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RADIOACTIVITY AND NUCLEAR HEATING MEASUREMENTS FOR FUSION APPLICATIONS

Anil KUMAR, Mohamed A. ABDOU

University of California,
Los Angeles, CA 90024-1597, USA

Yujiro IKEDA, Chikara KONNO

Japan Atomic Energy Research Institute
Tokai-mura, Ibaraki-ken 319-11, Japan

Induced radioactivity has been measured in samples of Fe, Ni, Cr, Mo, SS316, MnCu alloy, Co, V, Ti, Nb, W, Pb, Sn, Zn, Ag, Ta, Al, Si, Mg, In, Zr, $YBa_2Cu_3O_7$ and $ErBa_2Cu_3O_7$ in fusion neutron environment for different irradiation and cooling times. Analysis shows up inadequacies of activation and decay data of leading radioactivity calculation codes. Large discrepancies are observed for W, Mo, Zr, V and MnCu alloy though integrated decay γ-emission rates agree within 30% for Fe and SS316. Long half life measurements are still in progress. Nuclear heat deposition rate measurements have been made in small probes of Fe, Cu, graphite, Al and W. The analysis shows discrepancies of as much as 40% between measured and computed rates.

1. INTRODUCTION

Induced activity and nuclear heat deposition rates are among the most important parameters qualifying design of a fusion machine including its vacuum vessel and other components[1]. A range of structural and other materials are under consideration for next-step devices like ITER, CIT and NET. Prompt and decay heating rates are subject to large uncertainties as there is very little supporting experimental data base existing at the moment.

A program was planned and executed over the last two years for experimental verification of the data base and computer codes presently used for calculation of radioactivity and nuclear heating in fusion device design[2-5]. The measurements were carried out in 1988 and 1989 at fusion neutronics source facility of JAERI within the framework of USDOE/JAERI collaborative program on fusion neutronics[6]. The experiments on induced radioactivity were conducted inside prototypical blanket assemblies. The materials investigated in these experiments include: Fe, Ni, Cr, Mo, SS316, Mn, Cu, Co, V, Ti, Nb, Ta, Al, Si, In, Zr, $YBa_2Cu_3O_7$, $ErBa_2Cu_3O_7$. In addition , an experiment was conducted in June 1989 under average fluence of $7x10^{14}$ n/cm^2 for accumulating activation data on long half life radioactive isotopes, with half-lives ranging from 13.3 y (^{153}Eu) to 0.72 My (^{26}Al).

2. RADIOACTIVITY EXPERIMENTS

Experimental measurements have been conducted at fusion neutronics source facility (FNS) of JAERI over last few years inside prototypical fusion blanket assemblies within the framework of USDOE/JAERI collaborative program on fusion breeder neutronics[6].The measured quantities have consisted of tritium breeding ratio, neutron energy spectrum, foil activation rates and gamma heating rates. First measurements related to induced decay γ activity were conducted within this program during phase IIC in fall 1988.

Though entire phase IIC experimental program consisted of carrying out measurements in each of two prototypical blanket assemblies[7-8]- beryllium edge-on and coolant channel assemblies- the radioactivity measurements were conducted only inside 'coolant channel' assembly. This assembly had three polyethylene (PE) channels implanted in test section made of Li_2O bricks. Two spatial locations were chosen so as to have significantly different neutron energy spectra- the two locations being at 10 cm (in air) and 82 cm (5 cm inside Li_2O section) distance from the target center of 'rotating neutron target' (RNT) source. The materials irradiated included: Fe, Cr, Ni, Mo, SS316, MnCu alloy, V, Ti, Co, Al, Si, Zr, Nb, W, Au, In, Mg, Ta, $YBa_2Cu_3O_7$ and $ErBa_2Cu_3O_7$. Of these, $YBa_2Cu_3O_7$ and $ErBa_2Cu_3O_7$(on substrate of yttria stabilized zirconia) are known high temperature superconductors, and Au, In, Mg, Fe, Al, Nb, and Ta were also intended to serve as dosimetry foils for monitoring neutron energy spectrum. Two separate irradiations were carried out to cover each of these locations. Two foil packets were irradiated at each location to separately cover: (i) shorter half life products (less than 1 hour half life), (ii) longer half life products (1 hour to 5 year half life). Each irradiation period consisted of initial half an hour irradiation followed by pulling out of one of the two packets. The γ–spectroscopy of the foils in this

packet were to cover primarily shorter half life products. The full irradiation perids were 9 and 10 hours respectively for the locations at 10 and 82 cm, logging average source neutron intensities of 8.75 10^{11} and 1.12 10^{12} n/s.The γ–spectroscopy of each sample was done using three intrinsic germanium detectors and for multiple cooling periods ranging from 20 m to 10 d.

