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Using TFTR D-T Neutron Field

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Radioactivity Measurements of ITER Materials Using the TFTR D-T Neutron Field

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Abstract

The availability of high D-T fusion neutron yields at TFTR has provided a useful opportunity to directly measure D-T neutron-induced radioactivity in a realistic tokamak fusion reactor environment for materials of vital interest to ITER. These measurements are valuable for characterizing radioactivity in various ITER candidate materials, for validating complex neutron transport calculations, and for meeting fusion reactor licensing requirements. The radioactivity measurements at TFTR involve potential ITER materials including stainless steel 316, vanadium, titanium, chromium, silicon, iron, cobalt, nickel, molybdenum, aluminum, copper, zinc, zirconium, niobium, and tungsten. Small samples of these materials were irradiated close to the plasma and just outside the vacuum vessel wall of TFTR, locations of different neutron energy spectra. Saturation activities for both threshold and capture reactions were measured. Data from dosimetric reactions have been used to obtain preliminary neutron energy spectra. Spectra from the first wall were compared to calculations from ITER and to measurements from accelerator-based tests.

1. Introduction

The licensing of high power fusion reactors will require certification of calculations of induced radioactivity. A data base of measured radioactivity in environments with prototypical neutron spectra is crucial for this purpose. A concerted beginning was made by an extensive experimental program using accelerator-based neutron sources on induced radioactivity measurements in small samples of fusion reactor relevance in the framework of a USDOE/JAERI collaboration[1-5]. The analysis of those measurements with various radioactivity codes and activation libraries revealed relatively large sources of discrepancies in calculations. These discrepancies were related to many contributing factors, including: decay γ -half lives, γ -yields, neutron energy spectra, and activation cross-sections.

Engineering design activities of the International Thermonuclear Experimental Reactor (ITER) are already underway. Radioactivity calculations for the ITER neutron environment may suffer even larger discrepancies between calculations and measurements than did the accelerator-based experiments with their inherently superior neutron spectrum characterization. Conducting comparison experiments on existing tokamaks should significantly improve extrapolations to ITER. The Tokamak Efusion Test Reactor (TFTR) has been one of the front-line experimental devices on tokamak-based magnetic fusion research. There were previous attempts to characterize the neutron energy spectra emitted from the device using a point D-T neutron generator [6-7]. However, the errors on these experimental measurements were quite large due to poor counting statistics. Later, an extensive experimental campaign was conducted with various film badges and dosimeters to map the biological doses from the test cell walls out to the site boundary during high power D-D discharges [8-10]. The D-T campaign of TFTR initiated in November 1993 provided an excellent opportunity to carry out induced radioactivity measurements [11]. Measurements were made for samples of aluminum, silicon, titanium, vanadium, chromium, iron, cobalt, nickel, copper, zinc, zirconium, niobium, molybdenum, indium, tungsten, and gold at various locations around TFTR. In this paper, we report on measurements made close to the plasma and vacuum vessel. A companion paper will discuss measurements on samples irradiated on the inner walls of the TFTR test cell [12].

2. Experiments

Samples were exposed to the TFTR neutron field using the pneumatic transfer system of the neutron activation diagnostic[13-17]. They were irradiated for one to several plasma discharges, with the neutrons primarily emitted during the ~1 second duration of the neutral beam injection, and the discharges occurring ~10-20 minutes apart. A typical foil used for lower intensity D-D or D-T discharges measures 1 mm thickness (except gold foils were 0.025 mm thick) by 18 mm diameter (except stainless steel 316 foils have a diameter of 10 mm) and has very high purity. For high-yield D-T discharges the foils were broken into smaller pieces to limit the total dose rate just after its extraction. After irradiation, all the foils were taken out from a single capsule and different capsules (some containing more than one foil) were prepared for counting. Three different Irradiation Ends (IE) or terminal locations of the transport system were used. IE#8 is a reentrant end extending in from a racetrack flange on top of the vacuum vessel. It sees the hardest neutron energy spectrum with its proximity to the plasma (it represents the only irradiation end that falls within the nuclear boundary). IE#3 and IE#4 are located outside the vacuum vessel in the mid-plane of two different toroidal "bays" between TF coils. Two high-purity germanium (HPGe) detectors were used for γ -spectroscopy of the irradiated foils after appropriate cooling times. Absolute efficiencies for both detectors have been determined using NIST-traceable standard sources [15,16].

