STEADY STATE CALCULATIONS IN SUPPORT OF THE MUSE-4 EXPERIMENTAL PROGRAMME

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ABSTRACT

This paper describes steady state neutronic calculations which were performed (using the CEA's ERANOS code suite) in order to provide technical support to the MUSE-4 experiments which are currently being carried out at CEA Cadarache. The results described herein were generated in parallel with the experiments in an attempt to eliminate erroneous measurements at an early stage. Calculational results are presented for parameters such as reactivity, delayed neutron data, flux contours and sensitivities. The calculations concentrate on the reference MUSE-4 core which is a critical configuration (subsequent sub-critical cores will be realised in the immediate future).

The MUSE-4 project is a European collaboration partially sponsored by Euratom (via the Vth Framework Agreement).

1. INTRODUCTION

As a result of the continuing interest in Accelerator Driven Systems (ADS) as a possible means of ameliorating global nuclear waste arisings, the MUSE-4[1] (**MU**ltiplication **S**ource

Externe) experimental programme was initiated in 2000 (and is currently underway) in the MASURCA facility at CEA Cadarache. The MUSE-4 project covers the construction, characterisation and numerical analysis of a reactor which is representative of a fast spectrum MOX fuelled sodium cooled core. The novelty and uniqueness of the MUSE-4 experiments is due to the inclusion of the GENEPI deuteron accelerator, which guides and focuses a deuteron beam onto a deuterium or tritium target in order to produce neutrons via the $D(d,n)^3He$ or the $T(d,n)^4He$ fusion reactions. Several configurations will be analysed; a reference critical core followed by cores with varying degrees of sub-criticality (in which the neutron source due to GENEPI will act in a similar manner to that of the spallation source of a commercial ADS).

One of the objectives of the MUSE-4 project is to assess the applicability of deterministic neutronics packages such as ERANOS[2] (developed primarily for critical fast reactor analyses) to ADS in general. This paper will describe the analyses of MUSE-4 carried out via the ERANOS code suite and, where available, will also present direct comparisons between measured and predicted data.

2. REACTOR CONFIGURATION

Each of the MUSE-4 experimental configurations is composed of ~25w/o Pu mixed oxide (MOX) fuel loaded according to Figure 1 (given at the end of the paper) surrounded by a sodium/stainless steel (NaSS) reflector region. Finally, steel axial and radial screens surround the entire central structure. The GENEPI deuteron accelerator channel is situated at the mid-plane of the core following the north-south axis and is characterised by a steel tube which incorporates a tritium or deuterium target at its extremity. Lead is loaded around the target, and also in the canal extension beyond, in order to retain a certain amount of flux symmetry. The total critical MOX fuel mass is approximately 1550 kg.

3. CALCULATIONS

3.1 DESCRIPTION OF WORK

The work described in this paper was carried out in order to support the MUSE-4 experimental programme and to assist with the specification of the core configurations. A range of parameters such as reactivity, direct and adjoint fluxes, delayed neutron parameters, radial and axial reaction rate traverses and sensitivity analyses were generated. Wherever possible, direct comparisons were made between the ERANOS calculated values (generated using a dataset made available to all MUSE-4 partners) and the actual measured data. This was done in a bid to ensure the quality of the experimental results (i.e. any erroneous measurements should have become apparent).

3.2 CALCULATIONAL METHOD

All of the calculated data reported in this paper were generated using the ERANOS[2] deterministic code suite (**E**uropean **R**eactor **An**alysis **O**ptimised **S**ystem), which was developed by the CEA in collaboration with other R&D organisations. The JEF 2.2 nuclear data library was used throughout this work. Both 3D (TGV) and 2D (BISTRO) neutronic models of the MUSE-4 cores were constructed (using S4P1 transport theory) and the resultant flux solutions and group constants were then processed using the diverse range of functions embedded within the overall ERANOS calculational scheme.

