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PDS-XADS LBE and Gas-Cooled Concepts: Neutronic Parameters Comparison

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Within the European Fifth Framework Program, Preliminary Design Studies of an eXperimantal Accelerator Driven System (PDS-XADS) are focussed on options employing Lead-Bismuth Eutectic (LBE) and helium gas coolants. Two of the options employ 80 MWth subcritical cores which are driven by a 600 MeV proton beam with a maximum current of 6 mA, the proton beam impinging on a windowless LBE target near the core center.

The current comparison of the two systems in terms of static and kinetic subcriticality parameters exhibits a much larger transport effect in the Gas-Cooled XADS, reflecting the strong anisotropy of scattering in the low density regions. Generally speaking, the Gas-Cooled XADS is more difficult to calculate, the overall neutron balance being determined by enhanced core/reflector interface effects.

KEYWORDS: PDS-XADS, LBE, Ansaldo, Gas-Cooled, Framatome, transmutation, neutronics, ERANOS-2.0, ERALIB-1, kinetic parameters

1. Introduction

Though the problem of the closure of the nuclear fuel cycle is not completely solved, the largest part of the long-lived nuclear waste may be eliminated by partitioning and transmutation, provided that a neutron flux with adequate energy and intensity can be employed. In this framework, the Accelerator Driven System (ADS), coupling a high energy, high current proton accelerator with a subcritical reactor has a remarkable potential, allowing the minimisation of the high level waste while operating in a safe manner [1]. For such systems, the subcriticality requirement under all normal and off-normal operation conditions imposes restrictions on the maximal k_{eff}-design value, which additionally depends on the calculation uncertainty. In order to obtain improved design characteristics, the k_{eff}-uncertainties in current-day calculations should be further decreased. Also important, in this context, is an accurate prediction of the proton beam current needed to obtain the operational power. In order to be able to construct facilities of this type within a “medium” time-frame of approximately 10-15 years, the difficult task of developing minor actinide (MA) loaded fuel is bypassed by basing the design on existing fast reactor fuel. MAs and selected long-lived fission fragments will be introduced in dedicated cores only in a later phase, especially at locations where the neutron energy corresponds to enhanced resonance absorptions to maximise the incineration yield.

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The current investigations are focussed on two XADS options, employing Lead-Bismuth Eutectic (LBE) [2] and helium gas coolant, respectively. In the current comparison of the two systems, the cores analysed use fuel having the isotopic composition of the higher enrichment MOX fuel (23.25% Pu) of the second Superphénix core. The required transport-theory calculations are performed using ERANOS (Version 2.0) [3,5] in conjunction with the adjusted JEF-2.2 data library ERALIB-1. The distribution of the external neutron source in energy and space is set equal to the distribution in energy and space of the neutrons resulting from a stochastic calculation with the code MCNPX [6], in which the high energy neutrons originating from spallation protons are tracked until their energy becomes $\leq$20 MeV. The resulting yield amounts to $\sim$14 neutrons per accelerator proton and this value is used throughout the analysis. The three-dimensional nodal transport-theory code TGV-VARIANT is used in conjunction with 33 neutron broad group cross sections, the detailed geometry of the XADS being described with great care using a (hexagonal,z)-model. The required three-dimensional forward and adjoint calculations are performed using the simplified P_1 approximation.

Summarised in Section 2 are the computed subcriticality and main kinetic parameters for fresh fuel compositions, as well as the variations of k_{eff} resulting from the use of modified options in the deterministic calculation. Compared are in Section 3 the burnup characteristics of the two systems, including the impact key issue on the proton beam current. Section 4 summarises comparative cross section sensitivity studies, whereas Section 5 deals with investigations of the sensitivity of the subcriticality parameters resulting from variations in the external source term. Finally, in Section 6, conclusions are drawn.