For our studies several particular sets of measurements were done:

- A single capsule containing 14 foils (Al, Ti, V, Fe, Co, Ni, SS316, Cu, Zn, Zr, Nb, Mo, In, and W) was irradiated in IE#8 during four trace tritium discharges on November 22, 1993. The accumulated D-T and D-D neutron yields were 5.6×10^{15} and 5.0×10^{16} respectively, yielding 10% of the total source neutron emission being contributed by D-T neutrons alone. The radioactive products and γ -peaks of interest were same as those reported earlier in references 4 and 3. The cooling times ranged from 1h 41m to 15h 40m. The counting times ranged from 10 m to 3h 15m.
- Pairs of identical capsules were irradiated in single D-D supershots on February 24 and 25, 1994. Two identical capsules (Fe, Ni, Co, Cr, Mo, Nb, Al, and Au) were irradiated in IE#8 and IE#4 with D-T and D-D neutron yields of 1.4×10^{15} and 1.25×10^{16} respectively, for a D-T contribution again amounting to 10% of the total yield (this amount of D-T neutron

yield coming from tritium recycling from the wall). Cooling times ranged from 1h 36m to 1d 16h. Two identical capsules (Al, V, and W) were irradiated in IE#8 and IE#3 with D-T and D-D neutron yields of 8.1×10^{14} and 8.2×10^{15} respectively, for a D-T contribution amounting to 9.0% of the total yield. A second pair (Al, Ti, Zr, and Au) in IE#8 and IE#3 had D-T and D-D neutron yields of 1.2×10^{15} and 1.26×10^{16} respectively, for a D-T contribution amounting to 8.7% of the total yield. Cooling times ranged from 1h 32m to 5h 27m.

- Eight sets of two identical capsules were irradiated in IE#8 and IE#3 on February 28 and March 1, 1994 during different D-T supershots. An aluminum foil was in all the irradiated capsules. The other irradiated foils included Ti, V, Cr, Fe, Co, Ni, Cu, Zr, Nb, Mo, W, and Au. D-T neutron yields per discharge varied from 6.4×10^{17} to 2.2×10^{17} ; D-D neutron yields were unmeasurable in these conditions but expected to be ~40 times lower. The cooling times ranged from 12m 31s to 23d 23h.

In addition to these specific measurements, many other extensive measurements using aluminum, silicon, and indium foils have been made routinely .

3. Experimental analysis

The spectra from the HPGe detector were analyzed by an analysis package on an IBM-XT [13,15]. Decay γ -yields and half lives were adopted from a table of radioactive isotopes [18]; isotopic fractions were adopted from the older table of isotopes [19]. When counting with more than one foil in a single capsule, the calculation of accurate γ self-shielding for each γ -peak was very important. A Monte Carlo program was used to get net correction factors that take into account changes in absolute detector efficiency with distance as well as γ self-shielding for all γ 's emitted by each foil in a counted capsule. The largest number of foils in a counted capsule was five. Diameter, thickness, density of each foil, relative foil arrangement, capsule-detector distance, and detector diameter were among the parameters needed to be specified for this program. Energy-dependent γ -attenuation coefficients were taken from reference 20. Saturation activities for all observed γ -peaks from each radioactive isotope were inter compared and found to agree within experimental error.

A number of parameters affect experimental error estimation. These include: counting statistics, the half life of γ -emitter, accuracy of the HPGe detector efficiency, the cooling and counting times, the activation cross-section, and various nuclear coefficients. Sum-peak corrections also add to the error. It is impossible to give a single figure for even one sample material; however, for most of the experimental measurements, the accuracy of the saturation activity is between 6% to ~14% [17].

4. Discussion of processed data

As a large number of isotopic activities of importance to ITER were measured close to the TFTR device in different locations, there are a number of ways one can discuss the measured data. In what follows, we present a succinct discussion on various aspects of interest to both ITER and further experimental efforts at TFTR.