3.3 REACTIVITY

The core reactivity was estimated to be -277pcm using TGV. This compares with an experimental value of **-**80pcm. Note however that TGV has difficulty modelling void regions therefore the beam guide was represented as an homogenised region over which the guide material was smeared. BISTRO calculations (which can model void) estimated that the reactivity effect of this homogenisation is approximately +100pcm (due to the decrease in neutron streaming). If the -277pcm figure is adjusted accordingly then a reactivity of -377pcm is obtained. Note that an uncertainty of approximately ±300pcm is associated with this value.

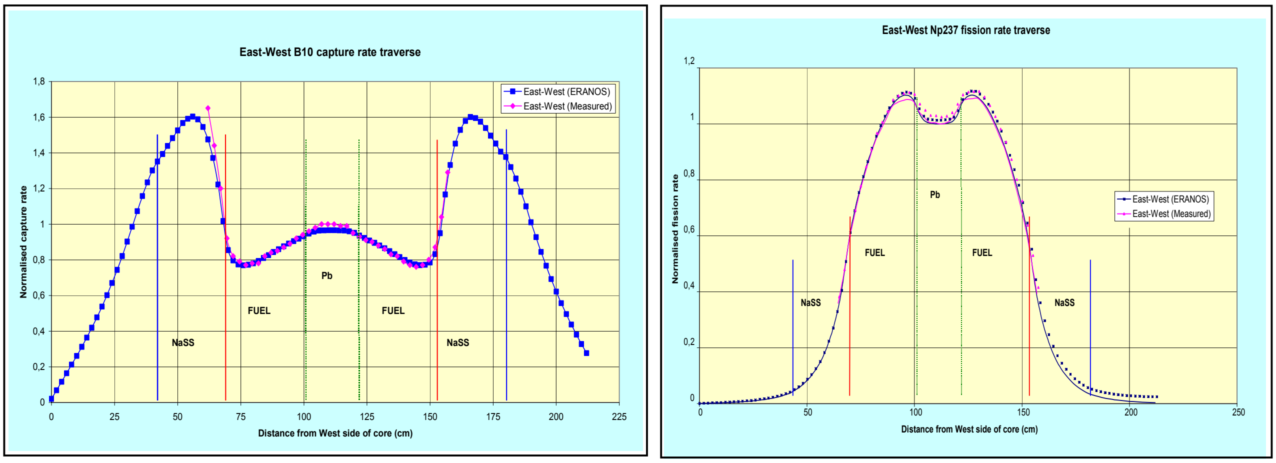
3.4 DELAYED NEUTRON PARAMETERS

Using an automated sequence in ERANOS β_{eff} was estimated at 327pcm with a corresponding generation time of Λ = 5.16 E-7 seconds. These results were required for the interpretation of dynamic measurements for MUSE-4[3,4].

3.5 FLUX CONTOURS

A matrix of radial and axial traverses was generated for MUSE4(Ref.) in order to facilitate a comparison between predicted and experimental reaction rates. The intention was to confirm that the ERANOS reaction rate predictions are consistent with the measured experimental values. If this is the case, then the total fission rate as calculated by TGV will be accepted with a certain confidence level.

As an example, Figures 2(a) and 2(b) compare provisional measured and predicted Np^{237} fission and B^{10} capture rates along the East-West measurement channel:-



Figures 2(a) and 2(b) : Exp. vs. calculated ^{237}Np fission rate and ^{10}B capture rate traverses

As an aid to visualising the reactions taking place in the core a set of radial traverses were carried out with ERANOS at the core mid-plane height (Figures 3(a) to 3(e)). The U^{235} microscopic fission rates mapped the entire plane over different energy ranges. These data are plotted for 4 energy intervals; 0-0.1 keV, 0.1-10 keV, 10-100 keV and 100 keV-20 MeV. An additional graph is included showing the total ^{235}U radial microscopic fission rate distribution. (Note that Figure 1 should be used in order to interpret these results, the reaction rates correspond to a total core power of 1W and the values are given in fissions/atom/sec).