2. Sensitivity to Approximations in the Deterministic Calculation

The reference static subcriticality parameters, k_{eff}, the total number M of fission neutrons born in the system, normalised to one external source neutron, the so called source multiplication factor k_s and importance φ^*, the required proton beam current I, accelerator power P and source strength $<S>$, are summarised in Table 1, whereas the main kinetic parameters, β_{eff}, Λ and λ^{-1}, are given in Table 2, assuming fresh fuel compositions. k_{eff}-variations resulting from the use of modified options in the deterministic calculations are given in Table 3.

Table 1 Reference static parameters for the LBE and Gas-Cooled XADS

XADS	k_{eff}	M	k_s	φ^*	I	P	$<S>$
					mA	MW	$10^{17}s^{-1}$
LBE	0.96802	29.9	0.96760	0.986	2.48	1.49	2.17
Gas-Cooled	0.94877	22.4	0.95736	1.212	3.46	2.07	3.02

Table 2 Reference kinetic parameters for the LBE and Gas-Cooled XADS

Parameter XADS	Value	
	LBE	Gas-Cooled
β_{eff} (pcm (a))	312	336
Λ (μs)	2.084	0.705
λ^{-1} (s)	12.03	11.37

XADS	Time group	1	2	3	4	5	6
LBE	β_{eff} (pcm (a))	8	67	56	111	51	18
Gas-Cooled		8	68	58	121	59	22
XADS	Nuclide	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
LBE	β_{eff} (pcm (a))	11	105	158	15	20	1
Gas-Cooled		10	144	146	16	18	1

(a) 1 pcm=10^{-5}

The smaller k_{eff}-target value of the Gas-Cooled XADS ($\sim$0.95) is dictated by general safety-related considerations for which criticality conditions must be excluded under any foreseeable occurrence pertaining to both Design Basis and Design Extemsion Conditions. The larger source importance φ^* results mainly from the fast-spectrum region around the spallation target, which is neutronically "less dense" in the gas-cooled concept. The source importance being $>$1, the source multiplication factor k_s is larger than k_{eff}, whereas the two values are found to be similar in the case of the LBE XADS characterised by a φ^*-value of $\sim$1. The much larger transport effect in the Gas-Cooled XADS (1267 versus 270 pcm) reflects the strong anisotropy of scattering in the low density regions and is consistent with MUSE 4 results [7], whereas special care must be additionally given to the correct calculation of subcritical region broad group cross sections: k_{eff} would increase erroneously by 2000 pcm if the subcritical regions were to be treated as homogeneous media.

Table 3 k_{eff}-variations for the LBE and Gas-Cooled XADS

XADS	LBE	Gas-Cooled
Effect on the VARIANT-k_{eff}-value resulting from the use of VARIANT with this type of modification	Δk_{eff} (pcm)	
Doubling the number of nodes	-5	-1
Modifying the nodal approximations	$<$100	$<$100
Doubling the number of groups	92	67
Transport (P_1) $\rightarrow$ Diffusion	-270	-1267
Effect on the VARIANT-k_{eff}-value resulting from the use of ECCO with this type of modification	Δk_{eff} (pcm)	
"Homogeneous" subcritical regions	267	2000
More detailed "reference route" (a)	151	58

(a) with explicit heterogeneous calculation in 1968 groups

The generation time Λ, which depends strongly on the neutron mean free path, is obviously larger in the LBE case, whereas the delayed neutron fraction β_{eff} is slightly smaller. Otherwise the kinetic parameters are similar, reflecting the fact that the same fuel composition is assumed.

The Gas-Cooled XADS is more difficult to calculate, the overall neutron balance being determined by enhanced core/reflector interface effects: Despite the lower k_{eff}-value, the k_∞-value of the reflected fuel subassembly of the Gas-Cooled XADS (1.472) is significantly higher than the k_∞-value of the reflected fuel subassembly of the LBE XADS (only 1.360).

