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October 2001

UWFDM-1173

Presented at the 10th International Conference on Fusion Reactor Materials, 14–19 October 2001, Baden-Baden, Germany.

# Application of the IEAF-2001 Activation Data Library to Activation Analyses of the IFMIF High Flux Test Module

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October 2001

UWFDM-1173

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# Abstract

A complete activation data library IEAF-2001 (Intermediate Energy Activation File) has been developed in standard ENDF-6 format with neutron-induced activation cross sections for 679 target nuclides from Z=1 (hydrogen) to Z=84 (polonium) and incident neutron energies up to 150 MeV. Using the NJOY processing code, an IEAF-2001 working library has been prepared in a 256 energy group structure for enabling activation analyses of the IFMIF D-Li neutron source. This library was applied to the activation analysis of the IFMIF high flux test module (HFTM) using the recent ALARA activation code which is capable of handling the variety of reaction channels open in the energy domain above 20 MeV. The IEAF-2001 activation library was thus shown to be suitable for activation analyses in fusion technology and intermediate energy applications such as the IFMIF D-Li neutron source.

## I. Introduction

The International Fusion Material Irradiation Facility (IFMIF) [1] will provide an intense high-energy neutron field produced by 40 MeV deuterons impinging on a thick lithium target. The resulting neutron source spectrum will extend up to ≅ 55 MeV neutron energy. Numerous reaction channels are open in this energy region giving rise to a variety of activation and transmutation reactions which do not exist in the traditional energy domain below 20 MeV.

To perform activation calculations for the IFMIF D-Li neutron source requires (i) a complete activation data library comprising all target nuclides that may be present in the IFMIF facility and taking into account all activation and transmutation reactions that may occur over the whole neutron energy range from 55 MeV down to thermal energy, (ii) an activation code capable of handling an arbitrary number for activation reaction channels. A suitable activation data library, the Intermediate Energy Activation File IEAF-2001 [2] has been developed by a collaboration of Forschungszentrum Karlsruhe and the Institute of Nuclear Power Engineering, Obninsk, as part of the IFMIF project. The activation code ALARA (Analytical and Laplacian Adaptive Radioactivity Analysis), previously developed at the University of Wisconsin-Madison as an advanced computational tool for simulating induced activation in nuclear facilities [3], has the ability to handle the IEAF-2001 activation cross section data in a straightforward way.

In the following a short description is given of the IEAF-2001 library and the main features of the ALARA activation code. The application of the IEAF-2001 data to the activation analysis of the IFMIF high flux test module (HFTM) is presented including a description of the methodological approach applied. Results of the activation analysis for the HFTM with the low activation steel Eurofer 97 as structural material are presented and discussed.

## II. Intermediate Energy Activation File IEAF-2001

The Intermediate Energy Activation File IEAF-2001 [2] has been developed by a collaboration of Forschungszentrum Karlsruhe and the Institute of Nuclear Power Engineering, Obninsk, with the objective to provide the nuclear data base required for the activation analysis of the IFMIF D-Li neutron source. The IEAF-2001 library includes 679 (stable and unstable) target nuclides from Z=1 (hydrogen) to 84 (polonium) with neutron induced reactions from $10^{-5}$ eV to 150 MeV incident neutron energy.

The European Activation File EAF-99 [4] served as basis for the activation cross-section data below 20 MeV neutron energy. Threshold reaction cross-sections were evaluated on the basis of geometry dependent hybrid exciton and evaporation models using a modified version of the ALICE code [5]. The principal changes applied to the code concern the incorporation of algorithms for describing pre-equilibrium cluster emission (d, t, $^3$He, $\alpha$), pre-compound $\gamma$-ray emission and the calculation of nuclear level densities according to the generalized superfluid model [6]. A new computational approach based on diffraction theory and a modified intra-nuclear cascade model [7] was employed to evaluate the reaction cross sections for the light nuclei up to Z = 12.

The IEAF-2001 data library has been prepared in standard ENDF-6 data format making use of the MT=5 (neutron, anything) option with the excitation functions stored in MF=3 and the product nuclide vectors in MF=6 (LAW=0). An MF=2 resonance parameter skeleton has been formally added to allow the processing of the activation library with the NJOY code [8].

