{208}Pb is well above 2 MeV, see Table 1.

One could therefore theoretically consider to enrich lead in ^{208}Pb. With energy-loss cross-section remaining below 0.003 cm^{-1}, a very hard neutron spectrum can be attained. As also the capture cross-section of ^{208}Pb is low in comparison to other

Table 1
Threshold energies for inelastic scattering of heavy metal coolants used in the study

Nuclide	Abundance	Threshold energies (keV)		
		1st	2nd	3rd
^{23}Na	100%	459.1	2166	2495
^{206}Pb	24.1%	806.9	1171	1347
^{207}Pb	22.1%	572.5	902.1	1641
^{208}Pb	52.4%	2628	3213	3492
^{209}Bi	100%	900.6	1617	2455

^{206}Pb has further five excited energy levels yielding threshold energies below or close to 2 MeV limit: 1474, 1692, 1713, 1793, and 2008 keV.

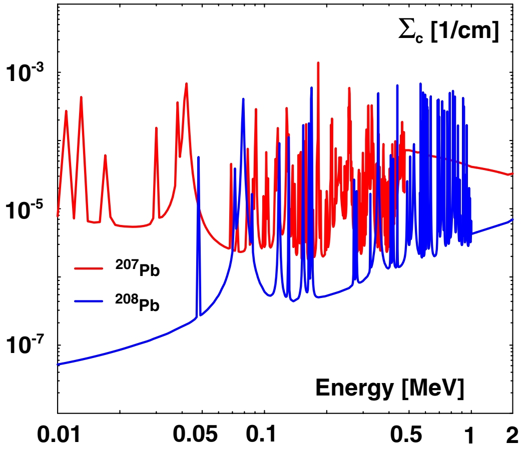

Fig. 4. Macroscopic capture cross-section of ^{207}Pb and ^{208}Pb. ENDFB/VI-8 cross-section library data were used.

isotopes, see Fig. 4, such a coolant would yield a very small void worth (Shmelev et al., 1992).

2.3. Calculation methodology

Our study of void reactivity is performed as a function of core geometry: reactor lattice pin pitch and fuel pin design parameters. Two types of fuel actinide isotopic compositions have been studied: corresponding to an immediate (four years of cooling), and somewhat delayed (30 years of cooling) use of spent LWR UOX fuel. The plutonium and americium vectors applied in our studies are presented in Table 2.

The void worth is typically a relatively small difference between two large terms, critically depending on a correct description of geometry as well as transport slowing-down and capture cross-sections properly adjusted for change in self-shielding. Hence, we used the Monte Carlo code MCNP, version 4C3 (Briesmeister,

Table 2
Pu and Am vectors used in the investigations

Isotope	Cooling time	
	4 years	30 years
^{238}Pu	0.024	0.020
^{239}Pu	0.520	0.521
^{240}Pu	0.226	0.229
^{241}Pu	0.119	0.035
^{242}Pu	0.065	0.064
^{241}Am	0.030	0.114
^{243}Am	0.016	0.017

The compositions correspond to those found in spent LWR UOX fuel with an averaged burnup of 41.2 GWd/tHM; fuel cooling time is 4 and 30 years, respectively.

2000), for the present study. The estimation of neutron creation and loss rates is performed exclusively in the eigen-state as modelled by MCNP KCODE mode. A temperature adjusted version of the JEF2.2 cross-section library is applied.

We start by evaluating the void worth in an infinite triangular fuel pin lattice for three heavy metal coolant candidates – sodium, lead, and lead/bismuth eutectic. Fuels with different fractions of plutonium and minor actinide, relevant for use in ADSs, are analysed. The impact of fast fission threshold for even neutron number nuclides is thus assessed.

In the 3-D reactor model, we further evaluate the effect of neutron leakage from the core on the void worth. The reactor core, axial plena, and bottom plenum spacer regions are modelled pin-by-pin, while materials were smeared in axial and radial reflectors, as well as in ADS target region. For simplicity, a ductless fuel assembly design is assumed. The target region consists of Pb/Bi eutectic, steel structures contain 90 at% iron and 10 at% chromium. For individual components of the het-