4.1 Overview of saturation activities

Tables 1 and 2, and Fig. 1 give the various dosimetric reaction products, and the saturation activity (activated nuclei per source neutron per target nuclei) for the materials irradiated at TFTR and discussed in this paper. All threshold reactions' activities were normalized to one D-T source neutron, whereas all capture reactions' activities were normalized to a TFTR source neutron (D-T + D-D). The reactions and their products include: (1) $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$, (2) $^{59}\text{Co}(n,\gamma)^{60\text{m}+g}\text{Co}$, (3) $^{58}\text{Ni}(n,p)^{58\text{m}+g}\text{Co}$, (4) $^{54}\text{Fe}(n,p)^{54}\text{Mn}$, (5) $^{46}\text{Ti}(n,p)^{46}\text{Sc} + ^{47}\text{Ti}(n,n'p/d)^{46}\text{Sc} + ^{48}\text{Ti}(n,n'd/t)^{46}\text{Sc}$, (6) $^{47}\text{Ti}(n,p)^{47}\text{Sc} + ^{48}\text{Ti}(n,n'p/d)^{47}\text{Sc} + ^{49}\text{Ti}(n,n'd/t)^{47}\text{Sc}$, (7) $^{48}\text{Ti}(n,p)^{48}\text{Sc} + ^{49}\text{Ti}(n,n'p/d)^{48}\text{Sc} + ^{50}\text{Ti}(n,n'd/t)^{48}\text{Sc}$, (8) $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, (9) $^{56}\text{Fe}(n,p)^{56}\text{Mn}$, (10) $^{59}\text{Co}(n,\alpha)^{56}\text{Mn}$, (11) $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$, (12) $^{59}\text{Co}(n,2n)^{58\text{m}+g}\text{Co}$, (13) $^{90}\text{Zr}(n,2n)^{89\text{m}+g}\text{Zr}$, and (14) $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$. Only a single target atom is to be understood as assigned to each of these twelve radioactive products and they are respectively as follows: (1) ^{197}Au , (2) ^{59}Co , (3) ^{58}Ni , (4) ^{54}Fe , (5) ^{46}Ti , (6) ^{47}Ti , (7) ^{48}Ti , (8) ^{27}Al , (9) ^{56}Fe , (10) ^{59}Co , (11) ^{93}Nb , (12) ^{59}Co , (13) ^{90}Zr , and (14) ^{58}Ni . The reactions on the abscissa, the horizontal axis, of Fig.1 are arranged approximately in the order of increasing effective neutron energy threshold, with the first two reactions being capture reactions. Note that each reaction is assigned a number, e.g., $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$, is assigned value of 1 on horizontal axis of Fig. 1. Where available, data for all the three irradiation ends, i.e., #8, #3, and #4, is shown. The largest saturation activities occur for the two capture reactions, i.e., $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$, and $^{59}\text{Co}(n,\gamma)^{60\text{m}+g}\text{Co}$. These clearly signal the strong presence of thermal neutrons at the low end of the neutron energy

spectrum. As for threshold reactions, the saturation activity varies from 5×10^{-33} to 1×10^{-30} per target nucleus.

Figures 2 and 3 show saturation activity per source neutron per sample atom for various materials of relevance to ITER, for other threshold (Fig. 2) as well as capture (Fig. 3) reactions. In these prototypical plots, we have primarily included those products which have earlier been subject of large discrepancies between calculations and measurements[1-4]. Each of these measured saturation activities has been normalized to all isotopes of a sample atom, including those that do not participate in reaction of interest. ^{69m}Zn is included in both the figures as there are two competing reactions: $^{70}\text{Zn}(n,2n)^{69m}\text{Zn}$, and $^{68}\text{Zn}(n,\gamma)^{69m}\text{Zn}$. Even though ^{99}Mo is included only in Fig. 3, both a threshold and a capture reaction produce it: $^{100}\text{Mo}(n,2n)^{99}\text{Mo}$, and $^{98}\text{Mo}(n,\gamma)^{99}\text{Mo}$. Similarly, ^{51}Cr has two contributing reactions, i.e., $^{52}\text{Cr}(n,2n)^{51}\text{Cr}$, and $^{50}\text{Cr}(n,\gamma)^{51}\text{Cr}$. From both the figures, it is clear that cobalt has largest saturation activities, both for threshold reaction, $^{59}\text{Co}(n,2n)^{58m+g}\text{Co}$, and capture reaction, $^{59}\text{Co}(n,\gamma)^{60m+g}\text{Co}$. Lowest threshold reaction activity comes from $^{51}\text{V}(n,\alpha)^{48}\text{Sc}$, primary component of vanadium-chromium-titanium alloys being considered actively as a low-activation structural material for ITER. Lowest capture reaction activity pertains to $^{64}\text{Ni}(n,\gamma)^{65}\text{Ni}$, being at least one to two orders lower than others (see Fig. 3). This is primarily due to the very low abundance of ^{64}Ni in natural nickel, being just 0.91%. Comparing the saturation activities for threshold and capture reaction products, one can notice that the largest capture radioactivity, i.e., $^{60m+g}\text{Co}$, is almost an order larger than the largest threshold radioactivity, i.e., $^{58m+g}\text{Co}$.

