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On the Feasibility of ADS-Representative Integral Experiments Using Limited Amounts of Low-Enriched U-Fuel

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A study has been carried out to show that generic integral experiments pertaining to the physics of accelerator-driven systems (ADS) are possible with an appropriately designed, multizone subcritical configuration employing limited amounts of low enriched U-fuel. Although plutonium and minor actinides would not be used in significant amounts (except for small samples, such as foils for activation), the suggested experiments would be representative of a typical minor actinide burning ADS in terms of the test zone neutron spectrum. The new experiments would thus enable a "first-of-its-kind" characterisation of the interface between a spallation target and a subcritical fast assembly and also give the opportunity of improving the nuclear data required for the calculation of such an ADS, their uncertainties being presently too high for design studies.

KEYWORDS: ADS, representative integral experiments, driven multizone configuration, fundamental mode spectrum, minor actinide burner, data validation

I. Introduction

The objective of the present study is to analyse the feasibility of multizone subcritical configurations employing relatively limited amounts of low-enriched U-fuel for generic zero-power experiments related to the design of accelerator-driven systems (ADS). These experiments would principally be dedicated to the study of the interaction between a spallation source and a fast-spectrum region surrounding the target.

Although plutonium and minor actinides would not be used in significant amounts (except for small samples, such as foils for activation), the experiments would be "first-of-their-kind". Their relevance would be ensured by their meeting appropriate design criteria such as:

- The k_{eff} value for the experimental configuration is in the range ~0.8 to 0.9.
- Calculated values of characteristic mid-plane spectral indices are almost constant across the test zone when the configuration is considered on its own (i.e. with the neutron source switched off). These values are close to corresponding fundamental-mode (FM) values, which would arise in a much larger single-region type of situation for the test zone having the same k_{eff} value as the experimental setup. In other words, the mid-plane neutron spectrum in the test zone is close to the FM-spectrum for the fast lattice under investigation.
- The test zone spectrum is similar to that of a minor actinide burner, e.g. that represented by the recently proposed NEA benchmark.[1)] Except for self-shielding effects, reaction rate ratios for capture and fission in the different actinides of interest hence have representative values from the viewpoint of assessing wastes transmutation capability.

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II. The Experimental Configuration Considered

Minimising the fuel inventory in conjunction with the need for a fast-spectrum region clearly calls for a driven system similar to those used for certain earlier programmes such as the PROTEUS-GCFR (gas-cooled fast reactor) experiments.[2)]

In the configuration proposed, fuel for the test zone is 5 wt% enriched UO_2. The fuel envisaged for the buffer region is natural uranium metal and that for the D_2O-moderated thermal spectrum driver is again 5 wt% enriched UO_2. A D_2O reflector forms the outermost region of the multizone configuration. The volume of the test zone is ~65 l, that of the complete system ~3200 l. The UO_2 and the U-metal inventories are as low as ~0.4 and 2 t, respectively. The use of H_2O or graphite as moderator and reflector, instead of heavy water, is less favourable with the given constraints. Due to the small fuel inventory, a thin boron layer needs to be inserted between the test and buffer zones all along the axial length of the system. The "1/v"-absorber acts as a neutron filter, further reducing the thermal driver's spectral perturbation of the test zone.

The specifications of the fuel rods envisaged are given in **Tables 1-2**. The p/d values (p being the pitch of the hexagonal lattice and d the diameter of the fuel rod including the cladding) are 1.12 for the test and buffer zones, and 4.10 for the driver region. The p/d value for the driver corresponds to a pitch of 5 cm, which was chosen such as to maximise the critical buckling for the corresponding unit cell.

A representative, central Pb spallation region has been considered. **Fig. 1** indicates the dimensions of the various individual zones constituting the experimental configuration. The proposed active length for the fuel rods positioned in the test zone is 55 cm, that for rods in the driver zone being 60 cm. The Pb rods used in the axial reflector region above the test zone would be arranged in the same way and have the same outer dimensions as the fuel rods positioned in the test zone. **Table 3** summarises the main design characteristics for the multizone experimental configuration considered.