Table 3
Reference system, pin, and pellet design specifications

Pellet density (% TD)	0.85
Pellet outer radius R_{fuel} (mm)	2.4
Clad inner radius R_{gap} (mm)	2.5
Clad outer radius R_{pin} (mm)	3.0
Active pin length (cm)	100
Length of upper fission gas plenum (cm)	150
Length of lower fission gas plenum (cm)	10
Length of bottom plenum spacer (cm)	10
Length of radial reflector S/As (cm)	140
Thickness of radial reflector (cm)	150
Length of upper reflector (cm)	200
Length of lower reflector (cm)	230
ADS target radius (cm)	20
Radius of accelerator beam tube (cm)	15
Distance of target window from centreplane (cm)	20

A triangular pin lattice is adopted.

erogeneous design, average stead-state temperatures are assumed: 1500 K for fuel, 900 K for pin clad in the core, and 600 K for coolant and steel structures of plena, spacer, target, and reflectors.

The model parameters as used in the calculations are summarised in Table 3. The total core power was set to 800 $\mathrm{MW_{th}}$. The assumed linear power of 30 kW/m then corresponds to cores with ~26,700 fuel pins.

A homogeneous, single zone core configuration is assumed in all cases. In this context, we note that core heterogeneity significantly alters the coolant void reactivity (Khalil and Hill, 1991). The results of this study should be thus considered rather as qualitative, in terms of a relative intercomparison of the void worths in-between different design options.

3. Results

Three types of fuel are used for our analyses: standard FBR fuel $(U,Pu)O_2$, a plutoniurn based – TRU mononitride fuel (TRU,Zr)N, and minor actinide based fuel (MA,Zr)N, relevant for ADS minor actinide burners operating in double-strata incineration scheme. An inert matrix has to be added to the fuel in order to compensate for high fuel reactivity and achieve a reasonably good stability at high temperature. In our studies we have chosen ZrN as a representative inert matrix material. In order to reduce production of ^{14}C, the use of nitride fuel with 99% ^{15}N enrichment is foreseen.

3.1. Elementary cell analysis

The void worth was analysed in an infinite pin lattice geometry, examining changes in neutron capture upon coolant voiding. The relative fractions of metals in the fuel is given in Table 4. In Fig. 5, the void worth for three types of fuel is displayed as a function of pitch-to-diameter ratio. We note that, as expected, the void worth increases with increasing fraction of higher actinides in the fuel; the difference being most significant for high pin pitches. Results of pin lattice sodium void worth decomposed into individual components are displayed in Table 5. The values given in the table corresponds to P/D = 2.0, in order to emphasise any effect of reduced capture in the coolant, should it be significant.

Table 4
Atomic fractions of metallic elements in fuels investigated in the elementary cell analyses

Element	$(U,Pu)O_2$	(TRU,Zr)N	(MA,Zr)N
U	0.750	–	–
Pu	0.250	0.165	0.133
Am	–	0.035	0.267
Zr	–	0.800	0.600

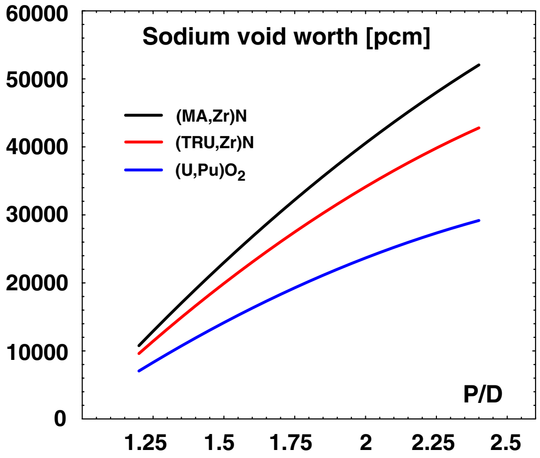

Fig. 5. Sodium void worth in an infinite pin lattice with a pin diameter of 6 mm.

Table 5
Infinite pin lattice void worth analyses

Fuel	ΔL_{f}	$\Delta L_{\mathrm{c,fuel}}$	$\Delta L_{\mathrm{c,cool}}$	$\Delta L_{\mathrm{c,clad}}$	$-\Delta L_{\mathrm{c,fuel}}/\Delta L_{\mathrm{f}}$	$\left(\frac{\sigma_{\mathrm{f}}}{\sigma_{\mathrm{a}}}\right)_{\mathrm{voided}}/\left(\frac{\sigma_{\mathrm{f}}}{\sigma_{\mathrm{a}}}\right)_{\mathrm{flooded}}$
$(U,Pu)O_2$	+0.078	−0.059	−0.012	−0.007	0.76	1.20
(TRU,Zr)N	+0.108	−0.090	−0.011	−0.007	0.83	1.22
(MA,Zr)N	+0.119	−0.111	−0.005	−0.003	0.93	1.33

Sodium void worth was decomposed into the individual constituents. Pitch-to-diameter ratio is 2.0. The neutron loss rates are normalised per one fission neutron generation.