A 256 group library has been generated with NJOY/GROUPR on the basis of the IEAF-2001 point data to enable activation calculations for the IFMIF D-Li neutron source. The group data were generated for a temperature of 300 K assuming a flat weighting spectrum for the group cross section averaging. The final multigroup data set is a GENDF-formatted (groupwise ENDF) working library as provided by the GROUPR module of NJOY and can be used by any activation code capable of handling an arbitrary number of reaction channels.

The 256 energy group structure consists of the 175 VITAMIN-J groups below 20 MeV and 81 groups above. Constant energy bins of 1 MeV and 2 MeV were used for the energy domains 20–50 MeV and 50–150 MeV, respectively. This group structure is suitable for applications both in fusion technology and intermediate energy applications such as irradiation simulations for the IFMIF D-Li neutron source.

## III. ALARA activation code

ALARA is a next generation activation code designed for accuracy, speed and usability, and validated for use in fusion activation calculations [9]. Its basic features include multipoint simulations in a variety of geometries, user defined accuracy, and the tracking of stable isotope accumulation including light ions. The advanced features include the exact modelling of arbitrary hierarchical irradiation schedules and the ability to perform "reverse" calculations. Most important for this application, ALARA does not rely on a table of fixed reaction types and reaction channels. The reactions are defined entirely by the library, requiring only a list of resultant isotopes and cross sections for the production of each. This makes it ideal for extension to intermediate and high energy activation calculations.

## IV. IFMIF high flux test module

IFMIF provides a total neutron production of $\cong 1.1 \cdot 10^{17}$ $s^{-1}$ by bombarding a flowing liquid lithium target with two 125 mA deuteron beams of 40 MeV. This results in a maximum neutron flux density of $\cong 7.5 \cdot 10^{14}$ $cm^{-2}s^{-1}$ at the front surface of the High Flux Test Module (HFTM) which is placed downstream the beam adjacent to the lithium target. The HFTM is a steel container of 20 cm width, 5 cm height and 5 cm depth housing 27 helium cooled rigs which hold the material specimens enclosed in capsules. The specimens, made of the low activation (LA) steel Eurofer [10], will be subjected to a displacement damage accumulation of 20 – 50 dpa (iron) per full power year to simulate the radiation load of the highest loaded structural material components of a future fusion power reactor.

## V. Neutron transport and activation calculations

The geometrical model of the HFTM consists of a rectangular Eurofer steel block with a mass density of 6.24 $g/cm^3$ and the proper dimensions divided into small cubic segments of size 0.5 x 0.5 x 0.5 $cm^3$. Neutron flux spectra are calculated with the newly developed McDeLicious code [11] in 256 energy groups for each of the 1000 segments of one HFTM quadrant. McDeLicious is a further enhancement of the McDeLi code [12] with the ability to sample the generation of D-Li source neutrons from evaluated d + $^{6,7}$Li cross section data. Both McDeLi and McDeLicious make use of the MCNP Monte Carlo code [13] for performing the neutron and photon transport calculation. Two 125 mA deuteron beams are assumed in the McDeLicious calculation to be impinging on the lithium target at an angle of 10 degrees with respect to the horizontal center plane (see Fig. 1). The neutron flux spectra were normalized to a beam current of 2 × 125 mA. Figure 2 compares neutron flux spectra calculated for the HFTM with both McDeLicious and

McDeLi. Note the differences in the high energy part of the spectra that will affect the activation characteristics of the materials under irradiation.

ALARA activation calculations are performed for the Eurofer LA steel in each of the 1000 spatial segments taking proper account of the associated neutron flux spectrum. A continuous irradiation over a period of 5 full power years is assumed for the activation calculations with a truncation tolerance of $10^{-5}$. The elemental composition of the Eurofer LA steel (Table 1) has been adopted from the specification for Eurofer 97 [10]. Yield data of manufactured Eurofer 97 largely agree with the specified elemental compositions.