From Figs. 1 and 3, one can observe that the measured saturation activities reflect a dependence on the irradiation end. Most often, IE#8 (inside the vessel) has the largest value of the three ends and represents the "hardest" or least scattered spectrum. In Fig. 4, we present saturation activities for irradiation ends #3 and #4 after normalizing with respect to the values at the irradiation end #8. All the dosimetric products covered in Fig. 1 are included. The spectrum for IE#3 is significantly softer than for IE#4. The measured activity for capture reaction product ^{198}Au is significantly larger (by ~25%) for IE#3 as compared to that for IE#4. On the other hand, the measured saturation activities for threshold reaction products ^{24}Na and ^{56}Mn in IE#4 are significantly larger (almost by as much as 30 to 50%) than those for IE#3.

MCNP [21] modeling of IE#8 has been performed to use saturation activities for a number of dosimetric products to determine neutron yields

on TFTR [17]. For all dosimetric threshold reactions considered the yields agree to within the $\pm 7\%$ accuracy of the TFTR systems [16]. This comparison ensures confidence in the quality of the processed data from the neutron activation system. However, it does not assure that accurate modeling is possible for the capture reactions in IE#8 or for all reactions for both IE#3 and #4. Further analysis is necessary to investigate the status of prediction capability for the bulk of the measured data.

4.2. Material-wise presentation of measured saturation activities

Extensive data has been obtained for practically all materials of interest to ITER. This database could be used variously by different users. For example, it could be used to test and adjust 3D models of TFTR. Engineering design studies and the regulatory licensing required for ITER can make use of these results as a reference for preliminary validation of activation calculations for the first wall. In what follows, we will give additional summary information not listed in Table 2 on the status on saturation activities measured in various materials, while graphical results will be presented for only a few of the materials. Once saturation activities are known, it is straight-forward to obtain decay- γ and other source terms required for decay-heat and/or biological dose calculations.

- **Aluminum**

2.24m (half life) ^{28}Al , 9.46m ^{27}Mg , and 15h ^{24}Na activities were measured. Along with silicon, aluminum activation has been done routinely at TFTR to monitor D-T neutrons.

- **Silicon**

Activities were measured for 2.24m (half life) ^{28}Al , 6.56m ^{29}Al , and 9.46m ^{27}Mg . Silicon has been used extensively at TFTR for D-T neutron monitoring due to its quite short half life.

- **Titanium**

Most frequently observed products include 3.93h (half life) ^{44}Sc , 43.7h ^{48}Sc , 3.34d ^{47}Sc , 4.54d ^{47}Ca , and 83.8d ^{46}Sc . In one of the very first measurements, 5.8m ^{51}Ti was also observed. Fig. 5 shows the saturation activity per sample atom per TFTR source neutron for IE#8 and #3. It turns that for both the locations, ^{48}Sc , ^{47}Sc , and ^{46}Sc dominate. Systematically, the measurements for IE#3 are significantly lower.

- **Vanadium**

3.75m ^{52}V , 5.76m ^{51}Ti , and 43.7h ^{48}Sc were observed.

- **Chromium**

41.9m ^{49}Cr , and 27.7d ^{51}Cr saturation activities were measured in a number of chromium samples.

- **Iron**

2.6h (half life) ^{56}Mn , 27.7d ^{51}Cr , and 312.2d ^{54}Mn were observed. Fig. 6 shows the measured activities for IE#8 and #3. ^{56}Mn activity dominates. Also, this activity is most sensitive to the spectrum as one sees a large divergence for the two ends (see Fig. 6).

- **Cobalt**

2.6h ^{56}Mn , 44.6d ^{59}Fe , 70.8d ^{58}Co , and 5.3y ^{60}Co were detected almost routinely in most of the irradiations. Fig. 7 is a graphic presentation of the saturation activities for IE#8 and #3. One can observe the dominance of ^{60}Co and ^{58}Co . Also, relative insensitivity of ^{60}Co to neutron energy spectrum comes out very clearly.