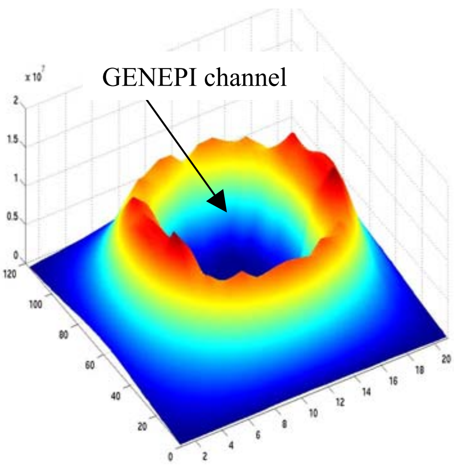


Fig. 3(a) : ^{235}U microscopic fission rate in core mid-plane (0-0.1keV)

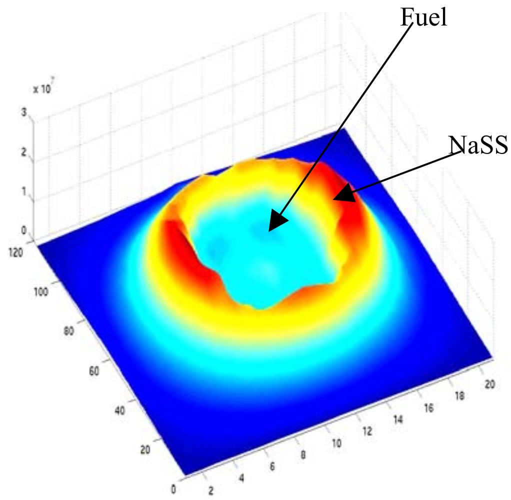


Fig. 3(b) : ^{235}U microscopic fission rate in core mid-plane (0.1-10keV)

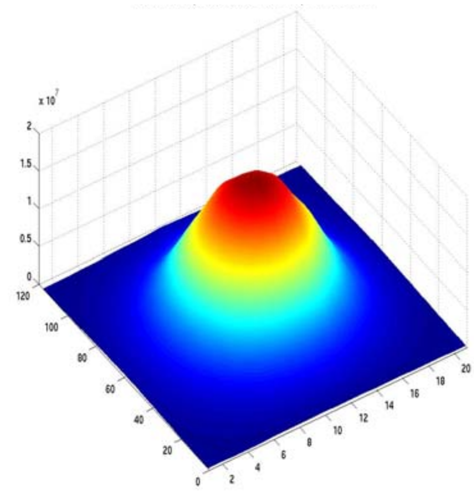


Fig. 3(c) : ^{235}U microscopic fission rate in core mid-plane (10-100keV)

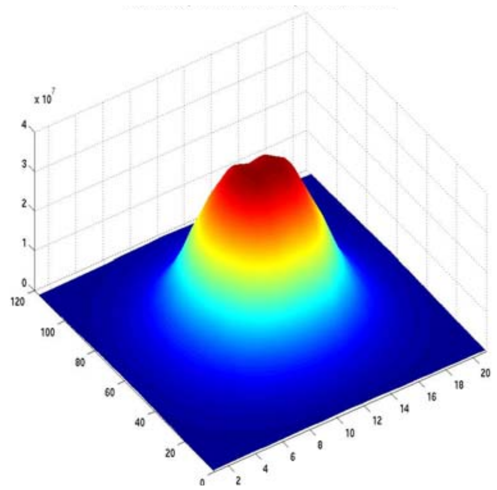


Fig. 3(d) : ^{235}U microscopic fission rate in core mid-plane (100keV-20MeV)