## VI. HFTM activation and afterheat

The specific activity and the afterheat power density of the HFTM are displayed in Figs. 3 and 4, respectively, as a function of the cooling time. These data have been averaged over the HFTM volume. The total activity inventory and afterheat power as calculated for the HFTM with a volume of 500 $cm^3$ and a mass of 3.12 kg steel is given in Table 2. At shutdown, the HFTM afterheat power amounts to 3.5% of the direct nuclear heating at operation. One day after shutdown, this value decreases to less than 1%. Only very few radionuclides are significantly contributing to the activity and the decay heat such as Mn-54, -56 and Fe-55 in the time range up to a few years after irradiation and H-3, C-14 afterwards. Both Mn-54, -56, Fe-55 and H-3 are primarily produced through (n,p), (n,2n) and (n,t) activation reactions on the natural iron isotopes whereas C-14 is an activation product of N-14. As a result of the various (n,t) reactions, there is a total tritium generation of some 4 mg per full power year in the HFTM. Threshold reactions in the high energy range above 20 MeV incident neutron energy do not significantly contribute to the activity and the decay heat of the HFTM. Likewise, the HFTM activation is not affected by reaction products of the heavy Eurofer constituents W and Ta.

## VII. Conclusion and outlook

The newly developed activation data library IEAF-2001 (Intermediate Energy Activation File) has been tested through the application to the activation analysis of the IFMIF high flux test module (HFTM) using the recent ALARA activation code. In this way, the IEAF-2001 activation library was shown to be suitable for activation analyses in fusion technology and intermediate energy applications such as the IFMIF D-Li neutron source. The IEAF-2001 library is thus ready for distribution via the NEA data bank. The IEAF-2001 cross section data can be used with any activation code capable of handling an arbitrary number of reaction channels. Testing of the IEAF data against integral experiments is considered an important next step to qualify and further improve the IEAF library.

## Acknowledgement

This work has been performed in the framework of the nuclear fusion program of Forschungszentrum Karlsruhe and is supported by the European Union within the European Fusion Technology Programme.

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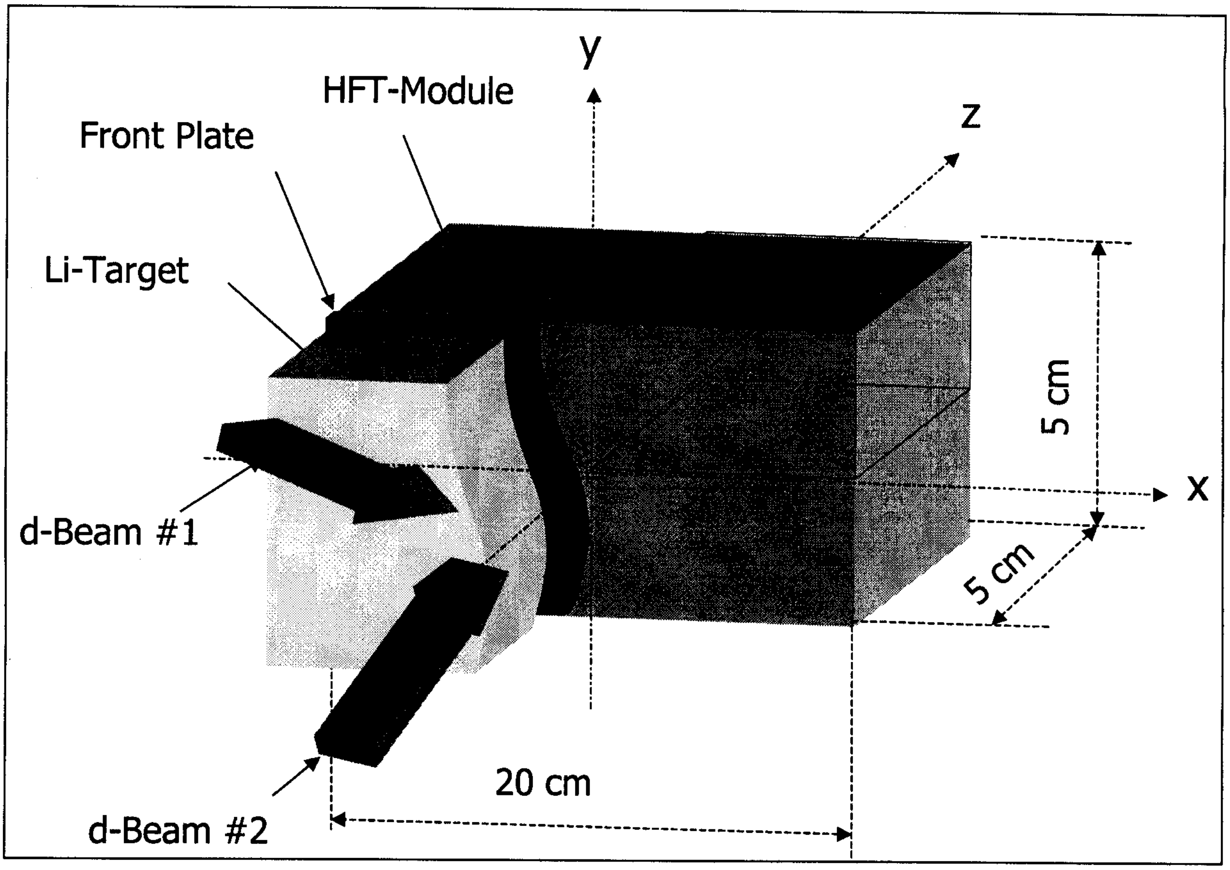