- **Nickel**

2.52h ^{65}Ni , 36h ^{57}Ni , 70.8d ^{58}Co , and 271d ^{57}Co activities were measured. Again, large divergence between IE#8 and #3 was seen for ^{57}Ni , ^{58}Co , and ^{57}Co .

- **Copper**

12.7h ^{64}Cu activity was observed.

- **Zinc**

2.52h ^{65}Ni , 12.7h ^{64}Cu , 13.8h $^{69\text{m}}\text{Zn}$, 2.58d ^{67}Cu , and 244.1d ^{65}Zn activities were observed.

- **Zirconium**

Measured activities included 49.7m (half life) $^{91\text{m}}\text{Y}$, 72m ^{97}Nb , 2.8h $^{87\text{m}}\text{Sr}$, 3.19h $^{90\text{m}}\text{Y}$, 9.52h ^{91}Sr , 16.9h ^{97}Zr , 78.4h ^{89}Zr , and 64d ^{95}Zr . ^{89}Zr saturation activity dominated, followed by ^{95}Zr , and ^{97}Zr . Large divergences for the two irradiation ends were observed for ^{89}Zr , $^{90\text{m}}\text{Y}$, $^{87\text{m}}\text{Sr}$, and $^{91\text{m}}\text{Y}$. ^{97}Zr , ^{91}Sr , and ^{97}Nb have much less divergences. ^{95}Zr appears to be an intermediate case. This might be due to this product receiving contributions from a contrasting set of reactions, i.e., a threshold, $^{96}\text{Zr}(n,2n)^{95}\text{Zr}$, and a capture, $^{94}\text{Zr}(n,\gamma)^{95}\text{Zr}$ reaction.

- **Niobium**

Both 3.19h ^{90m}Y , and 10.15d ^{92m}Nb saturation activities were measured.

- **Molybdenum**

Fig. 8 graphically displays the activities measured for IE#8 and #3. The observed products include 6.85h ^{93m}Mo , 23.4h ^{96}Nb , 66h ^{99}Mo , 78.4h ^{89}Zr , 10.15d ^{92m}Nb , and 34.97d ^{95}Nb . Again, relatively large divergences for the two ends were observed whenever a threshold reaction generates the radioactivity.

- **Stainless steel 316**

The observed activities included 2.6h ^{56}Mn , 36h ^{57}Ni , 66h ^{99}Mo , and 44.6d ^{59}Fe .

- **Indium**

54.2m ^{116m}In and 4.49h ^{115m}In activities were measured.

- **Tungsten**

23.9h ^{187}W was observed in all irradiations.

- **Gold**

9.7h $^{196m2}\text{Au}$, 2.69d ^{198}Au , and 6.18d ^{196}Au saturation activities were measured.

- **Water**

Preliminary measurements for the 7.13s ^{16}N [from $^{16}\text{O}(\text{n,p})^{16}\text{N}$] activity were performed. Characteristic activity for this reaction was observed following rapid counting of water-filled micro centrifuge tubes irradiated during two separate runs. The total transit time for the rabbit from the irradiation end #8 to the counting station was brought down to as low as 46 s following a shot. These measurements will be continued, associated studies of possible systematic uncertainties will be performed, and the results will be presented at a later time. Measurement of ^{16}N activity has assumed importance as one of the current design options of ITER deploys water as a coolant. Some designers predict that the transport of radioactive water (carrying ^{16}N) close to the super conducting toroidal magnets in this design would lead to excessive heating in the magnet and will necessitate significant changes in the current design.

5. Spectral information

There is a noticeable dependence of capture reaction products on the D-T neutron fraction. Fig. 9 shows saturation activities for 5 capture reactions, e.g., $^{59}\text{Co}(n,\gamma)^{60\text{g+m}}\text{Co}$, $^{96}\text{Zr}(n,\gamma)^{97}\text{Zr}$, ^{99}Mo from Mo, $^{186}\text{W}(n,\gamma)^{187}\text{W}$, and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$, as a function of D-T neutron fraction for IE#8. The activities were normalized to their values for D-T neutron fraction of ~ 0.94 (February 28, 1994 irradiation). Upto $\sim 50\%$ change in saturation activity is seen as the D-T neutron fraction is varied from 10% to $\sim 94\%$. ^{99}Mo shows a much smaller change. We infer that the "worth" of a D-T neutron to the low end of neutron energy spectrum is larger than that of a D-D neutron. A similar trend has also been observed for measurements made on inner walls of TFTR test cell [12].

