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ABSTRACT

The neutron-induced radioactivity of the torus vacuum vessel presents a significant exposure source to in-vessel workers. Assessment of the radiation field is of prime importance in accurately predicting the likely doses to personnel. This paper discusses the experience and results of personal radiation dose and ambient dose-rate measurements of the torus radiation field. Correlation of the ambient dose-rate, the time spent in-vessel, and the actual doses to individuals show an apparent inconsistency, with the effective dose being approximately half of the expected dose. This paper aims to show that simple comparison of the ambient dose-rate, and the effective dose-rate is not appropriate in this situation because of the unique isotropic irradiation geometry that applies to tokamak vessel structures. The relationship between these two dosimetric quantities is compared, based on data from published sources, and discussed in relation to observations of doses to JET in-vessel workers. The measured effective dose to ambient dose ratio which is found to be in the range 0.5 to 0.6, agrees with calculated values. Future shutdowns at JET in 2001 and 2003 will continue to involve manned entries to install new components and perform upgrades. For continued demonstration of JET policy on restricting doses to ALARP, and for optimising manpower and equipment resources, it is important to have a firm basis for predicting the doses to vessel workers.

1. INTRODUCTION

The major source of radiation exposure to personnel at the JET site arises not during plasma operations but in the periodic shutdown outages. Neutron irradiation of the inconel vessel structure produces a number of activation radionuclides, and presents a significant external radiation hazard to in-vessel workers. The principal radiation sources are gamma decay of Co-58 and Co-60 which arise from neutron activation of nickel. Doses to personnel are strictly controlled in-line with the site radiation protection policy. (Individual exposures have to be kept below 5mSv/year, ie below 25% of the current statutory annual limit [1, 2]). Early maintenance work in the vessel was performed almost entirely manually, however, as dose-rates have increased, the feasibility of using manual access is reduced. Dose-rates at the start of the 1998 RTE shutdown were ~5mSv/hr, although the underlying rate had decayed to ~440μSv/hr by the 1999 shutdown. Even at current dose-rates, doses approaching 5mSv can be accumulated in as little as 15-20 hours in-vessel.

Consistent with the site policy of restricting exposure to as low as reasonably practicable (ALARP), planning for shutdowns now requires that minimal staff rotation be used to achieve compliance with the dose-limit, and that remote handling methods be used in preference and whenever practical. Whilst remote means are desirable for reducing dose-uptakes, time and equipment resources required for remote handling preparation can be substantial, and shutdown lengths will be increased. Further, the technical capability of remote handling methods cannot at present perform all required in-vessel tasks. Certain structural welding operations and intricate manipulation or visual inspection continue to require manual access.

2. DOSE PREDICTION

Planning of in-vessel work for future shutdowns requires a good prediction of the starting dose-rates based on the neutron production in the preceding plasma operations campaign. A neutron activation code NPLAN has been used to estimate future in-vessel dose-rates. Historic dose-rates from 1990 to the present have been calculated from another activation code DOSE using recently re-calculated activation coefficients derived for a range of nuclides (Co-60, Co-58, Co-57, Cr-51, Mn-54) [3]. Ambient dose rates are calculated from a neutron transport model for the vessel, using compositional cross-sections, emission energies, decay rates and actual neutron production figures. Figure 1 shows the dose-rate contributions for the main activation nuclides. Calculated figures agree generally well with measured levels (shown as discrete points) within measurement error. Active control of the vessel dose-rate is achieved in machine operations through NPLAN which determines the limiting neutron production. For the 2001 shutdown, an upper limit of 350μSv/hr will apply for the first man-access.