Fig. 1. Schematic HFTM model with deuteron beams and lithium target assumed for the neutronic and activation calculations.

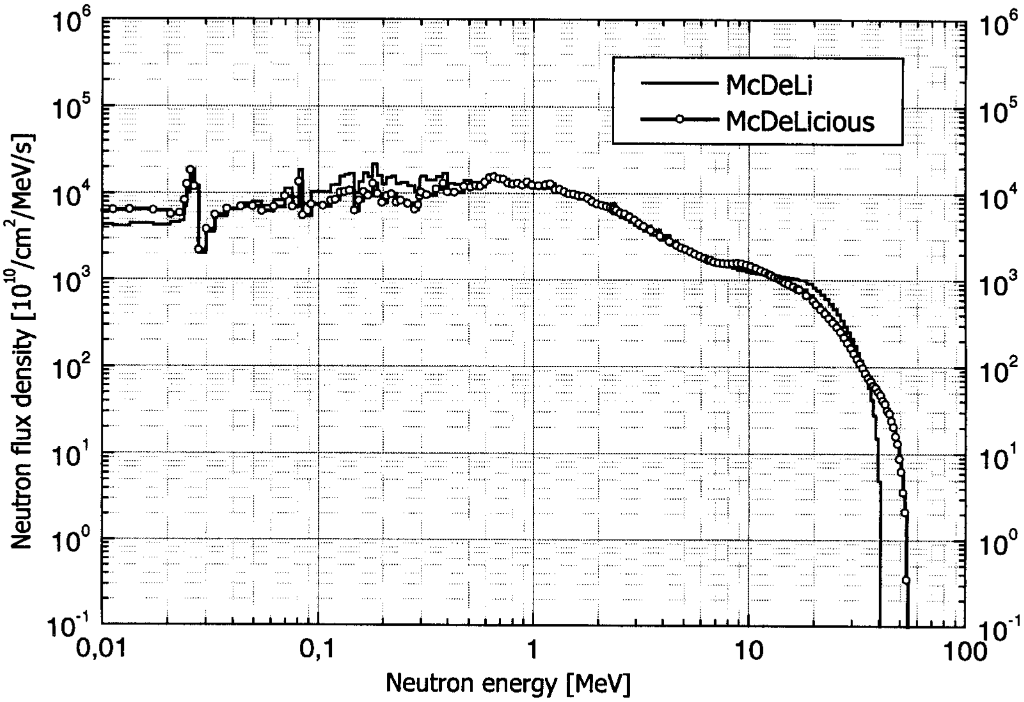

Fig. 2. Neutron spectra calculated with McDeLi and McDeLicious for the IFMIF HFTM.