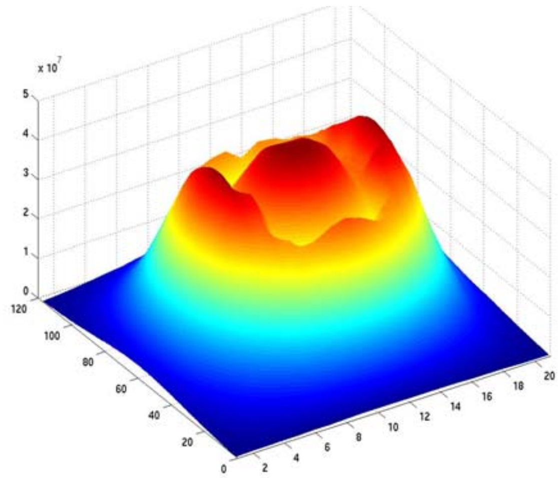


Fig. 3(e) : ^{235}U microscopic fission rate in core mid-plane integrated over energy

At lower energies the effect of the NaSS reflector on the microscopic reaction rate can be plainly seen, with the Na softening the flux spectrum (therefore increasing the U_{235} fission rate). In addition, the GENEPI guide tube can also be identified by virtue of its lack of moderating material (leading to a decrease in the ^{235}U fission rate).

When higher energy intervals are considered, it can be seen from the graphs that the majority majority of the ^{235}U fast fissions occur within the fuel region (as expected, since the spectrum will be at its hardest close to the MOX).

For completeness, the flux spectrum as calculated by ERANOS is presented in Figure 4 at the locations of detectors I, L and F (see Figure 1). The characteristic Na and O absorption troughs can be plainly seen within the reactor core (detectors I, L and F) at ~3keV and ~400kEV respectively.

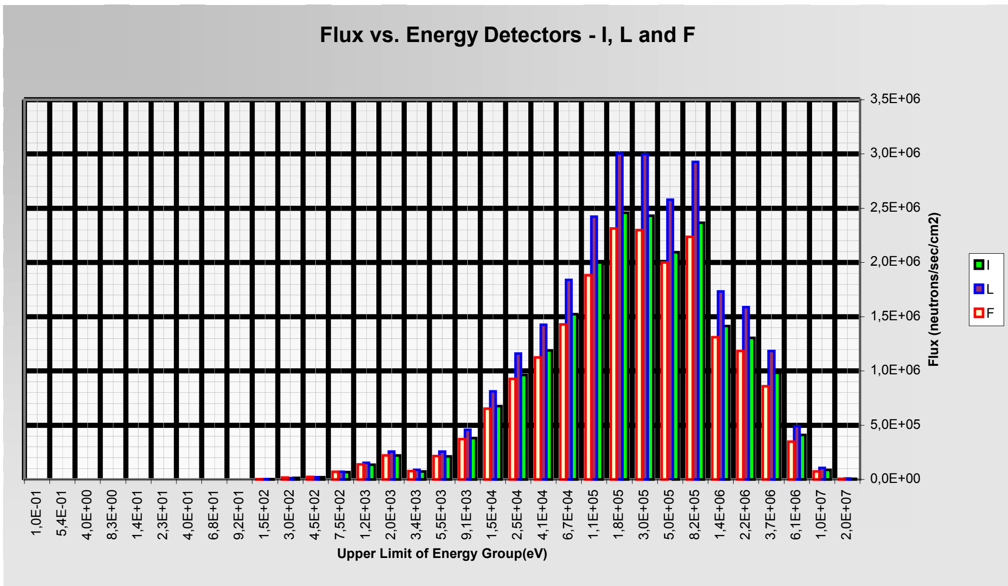


Figure 4 : Flux Spectrum at Detector Locations from ERANOS

3.6 SENSITIVITY CALCULATIONS

ERANOS contains a module which uses perturbation theory to evaluate the sensitivity of k_{eff} to a change in concentration of a given isotope. Results are given in the following Table for the fuel and the NaSS reflector. The isotopes are ranked in order of decreasing reactivity worth. The sensitivity factors, S, correspond to the estimated change in reactivity in pcm as a result of a 1% change in isotopic concentration. The full set of results gives a comprehensive breakdown of each S factor by core region (fuel, reflector, Pb zone, etc), isotope, energy and cross-section. This routine is particularly useful when determining the effect of nuclear data uncertainties for a given isotope on k_{eff}, for example.