3. Burnup Characteristics

Fig.1 displays the proton beam current, normalised number of fission neutrons born in the system, multiplication and source multiplication factor as well as source importance, as a function of burnup. By assuming, for example, one-batch operation, the fuel discharge burnup (corresponding to the maximum beam current of 6 mA) is $\sim$20 MWd/kg for the Gas-Cooled XADS and $\sim$25 MWd/kg for the LBE XADS. The larger source importance φ^* of the Gas-Cooled XADS ensures that these two values are relatively close in spite of the more negative reactivity level of the Gas-Cooled XADS. If the source importance would have been the same, the ratio of the currents would about equalise the ratio of the reactivities, which is $\sim$1.6 for Beginning of Cycle conditions (see Table 1). The 20%-larger source importance in the case of the Gas-Cooled XADS ensures that the actual value of the ratio of the currents is reduced correspondingly to $\sim$1.4. As indicated by perturbation-thoery considerations [8], the relative variation of φ^* is much smaller than for the other parameters, the φ^*-curve in Fig. 1 being that closest to a horizontal line.

The integral kinetic parameters are found to be almost burnup independent and insensitive to calculation approximations, mainly as a consequence of compensating effects between the Pu isotopes.

4. Cross Section Sensitivity Studies

The following cross section sensitivity study was performed based on first order perturbation theory assumptions. The uncertainty analysis is carried out using available covariance matrices from ERALIB-1 given in 15 energy groups. Table 4 below indicates that the overall uncertainty in k_{eff} is rather small which justifies the use of a "well" adjusted cross section library in these calculations. The LBE XADS, however, shows a higher uncertainty (439 versus 205 pcm) due to the significantly larger amount of Pb and Bi, the data of which has presently not been adjusted in the ERALIB-1 library.
The main uncertainty of the LBE XADS appears to be due to uncertainties in ^{209}Bi (285 pcm), Pb (231 pcm) and ^{239}Pu (195 pcm). Whereas in the case of the Gas-Cooled XADS employing PE16, a Ni-based alloy, as the main structural material, the main contributions are ^{58}Ni (118 pcm) and ^{239}Pu (115 pcm).