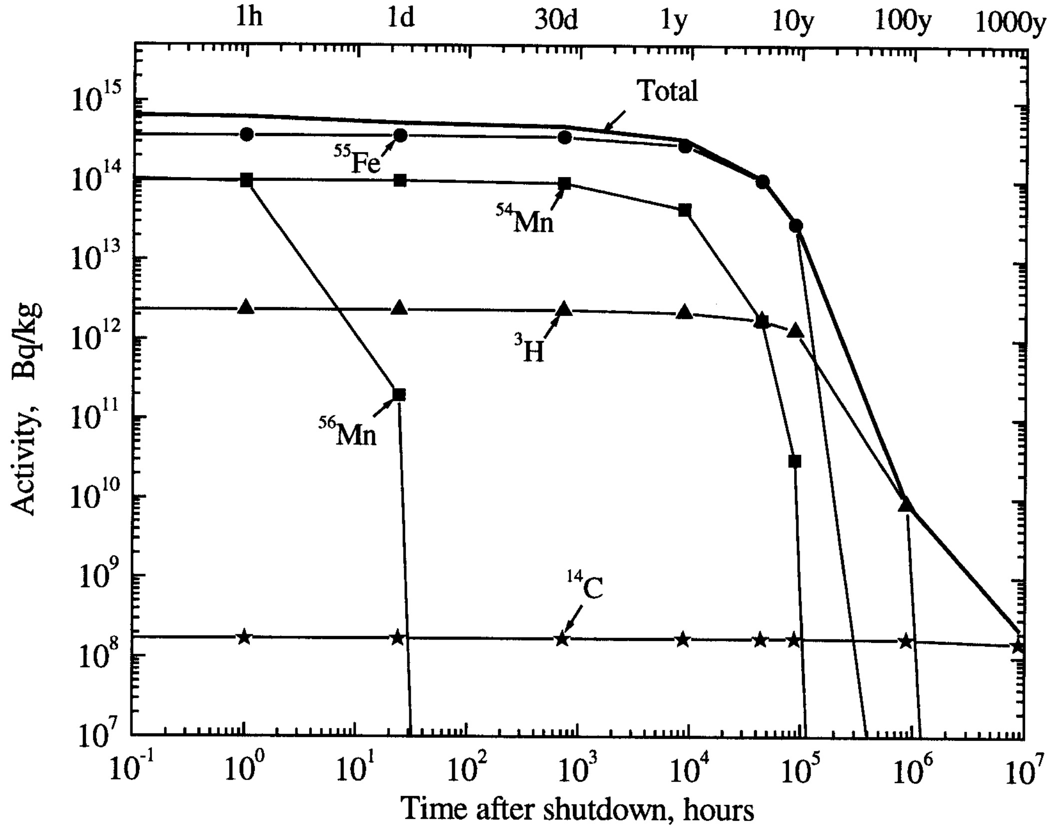

Fig. 3. Specific activity of HFTM as function of the cooling time.