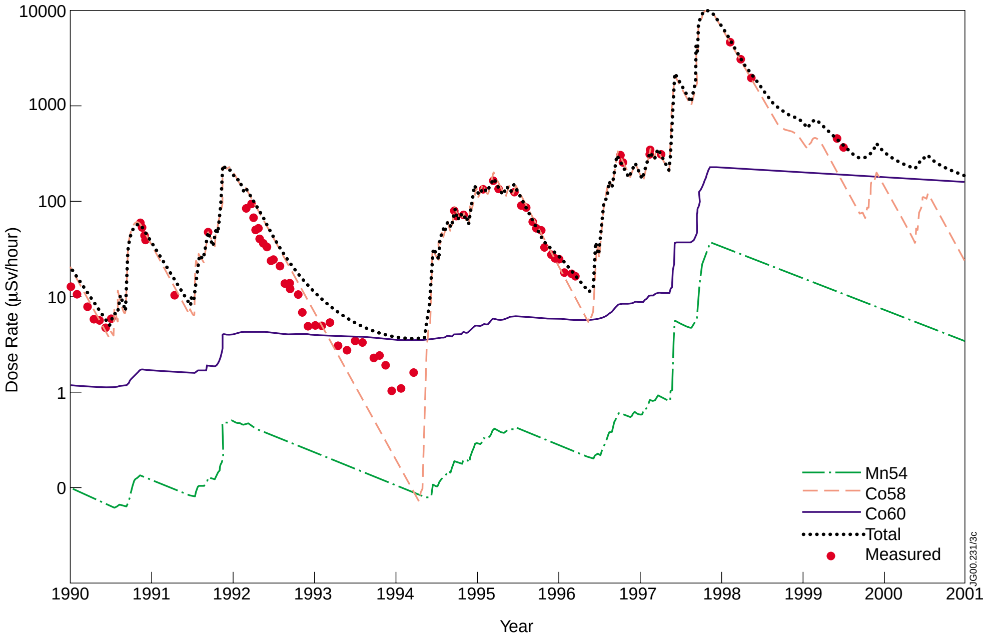

Fig.1: Predicted and Measured In-Vessel Dose Rates 1990-2000

3. DOSIMETRIC QUANTITIES

For the purpose of measuring ionising radiation detriment to the body, the International Commision on Radiological Protection has recommended several key dosimetric quantities in its ICRP60 document [4]. These are, the mean *absorbed dose* in an organ (D_t) which is the absorbed energy per unit mass of the tissue under irradiation; the *equivalent dose* (H_t) for an organ which modifies

D_t with the energy and radiation type weighting factor (w_r), and the *effective dose* (E) which sums H_t over all body tissues according to a tissue weighting factor (w_t). Therefore, the effective dose, $E=\Sigma_t w_t \Sigma_r w_r D_{t,r}$. For radiation protection purposes, it is the effective dose which describes the biological detriment after external radiation exposure, and it is this quantity which should be compared to the relevant dose-limit. However, the quantity E is essentially unmeasurable, since it requires detailed knowledge of H_t in all organs/tissues. Operationally therefore, other dosimetric quantities are necessary, and for external radiation these are, *ambient dose equivalent* (H*), and *personal dose equivalent* (H_{pd}). These are physical quantities that approximate to the primary dose quantities, allowing measuring instruments (dosimeters and dose-rate meters) to be designed for operational use in the control of doses. A dose-rate meter is therefore designed to read ambient dose-rate, and a dosimeter the personal dose equivalent, which itself represents the effective dose.

Organ doses can be calculated mathematically by modelling the body as an anthropomorphic phantom and performing Monte Carlo simulation of the physical interaction process of radiation with tissue. The phantom has organs represented by geometric shapes such as cylinders and cones whose mass and volume concur with ICRP Reference Man.

4. JET EXPERIENCE

Doses accrued by in-vessel personnel have been monitored closely since the first maintenance shutdowns in 1984. Progressively dose-rates have increased with increasing neutron production in D-D operations and in the short D-T phases in 1991 (PTE) and 1997 (DTE1) as seen in Fig 1. The doses accrued by personnel are essentially a function of the occupancy of the vessel, and the dose rates, and the length and nature of shutdown activities. Some shutdowns have spanned three years (1992-1994 Divertor Shutdown), whilst others have been only a few weeks long. Following the use of tritium, more extensive long-lived activity from Co-60 was expected, and as shown in Fig 1, this will continue to influence the dose-rate for some considerable time.