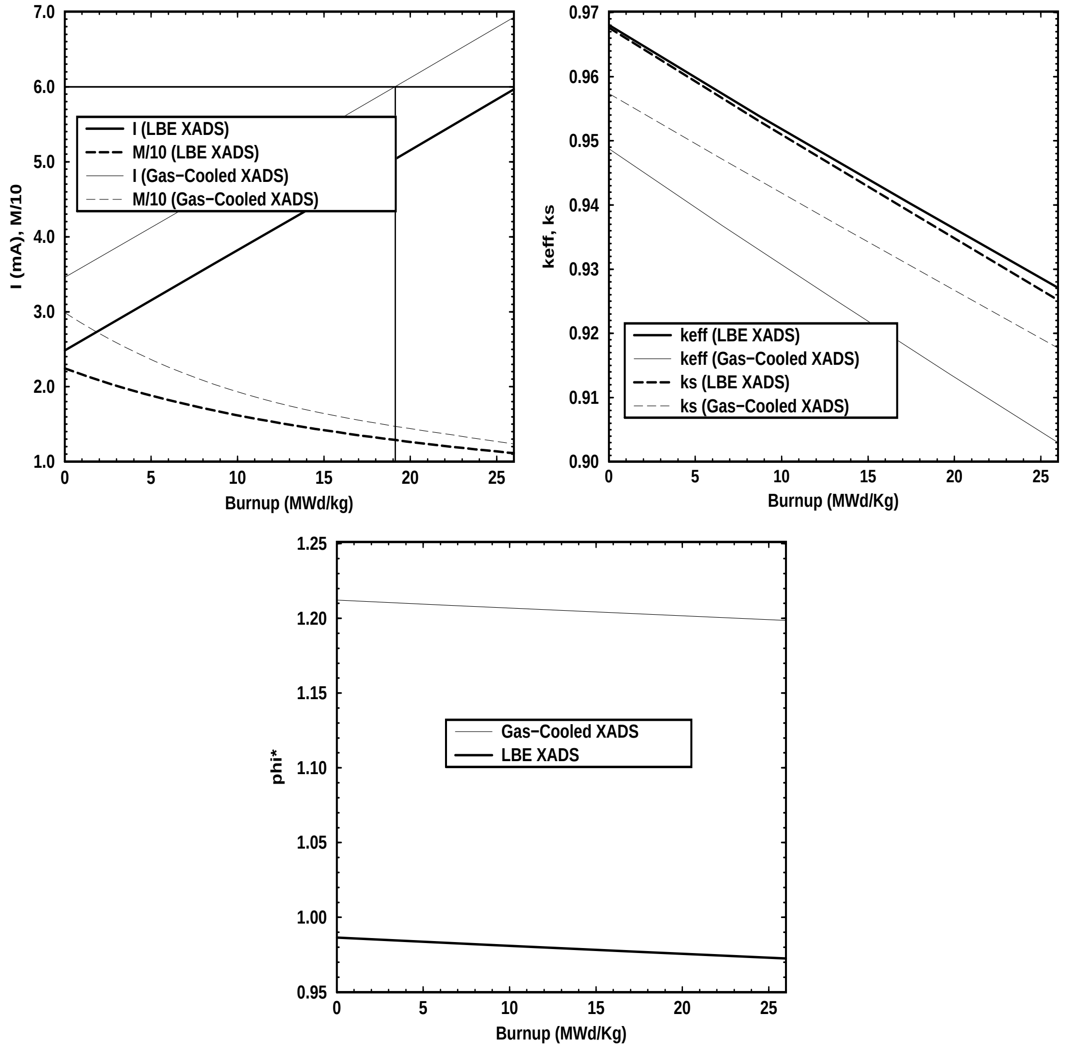

Fig.1 Beam current (I), normalised number of fission neutrons (M/10), multiplication factor (“keff”), source multiplication factor (“ks”) and source importance (“phi*”)

In Fig. 2, lethargy dependent sensitivity coefficients (e.g. $(\Delta k_{eff}/k_{eff})/(\Delta\sigma_g/\sigma_g)/\Delta U_g$, with g being the group index and ΔU_g the groupwise lethargy width) are displayed for representative high sensitivity materials, e.g. ^{239}Pu, ^{209}Bi, ^{238}U and ^{58}Ni for the Gas-Cooled XADS.

For the actinides in general it appears that despite the different neutron spectra such profiles exhibit similar trends for the LBE and Gas-Cooled XADS, e.g. a strong positive sensitivity of k_{eff} to the fission reactions between 100 keV and 1 MeV, the domain in which most fissions occur, and a lower negative sensitivity to the capture cross section. The sensitivity to the capture cross section is highest for ^{238}U, a nuclide for which the inelastic scattering reaction is also particularly important.

The k_{eff}-sensitivities to lead and bismuth are similar. The sensitivities are negative in the case of the LBE XADS and the most important reaction is by far inelastic scattering around 2 MeV. Particularly an increase of the inelastic scattering cross section of the coolant reduces the fission probability for neutron energies at which most fission neutrons are generated, and thus k_{eff} decreases. The presence of LBE only in the target in the case of the Gas-Cooled XADS is likely responsible for the positive k_{eff} sensitivity to the elastic scattering cross section. An increase of the elastic scattering cross section might increase the source multiplication, in this case.

The k_{eff}-sensitivity to the most important structural material (e.g. ^{58}Ni) of the Gas-Cooled XADS is particularly large for the elastic scattering and capture reactions.