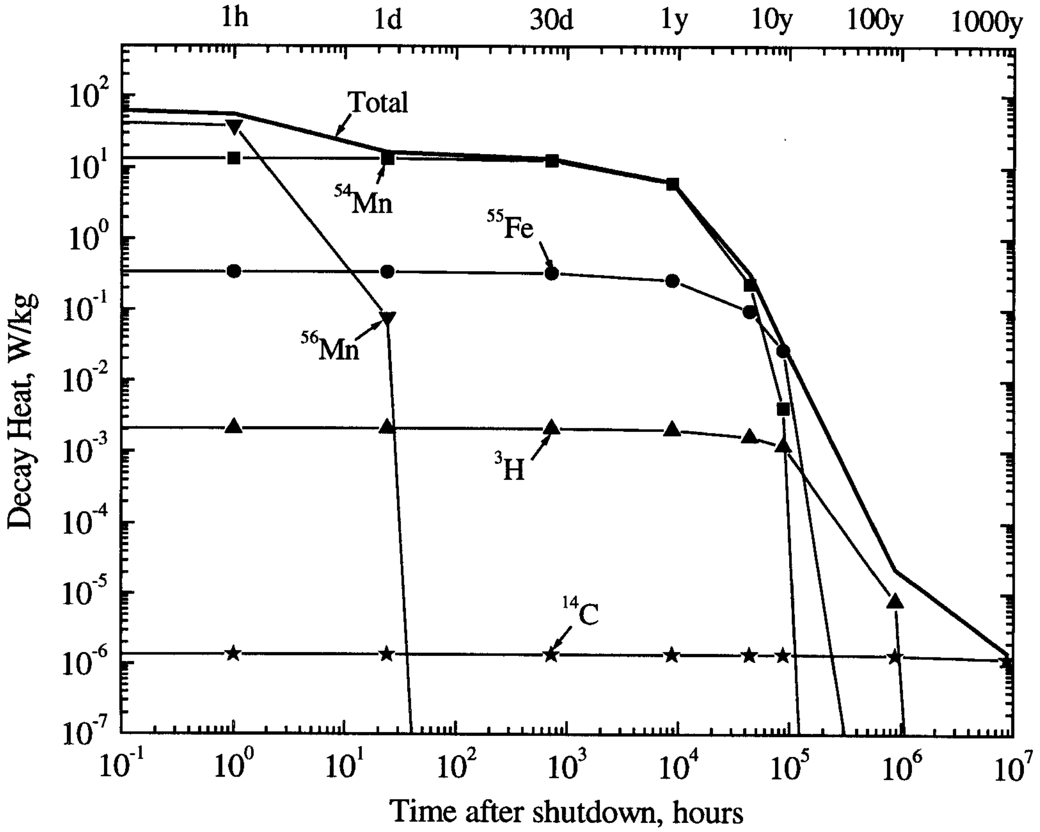

Fig. 4. Afterheat power density of HFTM as function of the cooling time.

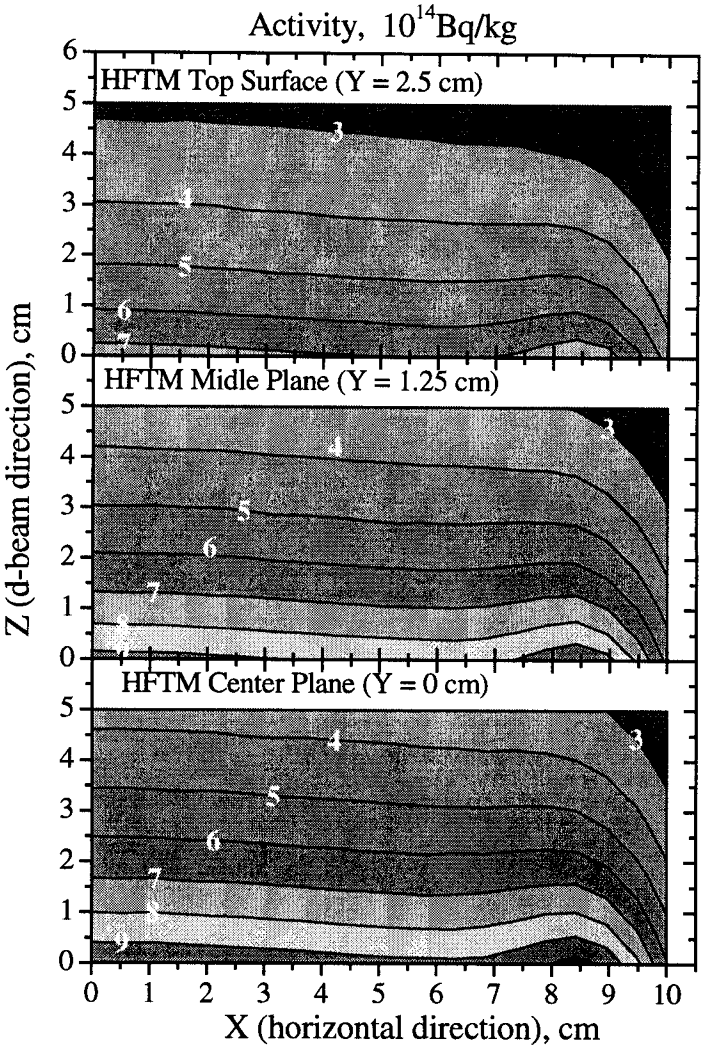

Fig. 5. HFTM contour plot of specific activity at three different vertical levels (1 day after irradiation).