The availability of measured, dosimetric, saturation activities can allow unfolding of the neutron energy spectrum for various irradiation ends. The D-T neutron fraction appears to impact saturation activity values, at least the ones resulting from neutron capture reactions. Thus both the D-D and D-T neutron sources must be modeled. Another crucial parameter required by most of the unfolding codes is the input neutron energy spectrum. This input guess has to be rather close to the real spectrum for getting meaningful output from these codes [22-24]. An extensive effort was invested in unfolding neutron energy spectra for the irradiation ends. The details of this effort will form the subject of another publication which will also include further improvements. Fig. 10 compares preliminary unfolded neutron energy spectra for irradiation ends #8 and #3, normalized to 1 D-T n/cm² in the energy range from 13.5 to 15 MeV. As qualitatively expected, the spectrum is considerably softer for IE#3 than for IE#8.

6. Relevance of the measurements to ITER

The unfolded neutron energy spectrum for IE#8 on TFTR can be compared to those expected for the first wall for ITER and measured in a prototypical USDOE/JAERI irradiation assembly (Fig. 11). Each spectrum has been normalized to 1 D-T n/cm². The neutron spectrum for ITER (ITER-FW) is for a first wall with a self-cooled Li/V blanket option, under extensive study at one time [25]. The spectrum for a water-cooled design is also available and shows a considerably higher fraction of low-energy neutrons [25]. The neutron energy spectrum for the USDOE/JAERI program (US/J-FW) is for a location that is ~ 5 cm deep inside a lithium oxide region behind a stainless-steel first wall, with a coolant channel assembly of

phase IIC [4]. One observes that though there are differences in the three spectra in practically the entire energy range, the spectral shapes are comparable. We have used the normalized spectra to calculate saturation activities for various dosimetric reactions using the activation cross-section library of DKR-ICF [26]. The calculated activities are shown in Fig. 12 along with the measured saturation activities on TFTR for IE#8, all normalized to 1 D-T n/cm². The calculated and the measured activities generally look remarkably comparable. Whatever differences exist are to be assigned to old activation cross-sections as well as differences in neutron energy spectra. Thus the measurements of radioactivity at the TFTR irradiation ends provide a useful validation of ITER calculations.

7. Summary and conclusions

Extensive measurements of radioactivity induced by fusion neutrons in various materials of interest to ITER were carried out at TFTR. The measurements were done at irradiation ends inside and outside the vacuum vessel. Clear differences were observed in saturation activities for the three irradiation ends, especially for threshold reactions. Saturation activities of capture reactions showed a ~50% dependence on the D-T neutron fraction. The measured saturation activities for dosimetric reactions were unfolded to obtain the neutron energy spectra. A comparison of measured activities was then done to the calculations for an ITER first wall and a first-wall-type location of a USDOE/JAERI experimental assembly. In spite of differences for some reactions, the normalized, measured activities were found quite comparable to those for the ITER first wall.

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is normalized such that there is 1 n/cm² (say, 1 D-T n/cm²) between energy range 13.5 to 15 MeV.

Figure 12 Comparison of normalized, measured, saturation activities for ITER first wall of self-cooled Li/V option (ITER-FW), USDOE/JAERI collaborative program first-wall-like (US/J-FW), and TFTR irradiation end #8. The normalization is done to 1 D-T n/cm² for both calculated as well as measured saturation activity.