Table 4 k_{eff}-uncertainty due to nuclear data uncertainties

	LBE XADS	Gas-Cooled XADS
Nuclide	Associated k_{eff}-uncertainty (pcm)	
^{235}U	25	15
^{238}U	88	59
^{237}Np	1	1
^{238}Pu	14	14
^{239}Pu	195	115
^{240}Pu	79	69
^{241}Pu	39	31
^{242}Pu	5	5
^{241}Am	69	62
Pb	231	34
^{209}Bi	285	42
^{56}Fe	31	48
^{52}Cr	17	50
^{57}Fe	24	28
^{58}Ni	3	118
Total	439	205

5. Sensitivity to the External Neutron Source Term

In an earlier study [8], effects have been investigated for the LBE XADS coming from the displacement of a prescribed external neutron source in a finite volume, in both axial and radial directions, from variations of the volume of the source region, as well as those resulting from spectral variations. The influence of external source neutrons born outside the target region was also estimated. All these effects being found to be small, similar analyses were performed for the Gas-Cooled XADS, revealing equally small sensitivities to the external neutron source characteristics. As an illustrative example, results are presented (see Table 5 below) , in which the subcritical cores of the LBE and Gas-Cooled XADS are driven, in turn, by two different sources with exactly the same spatial distribution as calculated by MCNPX. The spatially independent neutron spectrum of the first source corresponds to the average neutron spectrum resulting from the envisaged 600 MeV proton beam, whereas the neutron spectrum of the second source corresponds to the neutron spectrum resulting from a proton beam of 1 GeV (see Fig. 3 below). In these calculations, the same neutron yield of 14 neutrons per proton is assumed.