5. MEASUREMENTS AND THEORY

At the start of vessel access, the radiation field is characterised by measuring the mid-plane ambient dose-rate at each octant with a portable ion-chamber instrument (Eberline R02). The averaged value provides a single reference reading. This figure gives a reasonable basis to estimate the dose to personnel working in the torus centre position, however, the contact dose rates on the inner and outer walls can be higher and the occurrence of component hot-spots can produce elevated dose.

Personal dose-equivalent is recorded at JET by means of a thermoluminescent dosimeter (TLD) worn on the trunk of the body. The TLD result essentially provides the measurement of effective dose. Table 1 shows the ratio of effective dose to ambient dose for entries made to the

JET vacuum vessel in the period 1995 to 1999. Ambient dose here is the product of ambient dose-rate (as measured by the R02 instrument) and in-vessel occupancy. The observed ratio of 0.5-0.6 is generally consistent, and it has been taken to be a discrepancy in the measurement, since for simple radiation exposure scenarios, it would be expected that effective dose would be the product of ambient dose-rate and occupancy time. Underestimation of the true effective dose would be a serious flaw in radiation protection controls. However, the apparent discrepancy can be explained by taking account of the radiation quantities being measured and comparing the relationship between them under different exposure geometries.

Table 1: Observed Ratio of Effective Dose to Ambient for the JET Shutdowns

Shutdown Period	Measured Starting Dose Rate for manned access	Observed Ratio R, (Effective dose/Ambient dose)
June 1999	350µSv/hr	0.59
February 1997	333	0.54
October 1996	315	0.51
March 1996	17	0.48
September 1995	55	0.50
June 1995	125	0.61

Exposure of the body can occur in a number of ways. These are described according to the direction of irradiation, eg anterior-posterior (AP), its reverse (PA), rotational (ROT) or isotropic (ISO). Fig 2 illustrates the exposure of an anthropomorphic phantom in the AP, PA and ISO geometries. Given the definition of the primary and operational dose quantities, there is expected to be a variation in the response of these quantities under different irradiation conditions. Calculations can derive conversion coefficients for these quantities, eg from ambient dose equivalent to effective dose, for a range of photon energies [5]. In Fig. 3. the calculated ratio of effective dose equivalent (H_E) to ambient dose equivalent (H*) is given, based on irradiation simulations [6,7]. (The term H_E is essentially the same as effective dose). This shows that under the very specific and unique irradiation conditions in the torus vessel, where for a large part the exposure geometry is isotropic, this ratio varies from 0.4 to 0.7 dependent on the incident photon energy. In the period upto 1997, the in-vessel dose-rate was dominated by the Co-58 isotope, with its peak energy of 0.8MeV. The photon energy spectrum in-vessel would be downshifted due to scattering effects producing a continuum, however, the peak energy can be used as a reference point. The expected ratio R in this instance is in agreement with the observed ratio in Table 1. Vessel entries in the 1999 shutdown took place with higher mean energies in the vessel due to increased Co-60 presence, as shown in Fig 1. The peak photon emission is between 1.1-1.3MeV, giving a ratio R nearer 0.6, again as observed. Thus by comparison of the measured

