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EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3EA

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ABSTRACT.

Beryllium is a material favoured for plasma facing components in fusion reactors such as ITER. However, as a toxic material the safety aspects of beryllium handling need careful consideration. Beryllium has been used on a large scale since 1988 in JET, with more than 3000kg in the torus at one time, in the form of tiles and evaporators. The degradation of tile surfaces during plasma operations and the beryllium evaporated deposit produce dust particles that can mobilise to create potentially harmful exposures. Over 18 separate manual vessel interventions have been conducted since beryllium was introduced. Considerable operational experience has been gained over the last 14 years working in beryllium contaminated atmospheres, and handling beryllium contaminated materials, whilst minimising worker exposure. Although few solid tiles are used for current first wall configurations, a stringent regime for worker protection was developed for JET operations, and maintained extremely low exposures.

In the period 1988 to 2001, more than 81,000 personal exposure assessments were carried out. These show that when account is taken of the respiratory protection worn, 99.98% of exposures are below the statutory exposure limit of $2\mu g/m^3$ (8-hr TWA). More than 1200 beryllium workers have been engaged on JET in this period. To date no identifiable beryllium health effect has emerged in any of the JET workforce.

The regulatory exposure limit for beryllium is likely to be reduced from $2\mu g/m^3$ to $0.2\mu g/m^3$ in coming years. Future fusion devices will encounter even more challenging conditions involving the control of beryllium. JET continues to provide facilities well suited to test beryllium components and develop beryllium handling techniques.

1. INTRODUCTION

Beryllium will be used for plasma facing components on ITER and is a candidate material for next step devices such as DEMO. Its physical characteristics such as strong oxygen gettering, low affinity for tritium, good thermal conductivity as well as its nuclear properties make a leading material for first wall and divertor components, and as neutron reflector and multiplier in the blanket. In addition plasma spraying of beryllium is to be used as a coating technique on in-vessel components.

However, the major drawback of beryllium in fusion applications is its toxic properties and potential health effects due to uncontrolled exposures. Beryllium toxicity can occur as a lung disease (Chronic Beryllium Disease - CBD) caused by inhalation of particulate. A latency period of many years can occur between exposure and disease. In certain individuals even minor exposure can cause sensitisation, and increased likelihood of long term health effects. Use of beryllium on such a large scale, particularly in processes which render some of the material into dust forms, creates a major liability in terms of controlling the material, handling and maintenance implications, and waste disposal.

JET has been a valuable testing ground for the engineering and physics issues of beryllium components in fusion applications. Plasma operation in both limiter and divertor configurations has been conducted on JET and improved plasma performance has been demonstrated through reduced radiation losses and reduced plasma disruptions, and provided data validating its use for as plasma facing components [1]. Since its first use in-vessel from 1989, a large range of beryllium handling, in-vessel work, and decontamination activities has been carried out. As a means of assessing worker exposure, a large number of measurements have been made during work in beryllium areas. A comparison is made of the quantities of beryllium installed in the torus and the corresponding beryllium contamination levels, with a view to providing some operational data to support future handling activities.

2. JET HISTORY

Beryllium is evaporated onto in-vessel surfaces, and has been used as solid protection tiles (belt limiter, RF antennae screens and protection, dump plates, and Mk1 divertor target plate tiles). Table 1 shows a summary of beryllium installation and removal in shutdown periods.

Shutdown Phase	**Date**	**Beryllium Operation**	**Quantity Introduced (+)/Removed (−)**
1988-89	Apr 1989	^{4}Be evaporator heads installed	+12 kg
Mid 1989	Jul-Aug 89	Upper and lower belt limiter tiles and some ICRH tiles	+1860 kg
1989-90	May 1990	ICRH A1 antenna protection tiles, A1 antenna screens Lower beryllium dump plates	+440 kg +350 kg +670 kg
1990-91	Nov 1990	Removal of lower belt limiter, and lower dump plates	−930 kg −670 kg
	May 1991	New lower dump plate tiles	+420 kg
1992-94	Mar 1992	Major strip out, decontamination activities, removal of upper belt limiter, lower dump plates, RF antennae, evaporators for installation of pumped divertor	−930 kg −420 kg −440 kg −350 kg −12 kg
	Early 1994	Install A2 Be antennae, new Be evaporator heads	+350 kg +12 kg
1995	Mar-Apr 95	CFC target plate tiles on the divertor replaced with beryllium	+1600kg
1995-96	June 95	Installation of Mk2 divertor. Mk1 divertor (Be target plates) removed. Some Be elements on RF antennae, Be evaporators remain	−1600kg