We observe that the main contribution to the void worth is a reduction in fuel capture rate, with concurrent increase of fission probability of even neutron number actinides, see Fig. 6. While capture reduction in the fuel provides about 76% of the void worth in (TRU, Zr)N fuel, it is more then 93% for the fuel containing 60% of minor actinides. We further note that the spectral gradient accompanying removal of the coolant from a lattice is strongest for (MA,Zr)N fuel. The capture rate in the cladding is less significant and constitutes less than 10% of the void worth.

In Table 6, we illustrate the effect of increasing the pin pitch on the void worth. Comparing with Table 5, one may note that the contribution of the coolant capture reduction to the void worth is significantly higher for Pb/Bi than for sodium, for same P/D. With increasing P/D ratio, understandably, the relative contribution of coolant capture rate reduction to the void worth increases. Even for P/D = 1.2, 41% of the LBE void worth constitutes of $\Delta L_{\mathrm{c,cool}}$.

The void worth of lead is very similar to that of lead/bismuth for the whole range of pitches investigated, see Fig. 7. Both heavy metals – lead and lead/bismuth – feature very similar neutronic characteristics and we therefore further focus in our studies only on systems cooled by sodium and lead/bismuth eutectic.

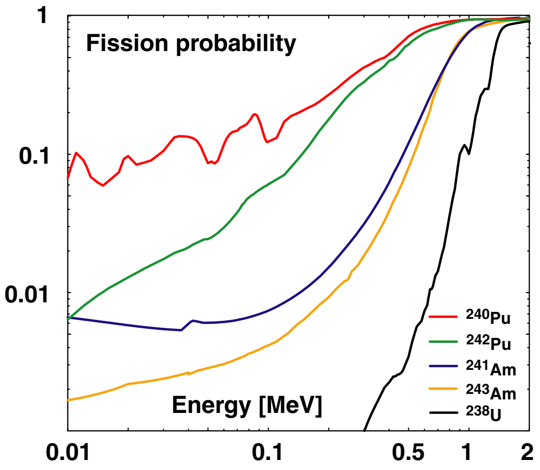

Fig. 6. Fission probability σ_f/σ_a of even neutron number actinides.

Table 6
Void worth analyses in an infinite pin lattice employing lead/bismuth coolant, and (TRU,Zr)N fuel; Pu/Am fraction was kept at 4/1

P/D	ΔL_f	$\Delta L_{c,fuel}$	$\Delta L_{c,cool}$	$\Delta L_{c,clad}$	$-\Delta L_{c,fuel}/\Delta L_f$	$-\Delta L_{c,cool}/\Delta L_f$
1.2	+0.022	−0.012	−0.009	−0.001	0.55	0.41
1.6	+0.057	−0.027	−0.028	−0.002	0.47	0.49
2.0	+0.090	−0.039	−0.048	−0.003	0.43	0.53
2.4	+0.121	−0.047	−0.070	−0.004	0.39	0.59

The neutron loss rates are normalised per one fission neutron generation.

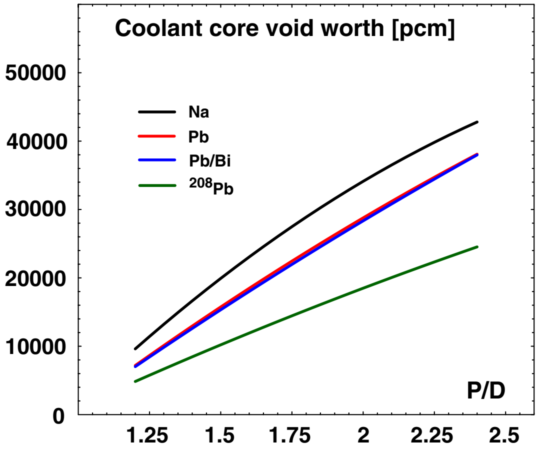

Fig. 7. Void worth in an infinite pin lattice of a system employing (TRU,Zr)N fuel. Four types of coolant were investigated – sodium, lead/bismuth, lead, and ^{208}Pb. ENDFB/VI-8 cross-section library data were used for ^{208}Pb.