Table 1

Observed γ -emitting isotopes of materials irradiated at TFTR

Material (foil)	Product & Half life	Material (foil)	Product & Half life
Al	2.24m ^{28}Al , 9.46m ^{27}Mg , 15h ^{24}Na	Zn	2.52h ^{65}Ni , 12.7h ^{64}Cu , 13.8h ^{69}mZn , 2.58d ^{67}Co 244.1d ^{65}Zn
Si	2.24m ^{28}Al , 6.56m ^{29}Al , 9.46m ^{27}Mg	Zr	49.7m ^{91}mY , 72m ^{97}Nb , 2.8h ^{87}mSr , 3.19h ^{90}mY , 9.52h ^{91}Sr , 16.9h ^{97}Zr , 78.4h ^{89}Zr , 64d ^{95}Zr
Ti	3.93h ^{44}Sc , 43.7h ^{48}Sc , 3.34d ^{47}Sc , 4.54d ^{47}Ca , 83.8d ^{46}Sc	Nb	3.19h ^{90}mY , 10.2d ^{92}mNb
V	3.75m ^{52}V , 5.76m ^{51}Ti , 43.7h ^{48}Sc	Mo	6.85h ^{93}mMo , 23.4h ^{96}Nb 66h ^{99}Mo , 78.4h ^{89}Zr , 10.2d ^{92}mNb , 35d ^{95}Nb
Cr	41.9m ^{49}Cr , 27.7d ^{51}Cr	SS316	2.58h ^{56}Mn , 36h ^{57}Ni , 66h ^{99}Mo , 44.6d ^{59}Fe
Fe	2.58h ^{56}Mn , 27.7d ^{51}Cr , 312.2d ^{54}Mn	In	54.2m ^{116}mIn , 4.49h ^{115}mIn
Co	2.58h ^{56}Mn , 44.6d ^{59}Fe , 70.8d ^{58}Co , 5.3y ^{60}Co	W	23.9h ^{187}W
Ni	2.52h ^{65}Ni , 36h ^{57}Ni , 70.8d ^{58}Co , 271d ^{57}Co	Au	9.7h $^{196\text{m}2}\text{Au}$, 2.69d ^{198}Au , 6.18d ^{196}Au
Cu	12.7h ^{64}Cu		

Table 2

Saturation activities for titanium, iron, nickel, cobalt, and molybdenum
(D-T discharges at TFTR)

Material (Foil)	Product	Saturation activity@		Material (Foil)	Product	Saturation activity@	
		IE#8	IE#3			IE#8	IE#3
Ti	⁴⁴ Sc	3.27.10 ⁻³³	-	Ni	⁶⁵ Ni	-	2.06.10 ⁻³³
	⁴⁸ Sc	5.40.10 ⁻³²	7.97.10 ⁻³³		⁵⁷ Ni	2.07.10 ⁻³²	2.62.10 ⁻³³
	⁴⁷ Sc	2.08.10 ⁻³²	3.26.10 ⁻³³		⁵⁸ Co	4.32.10 ⁻³¹	7.15.10 ⁻³²
	⁴⁷ Ca	3.80.10 ⁻³⁴	-		⁵⁷ Co	1.22.10 ⁻³⁰	1.74.10 ⁻³¹
	⁴⁶ Sc	3.13.10 ⁻³²	-				
Fe	⁵⁶ Mn	1.36.10 ⁻³¹	2.48.10 ⁻³²	Mo	^{93m} Mo	3.53.10 ⁻³⁴	-
	⁵¹ Cr	6.62.10 ⁻³³	-		⁹⁶ Nb	4.05.10 ⁻³³	5.07.10 ⁻³⁴
	⁵⁴ Mn	3.42.10 ⁻³²	1.89.10 ⁻³²		⁹⁹ Mo	3.53.10 ⁻³¹	1.49.10 ⁻³¹
					⁸⁹ Zr	4.89.10 ⁻³³	-
Co	⁵⁶ Mn	3.40.10 ⁻³²	6.14.10 ⁻³³		^{92m} Nb	1.59.10 ⁻³²	4.19.10 ⁻³³
	⁵⁹ Fe	7.23.10 ⁻³²	1.17.10 ⁻³²		⁹⁵ Nb	8.32.10 ⁻³³	-
	⁵⁸ Co	8.59.10 ⁻³¹	1.19.10 ⁻³¹				-
	⁶⁰ Co	3.59.10 ⁻³⁰	4.36.10 ⁻³⁰	W	¹⁸⁷ W	2.95.10 ⁻³⁰	3.07.10 ⁻³⁰

@ Each activity is normalized to one source neutron and one material atom. One standard deviation of mean experimental error is ~10% on all saturation activities.

Measured Radioactivity near TFTR Plasma
for Select Threshold Reactions

Measured Radioactivity near TFTR Plasma for Capture Reactions

Measured Saturation Activity near TFTR Plasma
in Titanium Samples

Measured Saturation Activity near TFTR Plasma
in Iron Samples

Measured Saturation Activity near TFTR Plasma in Molybdenum Samples

Fig. 10; KUMAR *et al*

FIG. 11: KUPAK et al.

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