The availability of clean D-T neutron source environment coupled with high intensity at rotating neutron target (RNT) at FNS was considered to be an asset for a high-fluence activation in June 1989 for obtaining cross-section data on long half life isotopes. Foil packages, each consisting of samples of Al, Re, Ho, W, Mo, Dy, Ir, Tb, Ag, ^{151}Eu, ^{153}Eu and Hf, were kept one each at 0, 45 and 75^0 with respect to beam-axis; the front end of a package was at a distance of around 22 mm from the target-center whereas the back-end was 49 mm away. The fourth package was kept at a distance of 12 cm and at an angle of around 115^0 with respect to the beam axis. Multiple Nb and Zr foils were placed inside each package to monitor neutron fluence (through Nb) and neutron spectrum (through Zr/Nb ratio). The foil packages were irradiated over 4 days for a total duration of 32 hours and total neutron yield of 1.3 10^{17} n.. This yield amounts to a fluence of 1.66 10^{15} n/cm^2 (first foil) to 3 10^{14} n/cm^2 for the packages in the forward direction; the average fluence being ~7 10^{14} n/cm^2. The isotopes of interest and their half lives are: ^{153}Eu (13.3 y), ^{178m2}Hf (31 y), ^{150m}Eu (35.8 y), ^{108m}Ag (127 y), ^{158}Tb (150 y), ^{192m}Ir (241 y), ^{166m}Ho (1200 y), ^{94}Nb (20.3 Ky), ^{186m}Re (0.2 My) and ^{26}Al (0.72 My). The γ–spectroscopy of these foils is still continuing.

Phase IIIA experiments of the collaborative program were conducted in fall 1989. This phase is especially noteworthy for the landmark implementation of line source concept employing a point D-T neutron source[9-10]. The line source simulation was achieved by moving detectors/blanket assembly back and forth along the beam axis with respect to the fixed point neutron source. The induced radioactivity experiments were conducted both with bare line source and with a blanket assembly. The materials covered in the experiments included: Fe, Ni, Mo, SS316, W, Al, Sn, Ta, Zr, Nb, Ag, Pb, Zn, Ti, V, Co and In. The length of the simulated line source was set at 200 cm. The average source intensities obtained were 1.11 10^9 and 9.66 10^8 n/s /cm with and without assembly for irradiation periods of 9h47m and 9h51m respectively.

3. NUCLEAR HEATING EXPERIMENTS

Nuclear heating rates were measured using microcalorimetric technique in june and december 1989. Bead (point-size) thermistors and platinum RTD's were employed as thermal sensors inside probes made of Fe, Cu, W, Al and C (graphite). High sensitivity digital nanovoltmeter (model 181 from Keithley) formed integral part of the measurement circuit for picking up temperature change rates as low as 5 μ^0K/s. The irradiation stability of thermistors was found excellent for fluence as high as 2.9 x 10^{14} n/cm^2 during the qualifying tests in june 1989. We did not check the stability at a higher fluence as there were plans to work much below this value in the experiments to follow. Four types of thermistors were employed, having 25 ^{0}C resistances of 2.252 KΩ, 10 KΩ, 22 KΩ, and 30 KΩ . A platinum RTD had resistance of 100 Ω at 0 ^{0}C. Temperature coefficient of resistance for a thermistor and a platinum RTD were -4.4 x 10^{-2} per ^{0}C (at 25 ^{0}C) and 3.6 10^{-3} per ^{0}C (at 0 ^{0}C) respectively. Measurements were made on probes of iron, aluminum, copper and graphite. Each probe consisted of a cylindrical core of 20 mm height and 20 mm diameter sitting symmetrically inside a 1 mm thick jacket that had external diameter and height of 32 mm each. Polystyrene stubs provide thermal insulation between the core and the jacket. Three locations were chosen for placing the thermistors inside a core: front, middle and back; two locations were used for the RTD's: in the central planes of first and second halves of each core. During measurements each probe was kept inside a vacuum chamber. Distance of the core of a probe from the neutron source ranged from 6.3 to 7.7 cm. The source neutron intensity varied from 1.9 to 1.1 10^{12} n/s through experiments with all these probes. Generally, neutron source intensity was modulated such that there were 3 to 10 minute duration spaced pulses.