Table 1 : Sensitivity of k_{eff} to a change in isotopic concentration

Homogenised Fuel region		NaSS Reflector	
Isotope	**S (pcm/%)**	**Isotope**	**S (pcm/%)**
Pu239	387	Fe56	38
U238	-379	Cr52	18
Pu240	15	Na	6
O	14	Ni58	5

Na	11	Fe54	5
Pu241	10	Ni60	3
U235	3	Si	2
Am241	-3	Mn	-2
Fe56	2	Co59	-2
Cr52	1	Cr53	1

3.7 GENEPI EFFECTS

Although analyses of dynamic tests from initial GENEPI runs have been carried out[3,4], at the time of writing this paper the experimental measurements of reaction rate profiles from a sub-critical MUSE-4 core coupled to GENEPI have yet to be fully determined. However, calculations have been carried out in advance in order to quantify the effect of the external neutron source on the flux distribution. The high energy neutrons from the (D,D) or (D,T) (2.67 and 14.1 MeV respectively) source will perturb the spatial flux distribution, leading to gradients which must be represented accurately in order to determine the power distribution (particularly in the regions adjacent to the neutron source).

By superimposing (via ERANOS) an external neutron source on a sub-critical MUSE4 core at the deuterium or tritium target location the effects of GENEPI on the flux distribution can be estimated. These analyses will be confirmed by the use of fixed in-core and ex-core detectors which should enable ERANOS predicted data (such as the following ^{235}U microscopic fission rate ($\sigma_f\phi$) maps (Figs.5(a) to 5(c)) for the MUSE-4 reference core at (i) nominal conditions, (ii) with a control rod inserted and (iii) with a control inserted and with GENEPI activated in (D,D) mode) to be verified :-

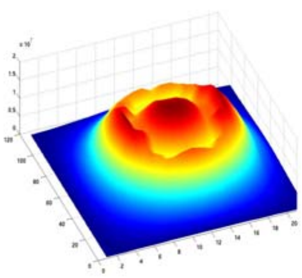


Fig.5(a) : MUSE-4 Ref.
rod
mode

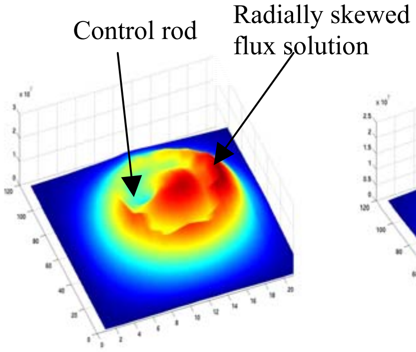


Fig.5(b) : MUSE-4 Ref. with 1 control rod inserted

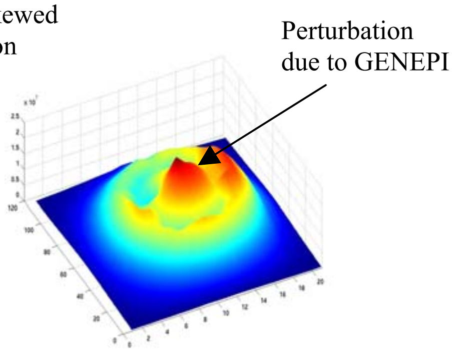


Fig.5(c) : MUSE-4 Ref. with 1 control inserted and GENEPI on in (D,D)

CONCLUSIONS

The ERANOS code suite has been used to construct 3D neutronic representations of the MUSE-4 fast reactor core configurations and to process the resultant flux solutions and group constants to obtain data required by the experimental team at the MASURCA facility at CEA Cadarache. The initial comparisons between measured and predicted data show that ERANOS gives good agreement with experimental results. Reaction rate measurements from a sub-critical core with GENEPI activated are expected shortly which will hopefully enable the validation matrix for ERANOS to be extended further.

ACKNOWLEDGEMENTS

The authors would like to thank Euratom for its sponsorship of the MUSE-4 project via the V^{th} Framework program.