Table 1 Specifications of the fuel rods in the test and driver zones

Fuel Rod Zone (i)	Outer Radius R_i (cm)	Material	Density (g/cm^3)
1	0.508	UO_2 (5 wt% ^{235}U)	10.4
2	0.55	Air	0.001
3	0.61	Al	2.702

Table 2 Specifications of fuel rods in the buffer zone

Fuel Rod Zone (i)	Outer Radius R_i (cm)	Material	Density (g/cm^3)
1	1.0	Natural U	18.96
2	1.02	Air	0.001
3	1.12	Al	2.702

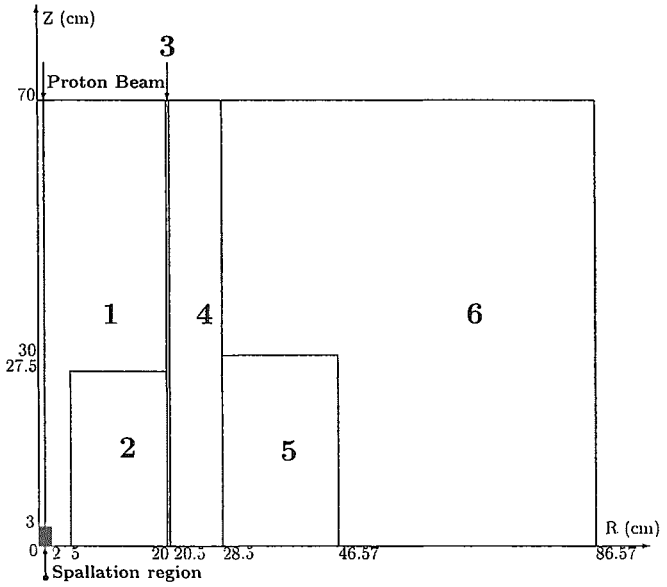
III. Calculational Methods

The various lattices were represented by the corresponding Wigner-Seitz cells, with Dancoff factors for hexagonal geometry being applied. For each cell, the two-region MICROX-2 cell code[3] was employed to generate 66-group cross sections, as well as the global fission spectrum, via a two-region resonance calculation on a hyperfine energy grid between 7.1 keV and 2.38 eV, cladding and coolant region being smeared. Non-fuel cells were treated by means of slowing-down calculations in infinite, homogeneous media with representative source spectra. In each case, the group structure consisted of 32 fast groups equally spaced in lethargy ($\Delta u = 0.5$) between 15 MeV and 2.38 eV, and 34 thermal groups below 2.38 eV. A JEF-2.2[4] based data library was used throughout. The broad group cross sections generated were subsequently employed in two-dimensional S_N-transport-theory calculations of the whole configuration with TWODANT,[5] using P_2S_8 approximations, with the system being assumed symmetric in the axial direction. In the calculations with spallation source, the spectrum of the neutron source was approximated by the one used in the ADS-Neutronics Benchmark Study coordinated by the IAEA, the source being assumed to be uniformly distributed in a central cylindrical volume of radius 2 cm and height 6 cm.

IV. Results

Table 4 characterises the experimental configuration considered in terms of k_{eff} values, thermal power and average neutron flux levels, 250 MeV protons having been assumed to impinge upon the spallation target. It is seen that sufficiently high neutron flux levels ($\sim 10^{10}$ n/s/cm^2) should be obtained for performing various types of integral measurements with accelerator currents as low as 0.1μA.

The quality of the proposed configuration needs to be assessed from the viewpoint of the desired spectral characteristics outlined in Section I. As indicated earlier, one criterion is to consider a hypothetical large configuration of the test-lattice with the same k_{eff} value as the system proposed. A reference FM-spectrum is thus clearly established in the central part of the hypothetical configuration, and modelling of its interaction with the spallation source can serve as standard for comparative purposes. Due to the relatively low k_∞ value of the currently considered test zone, the large reference system needs an additional driver region to achieve the target k_{eff} value of 0.839.



1: Pb region, 2: Test zone, 3: Boron layer,
4: Buffer zone, 5: Driver zone, 6: D_2O Reflector region.

Fig. 1 Proposed experimental configuration: R-Z model, mirror symmetric about the horizontal plane

Table 3 Main geometrical characteristics of the multizone system

Zone	p/d	Volume (l)	Fuel Type, Composition	Number of Rods	kg Fuel
Test	1.12	64.8	UO_2 (5 wt% ^{235}U)	728	339
Buffer	1.12	172.4	Nat. U	225	1876
Driver	4.10	255.7	UO_2 (5 wt% ^{235}U)	196	100

Table 5 gives a comparison of the resulting fuel inventories in the actual and large hypothetical configurations considered, thereby underlining the huge economy of materials implicit in the former.