Additional nuclear heat deposition rate measurements were carried out during phase IIIA of the collaborative program in fall 1989. Two generic kinds of experiments were scheduled: (1) single probe experiments using composite or single block structure probe (Fe, Cu, C, W, Al); the objective consisted in examining the reproducibility of earlier (June 1989) experiments, (2) multiple probe experiments employing many smaller size single probes in a much larger host medium; two host media, e.g., iron, graphite, housed single probes made of graphite, tungsten, iron/copper; the underlying objective was to obtain spatial distribution of heat deposition rates and possibly extract its neutron and gamma heating

components. Both kinds of measurements were conducted with probe kept inside an evacuated vacuum chamber.

4. RESULTS AND DISCUSSION

Analysis of the experiments on induced radioactivity and nuclear heat deposition rate measurements has been carried out after obtaining neutron and gamma spectra from two transport codes DOT4.3 (two-dimensional and deterministic)[11] and MCNP-3B (three-dimensional and Monte Carlo)[12] with cross-section data[13] based on ENDF/B-V. The induced radioactivity computations were then carried out using REAC-2[5], DKRICF[3], RACC[2], and THIDA-2[4]. The THIDA-2 analysis is patterned after reference 14.

4.1 Induced Radioactivity

The experimental data was treated to obtain decay gamma emission rate per g of irradiated material per normalizing source strength of 10^{12} n/s. Correction for self-absorption of γ spectra in each sample was also applied.

The neutron energy spectra at 10 and 82 cm locations is significantly different, e.g, there are only 66% neutrons above 100 KeV at later location as against 97% for the former. The maximum fluences at the two locations were 3.5 10^{13} n/cm^2 and 2.4 10^{12} n/cm^2 respectively. Figures 1a to 1c show comparison of calculated (C) to measured (E) integrated decay gamma emission rates for different materials for the three radioactivity codes DKRICF, REAC-2 and THIDA-2 respectively. The γ-energy range covered goes from 100 KeV to 3.5 MeV. Only upper and lower bounds are shown- embracing all the cooling periods for each material. The largest discrepancies are seen for DKRICF and REAC-2 codes. Regarding THIDA-2 results, the discrepancies are usually lower. For SS316, in particular, the results reported earlier (ref. 14) are reinforced. The largest discrepancies have been observed for tungsten in both REAC-2 and DKRICF, even as the origins are widely different. C/E for DKRICF ranges from 4.88 10^{-4} to 0.20; it ranges from 2.05 to 307 for REAC-2. The large discrepancies for DKRICF originate from the absence of decay data for ^{186}Ta, ^{187}W and ^{181}W. As for REAC-2, the discrepancies are due to inadequate decay/cross-section data for production of γ's from ^{179m}W, ^{187}W, ^{184}Ta, ^{183}Hf, ^{182m}Hf, and ^{180m}Hf. For SS316 and Fe all the three codes agree within 25% as for the integrated decay gamma emission rates. Mo, Zr, MnCu (80% Mn+20% Cu alloy), Ta, $YBa_2Cu_3O_7$ and V also show up large discrepancies.

The discrepancies on γ–spectra are, in general, much higher. Figures 2 to 6 display typical comparison of