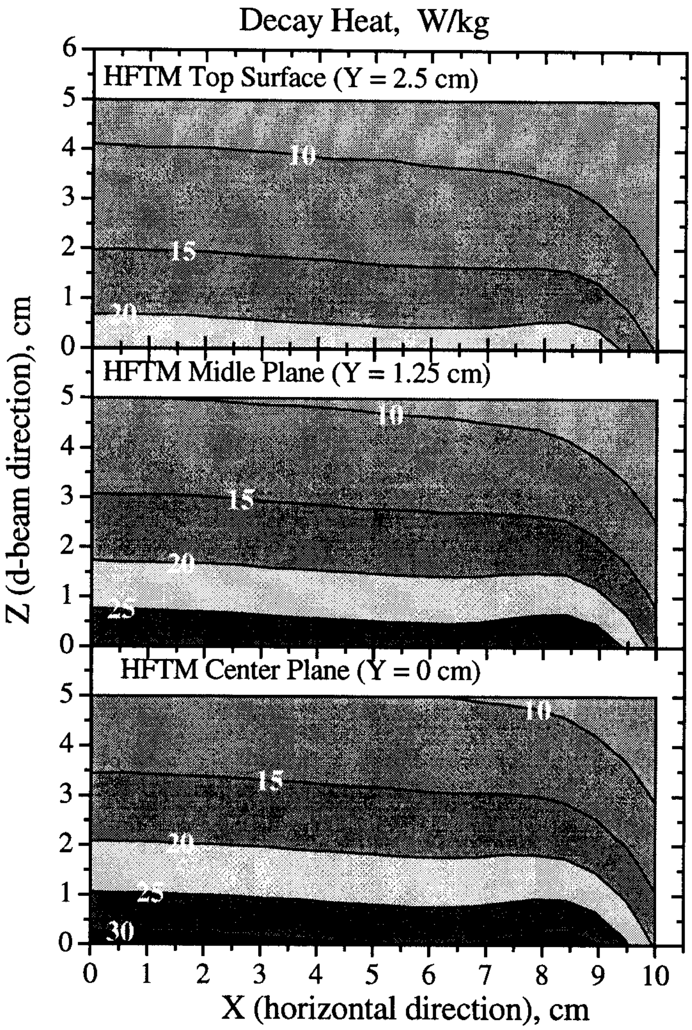

Fig. 6. HFTM contour plot of afterheat power density at three different vertical levels (1 day after irradiation).

Table 1. Elemental composition of the Eurofer LA steel [10] assumed for the activation calculations.

| **Element** | **w%** |
|---|---|
| Fe | 88.983 |
| O | 0.010 |
| C | 0.105 |
| Si | 0.050 |
| Mn | 0.400 |
| P | 0.005 |
| S | 0.005 |
| Cr | 9.000 |
| Ni | 0.005 |
| Mo | 0.005 |
| V | 0.200 |
| Nb | 0.001 |
| B | 0.001 |
| N | 0.030 |
| Al | 0.010 |
| Co | 0.005 |
| Cu | 0.005 |
| Ta | 0.070 |
| Ti | 0.010 |
| W | 1.100 |

Table 2. Total afterheat power and activity inventory of the HFTM.

| Cooling Time | shutdown | 1 h | 1 d | 30 d | 1 y | 5 y | 10 y | 100 y | 1000 y |
|---|---|---|---|---|---|---|---|---|---|
| Activity [$10^{14}$ Bq] | 22 | 20 | 16 | 15 | 10 | 3.3 | 0.94 | $2.8\ 10^{-4}$ | $7.2\ 10^{-6}$ |
| Afterheat power [W] | 244 | 172 | 51 | 41 | 19 | 1.0 | 0.10 | $7.1\ 10^{-5}$ | $4.6\ 10^{-6}$ |