Due to its low moderating power, lead enriched in double-magic isotope ^{208}Pb displays very low void worths. We note, however, that lead enrichment process is not realistically feasible.

3.2. Critical 3-D systems

The importance of enhanced leakage becomes apparent when observing the void worth in realistic system configurations, see Fig. 8. In Table 7 and Fig. 9, we display the coolant void worth as a function of pitch-to-diameter ratio for a model critical fast reactor employing (U,Pu)O_2 fuel cooled by sodium and lead/bismuth. In the case of the Pb/Bi-cooled core, we investigate two different radial reflector configurations

(a) similar to the one used for sodium cooled system, i.e. consisting of steel pins, immersed in the coolant; coolant volume ratio being 20 vol%,
(b) with the whole radial reflector region filled by lead/bismuth eutectic only. Such radial reflector configurations have been proposed in a number of studies (Rubbia et al., 1997).

In contrast to the standard notion of the leakage term (Waltar and Reynolds, 1981), L_e in our case denotes those neutrons leaking out of the *whole reactor system* to the surrounding shielding. We note that the probability of these neutrons to enter the core and induce fission is rather remote and these neutrons can be effectively perceived as captured in clad and capture material of reflector. The reason why we list the leakage component separately in our study is thus merely phenomenological.

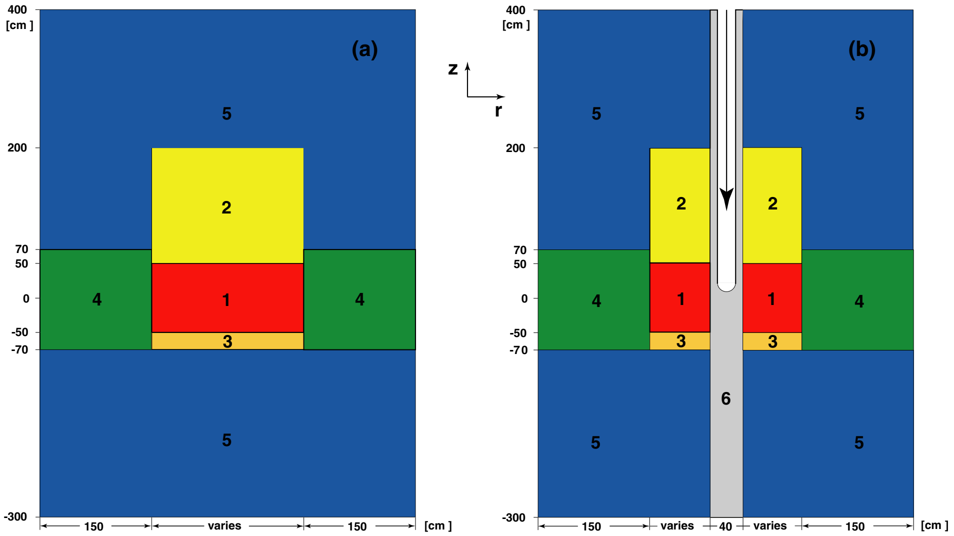

Fig. 8. *R–z* view of critical (a) and sub-critical (b) reactor model configurations. The regions are 1 – core, 2 – upper fission gas plenum, 3 – lower fission gas plenum and bottom plenum spacer, 4 – radial reflector, 5 – axial reflector, and 6 – target. Axial reflector and bottom plenum spacer regions are filled by their respective core's coolant. The spallation target consists of lead/bismuth eutectic.

Table 7
Void worth analyses in a model fast-breeder reactor, for sodium and lead/bismuth coolant with $(U,Pu)O_2$ fuel