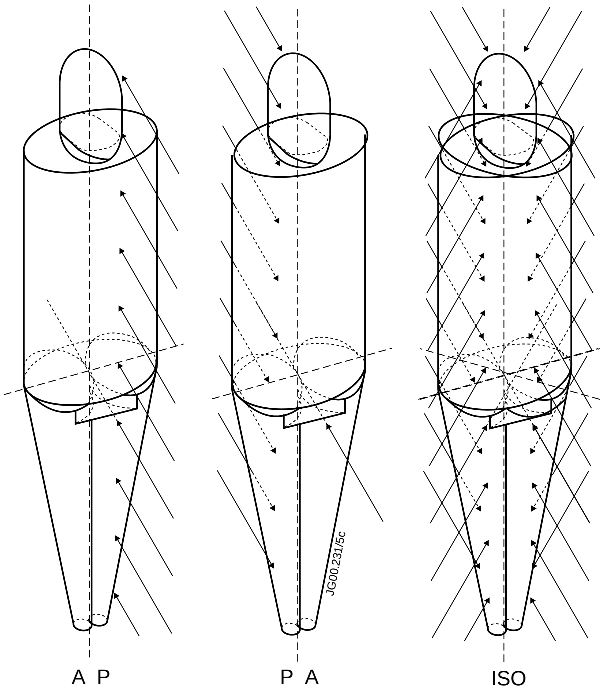

Fig.2: Anterior-Posterior, Posterior-Anterior, Isotropic Irradiation with an Anthropomorphic Phantom

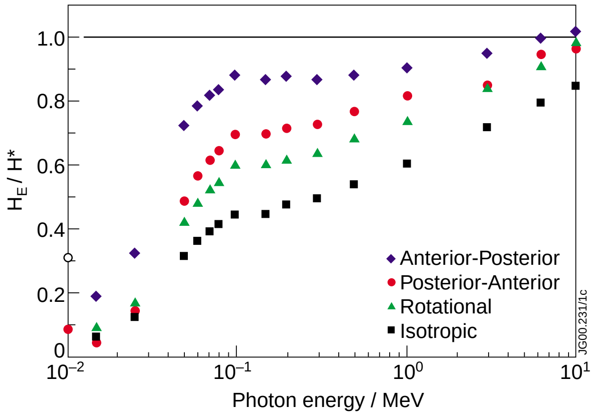

Fig.3: The ratio of effective dose equivalent, H_E (Effective Dose) for different orientations of an anthropomorphic phantom, to Ambient Dose Equivalent H, as a function of photon energy (From Ref. [7]).*

quantities, the observed figures are in agreement with calculation. Standard errors in the observed values of R are deviations from the mean, and can be explained by assuming that dependent on the actual location of the work in the vessel, the exposure may vary form true isotropic to directional - if the person is standing next to the vessel wall for example. Thus individual variations will occur, but the mean ratio R is expected to follow the isotropic irradiation situation. Additional errors arise from estimates made of true vessel occupancy times for some of the early data.

In the limit, where the dose-rate in-vessel is dominated by Co-60 ($t_{1/2}$=5.3y), the ratio R can be expected to be closer to 0.7. This may occur toward the end of a long shutdown when the Co-58 ($t_{1/2}$=71d) contribution diminishes. In-vessel planning for the 2001 and 2003 shutdowns has used a modifying factor 0.6, [8] which is reasonable given the likelihood that shortly after the end of operations the vessel dose-rate after D-D operations is invariably dominated by Co-58.

One further consideration is the likelihood of effective dose measurements being influenced by the shielding effect of the body itself under isotropic irradiation. It is likely that irrespective of where on the body the TLD is worn, there will be some shielding effect. However, the TLD is designed to be isotropic in response, and thus should not underestimate dose due to irradiation geometry. Given the low shielding property of tissue equivalent material, the shielding effect is small and not significant compared to the total dose received.

6. CONCLUSIONS

When account is taken of the definitions of the quantities ambient dose, and effective dose, and the differences in their properties in the isotropic field, there is good agreement between the two values in the JET vessel exposures. As neutron yields increase, higher activation of the vessel structure is likely. Experience shows that the ratio R is approximately 0.5 for peak gamma energies of 0.8MeV, and for higher photon energies, closer to 0.6. Accurate prediction of the likely doses to in-vessel maintenance workers will be of greater importance for future planning of in-vessel activities, and for radiation protection purposes. Experience from the recent JET shutdowns show that the doses can be predicted with good certainty, and that current measurement methods are reliable and give consistent results.

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