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A small lead-cooled reactor with improved Am-burning and non-proliferation characteristics

Janne Wallenius *, Sara Bortot

KTH, Division of Nuclear Engineering, Albanova University Centre, 10691 Stockholm, Sweden
LeadCold Reactors, Valhallavägen 79, 114 28 Stockholm, Sweden

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ABSTRACT

In this paper, a novel approach for transmutation of americium in fast reactors is presented. Using enriched uranium as fissile support, rather than plutonium, it is shown that a minor actinide burning rate of 25 kg/TWh$_{th}$ is possible to achieve in a passively safe, *critical* lead-cooled reactor. Moreover, the plutonium produced by transmutation of ^{241}Am features up to 38% ^{238}Pu, making it difficult to use for weapons production.

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1. Introduction

Transmutation of minor actinides in fast reactors has been investigated as a waste management option since the 70s (Beaman, 1979). Among the options most widely investigated are.

- Homogeneous transmutation in the driver fuel of fast reactors (Murata and Mukaiyama, 1984; Zhang et al., 2010; Buiron et al., 2011)
- Heteregenous transmutation in minor actinide burning blankets (Buiron et al., 2011; Koch, 1986; Kooyman et al., 2017)
- Transmutation in accelerator driven systems incorporating uranium free fuels (Takizuka et al., 1989; Tsujimoto, 2004; Fokau, 2010)

The introduction of americium in the driver fuel of fast reactors has a detrimental effect on safety parameters, such as the Doppler feedback, coolant temperature coefficient and effective delayed neutron fraction (Wallenius, 2012). Hence, the higher Am content in the fuel, the lower the permitted power density (Zhang et al., 2010, 2013; Zhang and Wallenius, 2014). This issue can be addressed by loading the americium in blanket assemblies, where the impact on reactor safety performance during transients is limited (Kooyman et al., 2017). However, the lower neutron flux in blanket positions, along with fuel cycle constraints, limit the specific minor actinide burning rate to about 2 kg/TWh$_{th}$ (Buiron et al., 2011).

Out of the above listed approaches, the highest specific transmutation rate (42 kg/TWh$_{th}$) is achieved in accelerator driven systems (ADS) (NEA, 2002). However, the costs associated with development, construction and operation of such systems would be considerable. Therefore, it is of interest to investigate if the impact on safety performance of critical fast reactors can be reduced by redesigning their driver fuel.

2. Rationales and design methodology

It is well known that the presence of even neutron number plutonium nuclides (^{240}Pu and ^{242}Pu) contributes significantly to the positive coolant temperature coefficient of liquid metal cooled fast reactors having a breeding ratio equal to unity. Substituting plutonium with ^{235}U, the reactivity increase resulting from a reduction in coolant density is significantly reduced, and the associated coolant temperature coefficient is usually negative for smaller cores with larger leakage (Tsuboi, 2012; Wallenius, 2018). In addition, the delayed neutron fraction in fission of ^{235}U is considerably higher than for fission in plutonium nuclides. Therefore, an initially plutonium free fuel, where enriched uranium is supporting the chain reaction, will improve safety parameters, allowing to introduce more americium into driver fuel assemblies. Moreover, the absence of plutonium reduces the build-up of americium from decay of ^{241}Pu and neutron capture in ^{242}Pu, which increases the specific minor actinide transmutation rate.

* Corresponding author at: KTH, Division of Nuclear Engineering, Albanova University Centre, 10691 Stockholm, Sweden.
E-mail addresses: janwal@kth.se (J. Wallenius), bortot@kth.se (S. Bortot).

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Whereas the breeding ratio of fissile nuclides in the conventional sense might be smaller than unity, the transmutation of ^{241}Am mainly leads to the production of ^{238}Pu, which in a typical fast spectrum has a fission probability of the order of 80% and an η-value as high as 2.3. In conjunction with ^{239}Pu ($\eta = 2.5$) produced by neutron capture on ^{238}Pu, the inventory of *reactivity* can be preserved. In addition, the prevalence of ^{238}Pu makes the plutonium formed during operation of the reactor less suitability for weapons production.

In this paper, we modify the existing SEALER core design (Wallenius, 2018) to explore the parameters space for americium transmutation in small critical lead-cooled reactors. The UO_2 fuel foreseen for the commercial SEALER concept is substituted with a (U,Am) N fuel, offering additional advantages in terms of higher fissile density and power to melt. We note that (U,MA) O_2 has been studied as a driver fuel for an accelerator driven system (Chen and Rineiski, 2016), though in that case, the advantages in terms of safety performance were not investigated.

2.1. Fuel and core design

The original SEALER design (Wallenius, 2018) is intended to replace diesel generators for commercial power production in remote areas. As uranium-oxide fuel is employed, SEALER's conversion ratio is much below unity. In order to improve the conversion ratio and preserve reactivity, a (U,Am) N fuel is applied for the design of the minor actinide burning variation of the reactor (SEALER-Am). For a given fraction of americium, the uranium enrichment is obtained by requiring a reactivity swing of less than 350 pcm for a peak damage dose to the fuel cladding of 120 dpa. At this dose, the core average burn-up is about 50 GWd/ton. No fuel reloading is required to achieve this burn-up.