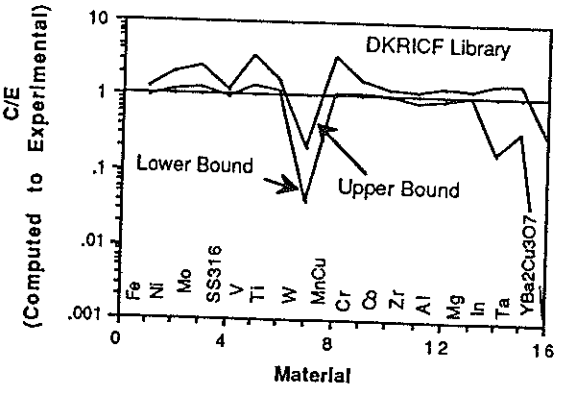

Figure 1a

Comparison of Measured and DKRICF computed decay γ emission rates

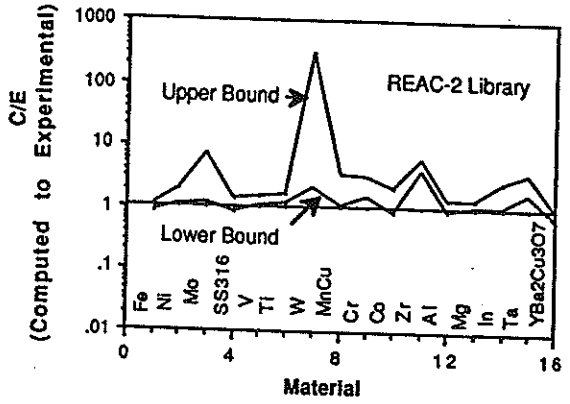

Figure 1b

Comparison of Measured and REAC-2 computed decay γ emission rates

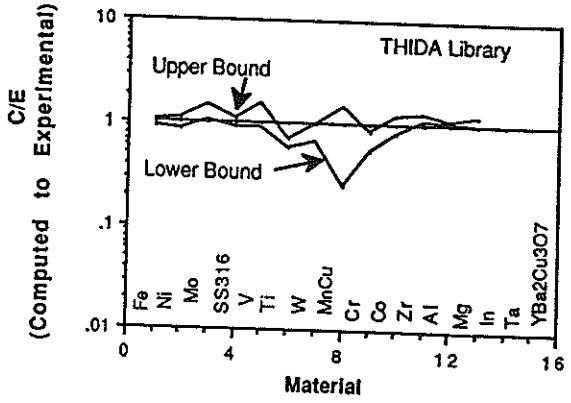

Figure 1c

Comparison of Measured and THIDA-2 computed decay γ emission rates

measured and computed decay γ–emission rates for Fe, SS316, Ni, and W. 'tr ' stands for irradiation period and 'tcool ' denotes sample cooling time after irradiation. It is obvious that significant revision of REAC-2 and DKRICF code systems would be called for to get reasonable agreement between the measured and computed γ–spectra.

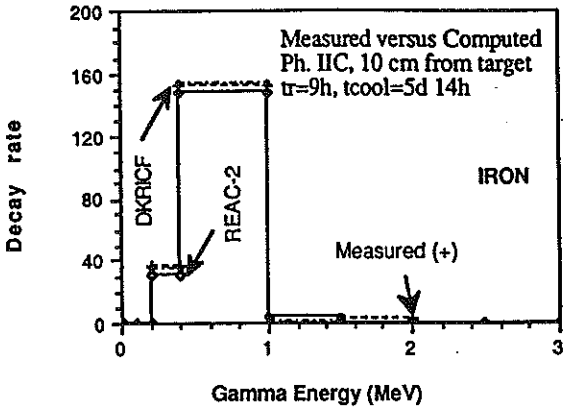

Figure 2

Comparison of Measured and computed decay γ emission spectra for Iron Sample

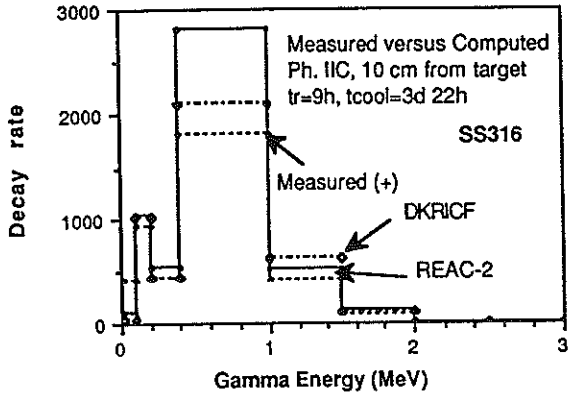

Figure 3

Comparison of Measured and computed decay γ emission spectra for SS316 Sample

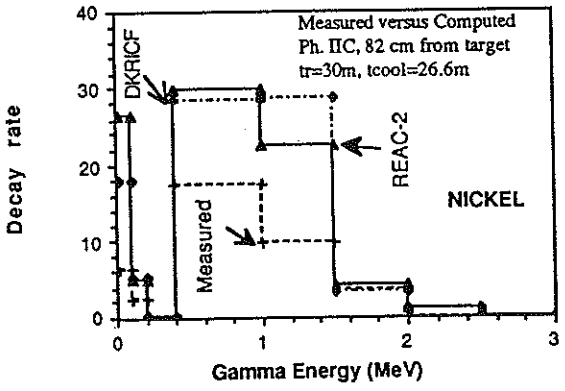

Figure 4

Comparison of Measured and computed decay γ emission spectra for Nickel Sample (cooling time = 26.6 m)

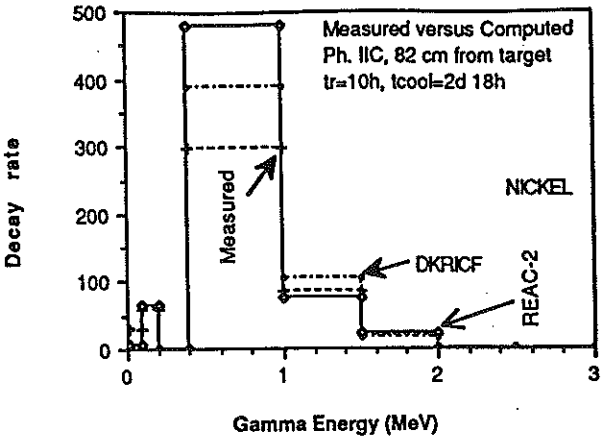

Figure 5

Comparison of Measured and computed decay γ emission spectra for Nickel Sample (cooling time = 2 d 18 h)