Coolant	P/D	Atomic fraction Pu/(U+Pu)	ΔL_f	$\Delta L_{c,fuel}$	$\Delta L_{c,cool}$	$\Delta L_{c,clad}$	ΔL_e	ΔG_x
Na								
Core void worth								
	1.2	17%	+0.0076	−0.0281	+0.0063	+0.0123	+0.0037	+0.0002
	1.6	22%	+0.0096	−0.0689	+0.0181	+0.0316	+0.0105	+0.0001
	2.0	27.5%	+0.0071	−0.0908	+0.0265	+0.0428	+0.0156	+0.0006
	2.4	33%	+0.0035	−0.1048	+0.0323	+0.0487	+0.0197	+0.0006
Core and upper plenum void worth								
	2.0	27.5%	−0.0166	−0.1282	+0.0471	+0.0397	+0.0598	+0.0006
Pb/Bi								
Core void worth, radial reflector with steel pins								
	1.2	16%	+0.0058	−0.0247	−0.0036	+0.0211	+0.0008	−0.0003
	1.6	19%	+0.0107	−0.0506	−0.0088	+0.0471	+0.0023	−0.0006
	2.0	22.5%	+0.0114	−0.0709	−0.0129	+0.0677	+0.0039	+0.0006
	2.4	26%	+0.0112	−0.0804	−0.0172	+0.0819	+0.0053	−0.0008
Core void worth, Pb/Bi radial reflector								
	2.0	22%	+0.0216	−0.0555	+0.0124	+0.0060	+0.0163	−0.0006

$\Delta L_{c,clad}$ includes capture in the structural material of the reflectors. Note that $\Delta G_x = \Delta C_x - \Delta L_x < 10^{-3}$.

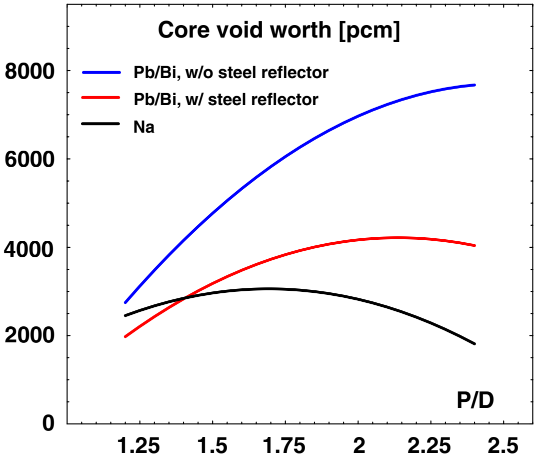

Fig. 9. Coolant void worth in a critical FBR employing $(U,Pu)O_2$ fuel. The Pu/(U+Pu) ratio was varied with P/D in order obtain $k_{eff} \sim 1$, for Na in the range between 17% and 33%, for Pb/Bi without steel pin reflector between 16% and 26%, and in the case of Pb/Bi with steel reflector between 17% and 27%.

In our model, the effect of the enhanced neutron leakage *from the core* upon coolant voiding is thus exhibited as a change in the capture of neutrons in coolant and structural material of plena and reflectors. Hence, in contrast to the infinite pin lattice analyses the changes in the capture probability in clad introduces a *negative* reactivity upon coolant voiding.

We note that the spectrum hardening responsible for reduction of neutron parasitic capture in fuel is the only source inserting positive reactivity into the system in the case of sodium. With increasing pitches we observe both reduction of the neutron capture probability in the fuel as well as its gradual increase in coolant and clad material of plena and reflectors. The probability of neutrons to leak out the reactor system increases consequently with increasing pitches too, though not as strongly as the coolant capture term. For $P/D > 1.6$, the coolant and clad capture and leakage terms together increase faster than the neutron capture probability in fuel is reduced, leading to a subsequent decrease of the void worth.

In comparison to sodium cooled system, the reduction of neutron capture in Pb/Bi during coolant voiding for the core with radial steel pin reflector introduces positive reactivity to the system. The negative reactivity feedback is then supplied mainly due to the increase of neutron capture in the *structural material of reflector.* However, this negative feedback is not able to compensate for the total reduction in fuel and coolant capture rates. Adding smaller leakage, in comparison to sodium, Pb/Bi-cooled FBRs thus yield higher void worths than systems cooled by sodium, for P/D larger than 1.4!

When the steel pin reflector is replaced by Pb/Bi, the only significant effect introducing negative reactivity to the systems is the increased neutron capture in coolant and surrounding reactor shielding material (manifested in our study as an increased leakage term L_e). This results in excessive void worths even for large pitch-to-diameter ratios.

One could therefore supply an absorbing material into the core reflector in order to increase the neutron capture upon coolant voiding and consequently reduce void worth.

The leakage effect itself becomes significantly pronounced when the upper plenum is voided together with the reactor core, providing more than 40% of the negative reactivity upon coolant voiding.