In **Table 6**, mid-plane spectral indices (microscopic reaction rate ratios expressed relative to ^{235}U fission) are compared between the actual and large systems, for one representative radial position (r = 8.75 cm), with the spallation source switched off. F25, F28, F37, F49, F51 and F53 respectively denote the microscopic (i.e. per atom) neutron-induced fission rates for ^{235}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{241}Am and ^{243}Am, as would occur in a fuel pellet. Similarly, C28 and C37 denote the microscopic neutron capture rates for ^{238}U and ^{237}Np, respectively. It is seen that agreement is quite satisfactory (within $\sim$10%) in most cases, indicating that the effects of the outer zones are not too significant in the experimental configuration proposed.

Table 4 Some key parameters for the experimental configuration

Parameter	System
k_{eff}	0.839
Power Dissipated in the System (kW/μA)	1.1
Average Flux (10^{10}n/s/cm^2/μA)	1.3
Average Flux in the Test Zone (10^{10}n/s/cm^2/μA)	8.1

Table 5 Zone-dependent fuel inventories (kg) for the actual and large hypothetical configurations

System	Test Zone	Buffer Zone	Driver Zone
Actual	339	1876	100
Large	262800	44740	7680

In order to demonstrate the representativeness of the fast spectrum of the considered test lattice, a comparison of cell calculations (with leakage effects taken into account via appropriate buckling values) has been made with those for the minor actinide (MA) burner benchmark proposed by the NEA.[1] **Table 7** gives the results for spectral indices in the two different cases.

The relative differences in the microscopic reaction rate ratios (~30% on average) are not that large, confirming that the values in the proposed configuration would be quite representative for the experimental assessment of wastes transmutation capability. Viewed from the perspective of data validation, the proposed experiments would clearly help resolve the significant MA-specific discrepancies being reported in the context of ADS benchmarks.[7]

As expected, good agreement is achieved between the results from the cell calculation of the test zone and the corresponding results for the large system as given in **Table 6**. The slight discrepancies observed can be attributed to differences in leakage treatment between MICROX-2 and TWODANT.

In **Table 8**, the proposed multizone configuration is compared with the large hypothetical system, with the spallation source switched on in each case. The agreement is seen to be satisfactory, i.e. within ~10% for each spectral index at the chosen reference position (r = 8.75 cm).

Table 6 Results from 2-D k_{eff} calculations, without source, for the actual and large systems (spectral indices, rel. to ^{235}U fission, at r = 8.75 cm)

Ratio	Actual System	Large System
C28/F25	0.127	0.137
F28/F25	0.021	0.018
C37/F25	0.876	0.892
F37/F25	0.148	0.124
F49/F25	0.941	0.892
F51/F25	0.124	0.105
F53/F25	0.095	0.080

Table 7 Comparison of spectral indices for the considered test lattice and for the NEA MA burner benchmark

Cell Type	Test Zone	MA Burner
	FM	
	k_{eff} = 0.839	k_{eff} = 0.950[a]
k_∞	0.803	1.196
M^2 (cm^2)[b]	300.6	230.2
C28/F25	0.137	0.161
F28/F25	0.018	0.022
C37/F25	0.888	0.772
F37/F25	0.127	0.198
F49/F25	0.895	0.992
F51/F25	0.108	0.161
F53/F25	0.083	0.126

[a] Calculation performed with the ECCO cell code.[6]
[b] $M^2=[(k_\infty/k_{eff})-1]/B^2$.

In **Table 9**, the proposed configuration is compared with the large system in terms of changes induced by the source in values of the spectral indices. The relative effects of the source are seen to be quite similar, indicating the representativeness of the proposed configurations from the viewpoint of investigating the physics of the interface between spallation source and subcritical fast assembly.