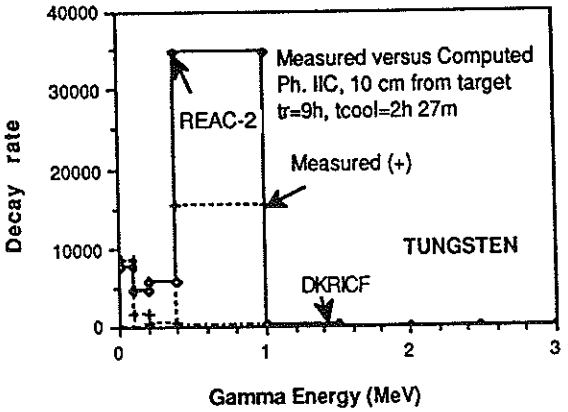

Figure 6

Comparison of Measured and computed decay γ emission spectra for Tungsten Sample

4.2 Nuclear Heat Deposition

Various sensors kept inside a probe in vacuum chamber gave very close values for heat deposition rate. This is understandable as relatively small size of a probe allowed rapid equilibration of initial thermal gradients inside the probe. The heat deposition rate was averaged over the probe dimensions so as to compare it to measured value. Figures 7 and 8 show typical resistance change per cycle (length = 30 s) for a thermistor and a RTD sensor kept inside an iron probe.

The analysis of the measurements of june 1989 showed that the computed and measured data agreed within 40%. It is interesting to point out that measured rates of temperature change, normalized to 10^{12} source neutrons per s, were respectively 18, 20, 39 and 16 μ^0K/s for Fe, Al, C (graphite) and Cu probes. These are rather small

rates, showing up the sensitivity of the experimental equipment and procedure.

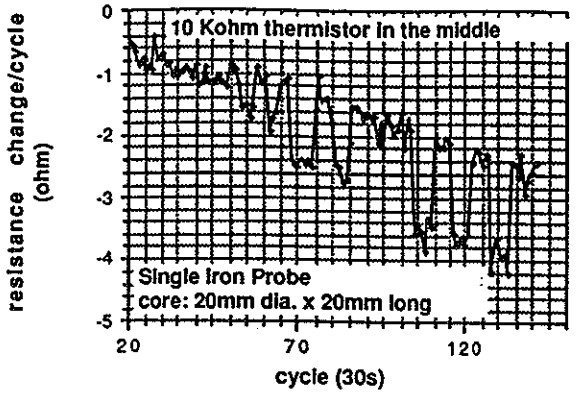

Figure 7

Nuclear heat deposition in an Iron probe: response of a thermistor

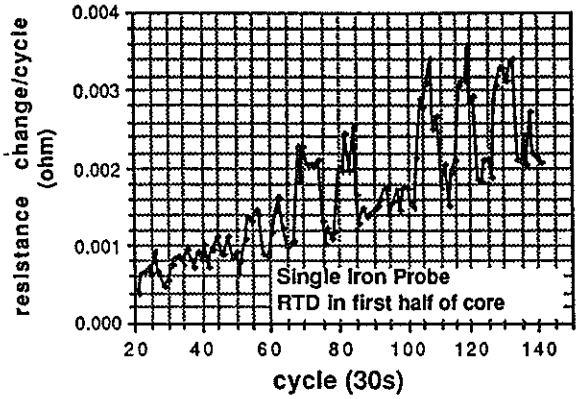

Figure 8

Nuclear heat deposition in an Iron probe: response of an RTD

5. CONCLUSIONS

Experimental measurements of induced radioactivity and nuclear heat deposition rates in fusion neutron environment have been carried out and compared to analysis made with two and three dimensional transport codes and different decay radioactivity codes. Integrated decay gamma emission spectra is found to agree within 30% for SS316 and Fe samples. However, larger deviations are found for W and some other materials. The discrepancies for decay γ-spectra are found to be much larger. The activation cross sections and decay data libraries asscociated with REAC-2 and DKRICF code systems need to be given a closer look with a view to improve the agreement between measured and computed data. The nuclear heat deposition rates have been measured in probes of Fe, graphite, Cu, Al and W.

The measured and computed rates differ considerably. Additional measurements will help in accumulating the data bases for both induced radioactivity and nuclear heat deposition so as to permit an early and extensive revision of the basic nuclear data.

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