3.3. ADS

The void worth was further studied in realistic models of ADSs for fuel compositions relevant for transmutation purposes.

Fig. 10 shows coolant void worth for TRU fuels having a fixed inert matrix fraction, a condition which might be imposed by reasons of high temperature stability or fabricability of fuel (Wallenius and Eriksson, submitted). In order to keep k_{eff} constant, the Pu/Am ratio is hence varied as a function of P/D. We note that the absolute value of the core void worth is a factor of 2–3 higher than for FBRs utilising $(U,Pu)O_2$ fuel. However, on the contrary to the situation in the FBR, lead/bismuth yields *lower* core void worth than sodium for pitch-to-diameter ratios less than 2.3!

A dramatic change in core void worth behaviour with respect to increasing P/D is observed when the Pu/Am ratio in fuel is kept constant at $Pu/Am = 2/3$, corresponding to the equilibrium fraction of fuel in MA-ADS burner in double-strata

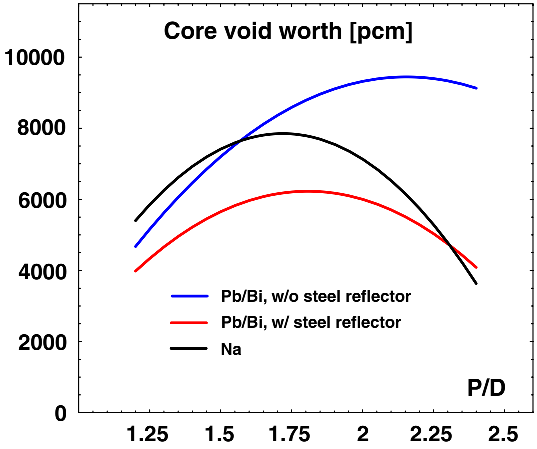

Fig. 10. Core void worth in ADSs cooled by sodium and lead/bismuth. The inert matrix fraction is kept constant at 50 vol%, and Pu/(Pu+Am) ratio is adjusted to obtain $k_{\mathrm{eff}} \sim 0.96$, for Na in the range between 23% and 67%, for Pb/Bi without steel pin reflector between 20% and 49%, and in the case of Pb/Bi with steel reflector between 21% and 51%. The Pu and Am vectors are those of spent LWR UOX fuel after 30 years of cooling.

scheme (Takizuka et al., 1998). In this case, the enhanced neutron leakage and capture in structural material are not able to compensate for reduction of neutron capture rate in the fuel and coolant, causing core void reactivity to grow with P/D, see Fig. 11. A similar behaviour was also observed for solid solution oxide fuels (Wallenius, 2003).

In Fig. 12, the change in reactivity while voiding both core and upper plenum is compared to the core void worth. In this case, neutron leakage is enhanced proportionally to P/D, reducing the void worth by several thousands of pcm (for standard size pitch-to-diameter ratio equal to 1.6, by more than 2000 pcm). W however remains positive, even for P/D = 2.4.

Fig. 13 displays results of the void worth calculations in a TRU-ADS burner cooled by lead/bismuth eutectics for two pin diameters, 6 and 8 mm. The ratio of Pu/Am is kept at 4/1, corresponding to a case when all Pu from the LWRs is directed to the ADS, a so called two component scenario. The relative fraction of MA in fuel is small and the increase in neutron fission-to-capture ratio upon coolant voiding is thus not as dramatic as in MA-based ADSs, leaving the reduction of neutron capture probability in fuel to be the only significant factor introducing positive reactivity to the system. Generally, the void worth is now found to be decreasing with growing pitch due to increasing neutron leakage.

In order to illustrate an effect of the fissile isotope content in the Pu-vector on the void worth, the same calculation was also made for "fresh", high quality, plutonium, coming from LWR UOX spent fuel after 4 years of cooling. In this case, the minor actinide content in fuel is further decreased, lowering consequently also the void worths.