Table 8 Spectral indices at r = 8.75 cm, from 2-D calculations with source

Ratio	Actual System	Large System
C28/F25	0.108	0.109
F28/F25	0.075	0.078
C37/F25	0.588	0.585
F37/F25	0.403	0.407
F49/F25	1.139	1.132
F51/F25	0.382	0.390
F53/F25	0.310	0.318

Table 9 Changes (%) in spectral indices at r = 8.75 cm induced by the source

Ratio	Actual System	Large System
C28/F25	-15	-20
F28/F25	257	333
C37/F25	-33	-34
F37/F25	172	228
F49/F25	21	27
F51/F25	208	271
F53/F25	226	297

For providing deeper insight, **Fig. 2** gives mid-plane profiles in the test zone for a representative spectral index, viz. F37/F25. The figure contains curves for the actual and large systems, with and without the source. Furthermore, neutron spectra at r = 8.75 cm in the large hypothetical system, with and without the source, are displayed in **Fig. 3**, the FM-spectrum of the MA burner being shown additionally for comparative purposes.

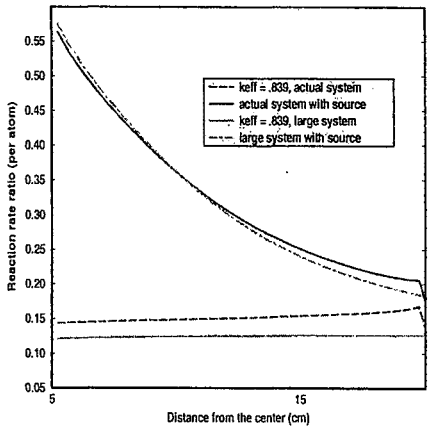


Fig. 2 Mid-plane profiles for F37/F25

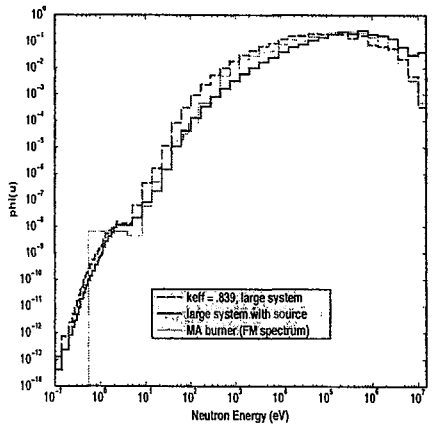


Fig. 3 Representative neutron spectra

The following principal observations may be made from **Figs 2** and **3**:

For the cases in which the spallation source is switched off

- the spectral index profiles are almost flat across the test zone
- the profiles for the actual and large systems are similar, implying that the ratios of spectral indices in the former are close to the FM values aimed for
- the test zone spectrum is quite similar to the FM-spectrum of the minor actinide burner cell.

When the spallation source is switched on

- the test zone spectrum becomes harder
- the source effects diminish with distance, almost vanishing completely at the test zone boundary
- the profiles for the actual and large systems are quite similar.

V. Conclusions

The present first-level feasibility study has shown that generic integral experiments in ADS physics are possible with an appropriately designed, multizone subcritical configuration employing limited amounts of low-enriched U-fuel. Assuming 250 MeV protons to be impinging on the central Pb spallation target, the designed k_{eff} value of $\sim$0.85 for the multizone assembly would result in neutron flux levels of $\sim 10^{10}$ n/s/cm^2/μA. The suggested experiments would be representative of a minor-actinide burning ADS in terms of the test-zone neutron spectrum and would enable "first-of-its-kind" characterisation of the interface between a spallation target and a subcritical fast assembly.

In the configuration proposed, fuel for the fast test zone is 5 wt% enriched UO_2. The fuel envisaged for the buffer region is natural-U metal and that for the D_2O-moderated thermal-spectrum driver is again 5 wt% enriched UO_2. A D_2O reflector forms the outermost region of the multizone configuration. The volume of the test zone is $\sim$65 l, that of the complete system $\sim$3200 l.

In separate calculations, a strong sensitivity of the results to the modelling of the spallation source was observed, particularly with respect to assumptions regarding homogeneity and isotropy. It should be noted that no explicit intermediate-energy calculations have currently been performed for detailed treatment of source characteristics. Further numerical investigations related to modelling of the spallation target would thus be useful for confirmation of the broad conclusions drawn from the current study. Also worthwhile in this context would be to consider the effects of varying the test zone fuel composition, e.g. of employing a higher enrichment for the UO_2 and/or of replacing the oxide by more dense, metallic uranium.

Acknowledgment

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