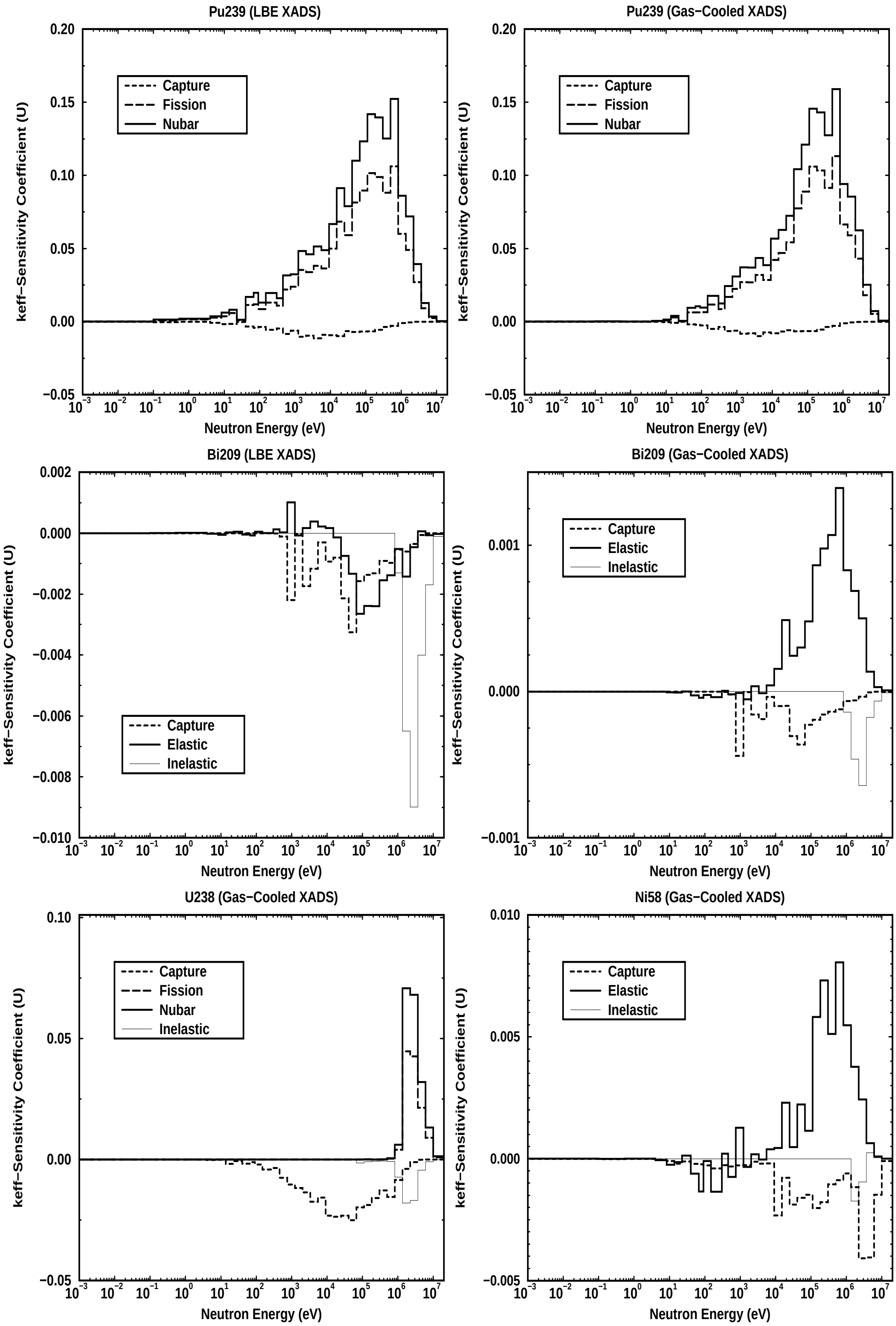

Fig.2 Sensitivity profiles of k_{eff} due to important nuclides and reactions

Table 5 Static parameters for external sources with different energy distributions

XADS	Proton energy	M	k_s	φ^*	I	P	<S>
	MeV				mA	MW	$10^{17}s^{-1}$
LBE	600	29.9	0.96760	0.986	2.48	1.49	2.17
	1000	30.4	0.96812	1.003	2.45	1.47	2.14
Gas-Cooled	600	22.4	0.95736	1.212	3.46	2.07	3.02
	1000	22.8	0.95794	1.230	3.41	2.04	2.97

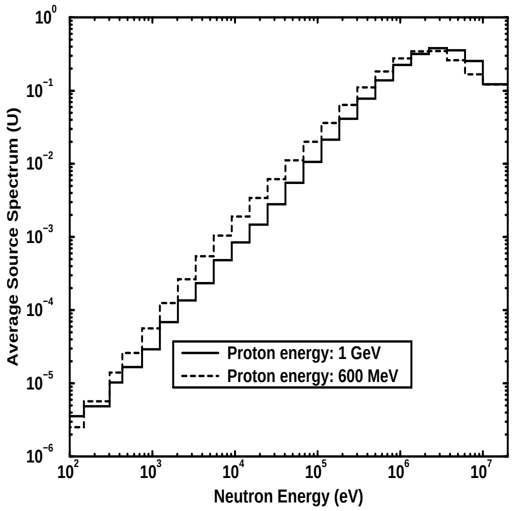

Fig.3 Average energy spectra of the external neutron source

Even under the assumption of a much harder source spectrum, the decrease of the proton beam current due to the resulting harder neutron spectrum is quite modest. Of course the effects would be much more significant, if the correct neutron yield for 1 GeV protons (∼20) would be used.

6. Conclusions

Comparative numerical simulations have been performed for two systems: the liquid lead-bismuth eutectic (LBE) cooled experimental accelerator driven system currently envisaged by Ansaldo and the corresponding gas-cooled system proposed by Framatome. Though the current project option of employing Superphénix MOX fuel was considered, similar trends can be expected for advanced minor actinide based fuels. Whereas variations in the methods (diffusion, transport, etc.) have a significant impact on the computed k_{eff}-value particularly for the gas-cooled concept, their influence on kinetic parameters is marginal. The sensitivity to the characteristics of the external neutron source being used in the calculations is quite small. Reducing the uncertianties in the high energy spallation source calculation for systems using Pb-Bi for the target and either Pb-Bi or He for the coolant materials does not appear to be a crucial issue, except for the neutron yield per accelerator proton, since its value has a direct impact on the subcriticality parameters.

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