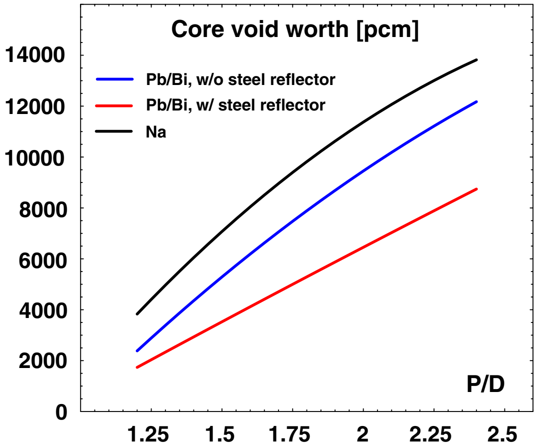

Fig. 11. Core void worth in ADSs cooled by sodium and lead/bismuth. The Pu/Am ratio was kept constant at 2/3, and actinide fraction (AcN) in fuel was adjusted to obtain $k_{\text{eff}} \sim 0.96$, for Na in the range between 35 and 85 vol%, for Pb/Bi without steel reflector between 31 and 59 vol%, and in the case of Pb/Bi with steel pin reflector between 33 vol%. and 63 vol%. The Pu and Am vectors are those of spent LWR UOX fuel after 30 years of cooling.

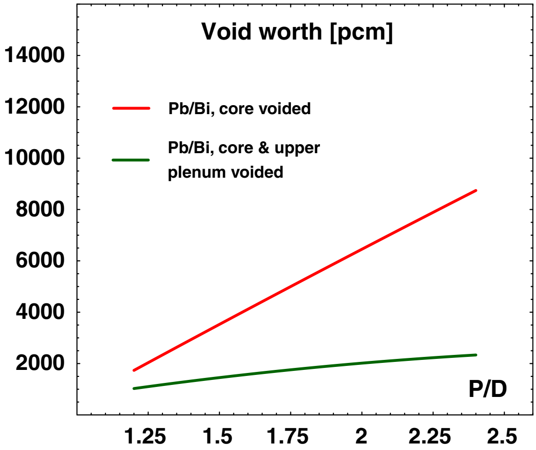

Fig. 12. Core and plenum void worths in ADS employing Pb/Bi coolant and steel pin radial reflector. Pu/Am fraction was kept at 2/3, AcN fraction was varied to obtain $k_{\text{eff}} \sim 0.96$. The Pu and Am vectors are those of spent LWR UOX fuel after 30 years of cooling.

Fuel pins with smaller pin diameter appeared to be more favourable with respect to the void worth, the difference being most pronounced for larger-pitches.

Exchanging ZrN for an absorbing matrix, in our case HfN, increases the void worth, but in the case of TRU-based fuel, W remains at acceptable levels, see Fig. 14. While the core void worth becomes slightly positive, the coupled core and upper plenum void is still strongly negative for all pitches.

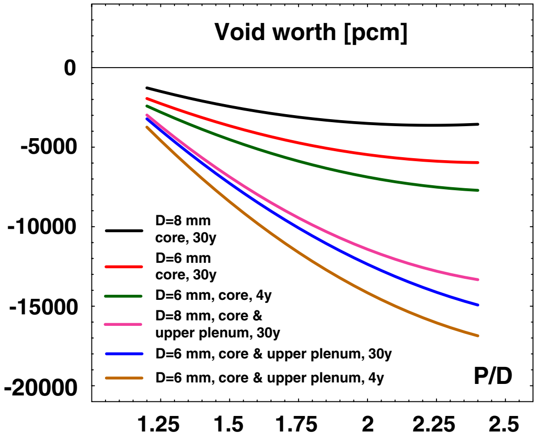

Fig. 13. Coolant void worth in ADS employing (TRU,Zr)N fuel, Pb/Bi coolant and steel pin radial reflector. Pu/Am ratio is 4/1, AcN fraction is varied with P/D to obtain $k_{\mathrm{eff}} \sim 0.96$, for pins with a radius of 3 mm in the range between 13 and 25 vol% (when applying 30-y actinide vector) and between 12% and 23% (for 4-y actinide vector). For 4-mm-radii pins, AcN volume fraction was adjusted in the range between 10% and 19%.