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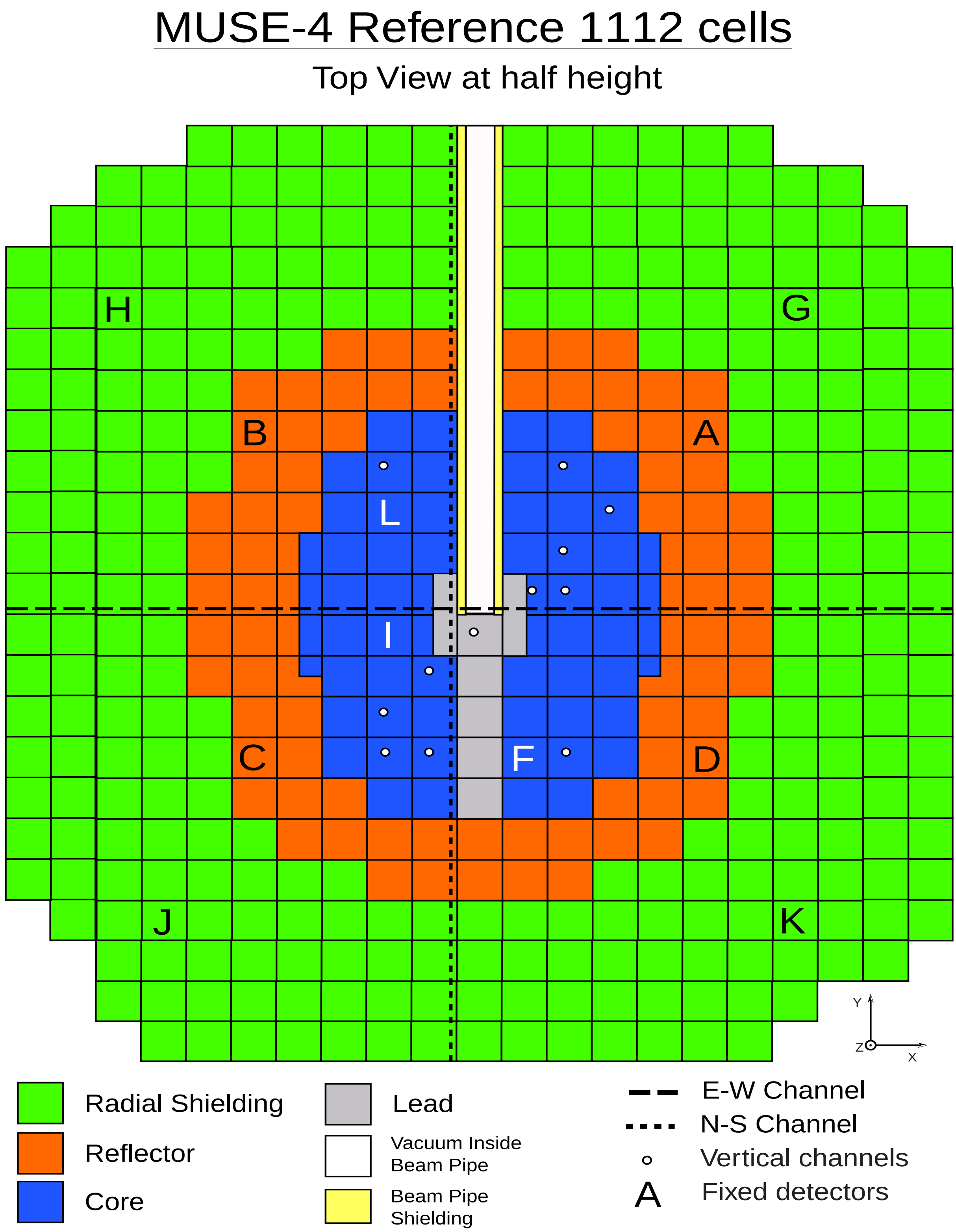

Figure 1 : MUSE-4 Reference Loading Pattern