By varying the fraction of americium in the fuel between 10 and 18% it is found that uranium enrichments between 17 and 20% (i.e. LEU) allow to meet the reactivity swing criterion. In a fuel with 18% americium, the decay heat in the fresh fuel assembly remains below 5 kW, keeping a sufficient margin to the limit of 7.5 kW where handling in air would become problematic (Buiron et al., 2011).

The approximate actinide mass in the SEALER-Am core is three tons. Adopting a fuel specific power density of 100 W/g results in a total core power of 30 MW_{th}. With such operational parameters, the damage dose limit of 120 dpa corresponds to a core life of 14 full power years. A total life of the plant of 30 years may then be accommodated by conducting a mid-life replacement of the core, combined with a major refurbishment campaign.

The small reactivity swing means that conventional control rod assemblies are not required. Instead, injection of lead-lithium in centrally located rods in each of the seven central fuel assemblies can be used to compensate for the reactivity swing. The control rod assembly positions of the original SEALER design are here occupied by reflector assemblies. Moreover, expensive shield assemblies have been eliminated, since the core barrel may be replaced during the mid-life core replacement.

The core map is depicted in Fig. 1. The core consists of 19 fuel assemblies, 6 shutdown assemblies (shown withdrawn in Fig. 1) and 36 reflector assemblies.

It may be noted that when varying the Am content from 10 to 20%, the total decay heat of fresh fuel assemblies ranges from 50 to 100 kW, which is roughly equal to heat losses by radiation through the primary vessel. Hence, costs for keeping the lead-coolant liquid during outages are reduced.

In order to ensure adequate heat-removal, the pin pitch is increased from the original SEALER design to reach an overall coolant volume fraction of 40% in the core. Since the shield assemblies are eliminated, the diameter can be kept unchanged at 2.75 m.

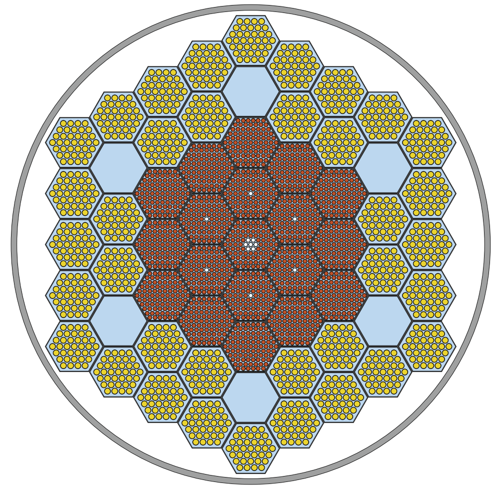

Fig. 1. Core map of SEALER-Am.

Fuel cladding tubes are made of Sandvik's 15-15Ti grade 12R72, which contains less silicon than AIM1, while having a composition similar to the 1.4970 grade. Such tubes were recently produced by Sandvik for the MYRRHA project (Delville et al., 2014). Corrosion protection is ensured by surface alloying the tubes with Fe-10Cr-6Al-RE (Ejenstam et al., 2013), using the GESA method developed by KIT (Weisenburger, 2011). "RE" is short for "Reactive Elements", which are added to the steel in trace amounts to improve the quality of the alumina layer forming once the material contacts with oxygen containing lead.

The SEALER-Am fuel rod has the same radial dimensions as the original SEALER rod. However, due to the large production of helium resulting from transmutation of ^{241}Am, the internal gas plenum length has to be increased from 350 mm to a length equal to the fuel column height.

Dimensions of the assembly hex-cans are adjusted to fit the larger pin-pitch of SEALER-Am. Further details about the SEALER-Am geometry are provided in Table 1.

Assembly ducts are assumed to be manufactured from Fe-10Cr-4Al-RE (Ejenstam et al., 2013; Ejenstam and Szakalos, 2015), which is expected to be weldable and irradiation tolerant. Recently, Sandvik has produced an industrial ten ton batch of this material for the H2020 NEXTOWER project. Shapes (bands) suitable for making ducts are readily manufacturable.

Table 1
Core design parameters of SEALER-Am.

Item	Value
Fuel assemblies	19
Fuel pins per assembly	91
Fuel rod diameter	1.452 mm
Fuel rod pitch	1.760 mm
Fuel rod P/D	1.212
Shut-down assemblies	6
$(W,Re)^{10}B_2$ rods/shut-down assembly	7
$(W,Re)^{10}B_2$ rods diameter	37.40
Shut-down assembly rod pitch	45.00 mm
Reflector assemblies	60
Reflector rod diameter	2.140 mm
YSZ rods/reflector assembly	37
Reflector rod pitch	25.07 mm
Hex-can inner flat-to-flat	170.4 mm
Hex-can outer flat-to-flat	174.4 mm
Hex-can pitch	176.4 mm

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