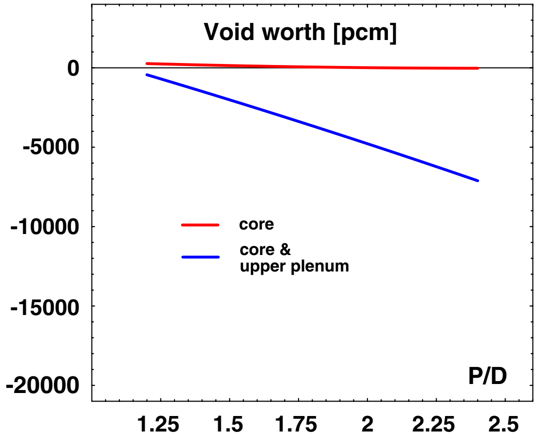

Fig. 14. Coolant void worth in Pb/Bi-cooled ADS employing TRU fuel with an absorbing matrix – (TRU,Hf)N. The steel pin reflector is used. Pu/Am fraction is kept at 4/1, AcN fraction in fuel is varied between 28 and 41 vol% to obtain $k_{\mathrm{eff}} \sim 0.96$. Pin diameter is 6 mm, the Pu and Am vectors are those of spent LWR UOX fuel after 30 years of cooling.

In Table 8, we display the coolant void worth for different types of mononitride fuels employed in a model ADS burner with lattice pitch-to-diameter ratio equal to two and decomposed into the individual terms with respect to capture in fuel, clad, coolant, and with regards to neutron leakage. We note that the statistical error of calculations is of the same order of magnitude as ΔG_{x}, which we therefore do not list.

Table 8
Breakdown of coolant void worth into individual components shown for different types of mononitride fuels employed in a model ADS with sodium or lead/bismuth coolant; pitch-to-diameter ratio is 2.0

Coolant	Atomic fraction Pu/(Pu+Am)	Volume fraction AcN/(AcN+inert matrix)	R_{pin}	ΔL_f	$\Delta L_{c,fuel}$	$\Delta L_{c,cool}$	$\Delta L_{c,clad}$	ΔL_e
Core void worth								
Na	80%	29.5%	3 mm	−0.0102	−0.0839	+0.0205	+0.0524	+0.0214
	55%	50%	3 mm	+0.0164	−0.0910	+0.0171	+0.0409	+0.0172
	40%	66%	3 mm	+0.0296	−0.0948	+0.0148	+0.0361	+0.0150
Core void worth, radial reflector with steel pins								
Pb/Bi	80%	20%	3 mm	−0.0226	−0.0650	−0.0104	+0.0903	+0.0060
	80%	15.5%	4 mm	−0.0156	−0.0690	−0.0138	+0.0908	+0.0059
	42%	50%	3 mm	+0.0109	−0.0794	−0.0019	+0.0649	+0.0048
	40%	52%	3 mm	+0.0127	−0.0803	−0.0019	+0.0646	+0.0046

Similarly to the results obtained for the pin lattice model, the amount of positive reactivity introduced upon coolant voiding by reduction of capture in fuel increases with growing MA fraction in the fuel. Evidently, this is due to the pronounced increase of fuel fission-to-capture ratio. As a common characteristics for all fuels studied, the positive reactivity introduced by the reduction of capture in fuel is lower in sodium cooled systems than for lead/bismuth. We also observe that the reactivity being introduced by a change in coolant capture is lower for high MA content fuel than for fuels dominated by plutonium.

4. Conclusions

We found that reactor cores with high minor actinide content fuel exhibit generally higher void worths than cores fuelled primarily with plutonium. A disadvantage of sodium versus Pb/Bi in terms of larger positive coolant void worth is apparent for all transmutation type fuels investigated.

For an FBR with $(U,Pu)O_2$ fuel, on the contrary, Pb/Bi yields larger void worth than sodium when $P/D \gtrsim 1.4$, which is in contradiction with the results obtained by Yiftah and Okrent (1960). While in sodium cooled FBRs the negative reactivity is introduced upon coolant voiding by both increase of neutron capture in structural material and coolant (in the reflectors and plena), in Pb/Bi-cooled reactors the reactivity contribution is negative only from the former.

In lead/bismuth-cooled systems, a radial steel pin reflector has to be applied, if coolant void worth is to be significantly reduced.

Enlarging the pitch-to-diameter ratio lowers the coolant void worth in ADS burners operating in two-component scenario, while ADS reactors with MA based fuel should be designed with minimum allowable P/D.

Pins with small diameters and non-absorbing fuel matrices are preferable with regard to obtain low coolant void worth. However, even an application of strongly absorbing matrix (HfN), does not have to deteriorate the void worth critically; large amount of negative reactivity still being introduced into the reactor upon voiding both core and upper plenum, as e.g. in the case of TRU-fuelled ADS.

Acknowledgements

Financial support of the Swedish Nuclear Fuel and Waste Management Co (SKB AB) is acknowledged.

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