Table 1. History of Beryllium Use in the JET Vessel

The first use of beryllium began with four evaporators installed in May 1989. Periodic use of the evaporators has continued to the present, with weekly evaporations during machine operations, each evaporation depositing some 1 to 10 grams. Although the evaporated beryllium has good adhesion on some vessel surfaces, the effects of spallation and loading produces friable material. The shutdowns of July-Aug 89, Oct 89-June 90, Aug-Sept 90, and Nov-May 91 followed plasma operations with the beryllium belt limiters in place. The dump plate and RF components installed in May 90 further increased the total beryllium content in-vessel, such that the amount at the start of the Aug 90, and Nov 91 shutdown was 3.3 tonnes. Some of the highest in-vessel concentrations are associated with these four shutdowns, principally due to disturbance of tile surfaces or evaporated deposits during maintenance work, or grinding of (inconel) vessel components, and wire brushing of the evaporators. Peak concentrations of 786µg/m^3 were observed in the Aug 1990 shutdown (caused by resuspension of dust due to compressed air). Surface contamination levels >50µg/m^2 are found routinely, although the majority of surface contamination is not readily liberated into air. In-vessel entries have predominantly been in full pressurised suits (protection factor = 2000 for particulate), although in some shutdowns it was possible to use face masks only, or dispense with respiratory protection altogether (for the Mk1 divertor installation in 1993).

The highest level seen outside the torus is associated with a period of machining of beryllium tiles in a beryllium handling facility. Despite use of isolator containment, the transfer process allowed some release of contamination giving rise to concentrations of 9µg/m^3 and intakes of 2.6µg/m^3 (8hr-TWA).

3. PROCEDURES FOR HANDLING BERYLLIUM

Adequate control of beryllium requires dedicated facilities for preparation, handling, decontamination, storage and processing of beryllium contaminated material. Controls include confinement through ventilation, containment by use of total enclosures or plastic membranes (tents/isolators) and respiratory protective equipment [2, 3]. Breach of the torus requires access facilities or tents for containment, and an air in-flow of at least 0.5-1m/s across open ports to minimise dust release into the torus hall. Opening of diagnostic ports, beamlines, waveguides, and viewing windows need prior assessment. Peripheral systems, such as NB and pellet injector boxes are routinely tested for migration of dust. Torus upper diagnostic ports have shown little migration of dust, but the risk is greater in horizontal ports and lower ports.

In many cases the methods of ventilation control and containment are identical to those applied for control of tritium hazards. However, these are not necessarily compatible; eg control of beryllium dust may demand large ventilation flows to avoid diffusion of small particles across open ports, however this may result in high tritium discharge. Further, isolators and tent containments offer good control of beryllium but its value against tritium is time dependent.

In principle, use of RPE is limited to situations when engineering controls are unlikely to provide adequate control. In practice, RPE is often used as an additional means of minimising exposure, or as an ALARP measure. This policy has been successful in keeping actual exposures below 2µg/m^3 in certain situations where unexpected contamination was found.

4. MONITORING AND CONTROL STANDARDS

Entries into beryllium areas are covered by individual and static air sampling. The sampler used for personal sampling is a UK seven-hole head connected to 2 litre/min low flow pump (0.8m pore size paper). This unit samples the inhalable fraction of airborne dust (<50m) in compliance with current UK regulatory guidance [EH40, MDHS 14/3] which requires this quantity to be compared the 2µg/m^3 (8hr TWA) occupational exposure limit. However it is the respirable fraction (<10m) which is most likely to reach the deep alveolar region of the lungs and remain trapped, and thus of most significance toxicologically. Measurement of the total inhalable fraction may therefore overestimate the risk, although this is balanced by inherent uncertainties in the measurement method and variations in practical usage of sampling equipment. Particulate contamination <10m has been observed in-vessel. There is evidence justifying the re-standardisation of exposure limits in terms of three respiratory fractions of concern (respirable, thoracic, inhalable) [4], so definition of future exposure limits may follow this categorisation. It is possible that the risk may be better defined in terms of particle count rather than mass.

Reports of excess cases of CBD in subjects exposed to levels near 2µg/m^3 [5] and on going concerns about the carcinogenicity of beryllium have triggered a review of working practices in the beryllium industry. The present beryllium standard originates from 1949, derived by empirical evaluation of its hazards compared to heavy metals. Consequently government advisors in the USA have placed beryllium on the list of materials whose toxicology is being reviewed with a view to reducing the occupational exposure limit to one tenth of the current level, to 0.2µg/m^3 (8hr TWA) [6]. Such a change is likely to occur within the next 2-3 years, and will probably result in equivalent changes to exposure standards in other industrial countries. Procedures at Culham are therefore being reviewed in anticipation of this change.

5. Exposure Monitoring Results

In the period 1989 to 2001, some 85,000 measurements (81,000 assessments) were made. 95% are below the detection limit of 0.03mg. 99.83% are below the 0.2µg/m^3 level, and 99.98% 2µg/m^3 (8hr-TWA) with RPE taken into account. Of the 12 cases of exposure >2µg/m^3, all are in the period 1989-93, although not all are related to in-vessel work. Figures 1 and 2 summarise the exposure data, and Figure 3 shows some of the highest in-vessel beryllium levels observed.

5. MEDICAL SURVEILLANCE

Medical surveillance for Be work in JET involves a pre-employment review of fitness and test of lung function (baseline spirometry and chest x-ray), and electrocardiograph. An annual repeat test is made of lung function, for the 350 current workers. A gas transfer test was used additionally, but in use it was found that the non-occupational causes (eg smoking) which affected results to such a large extent, that its use for accurate diagnosis in lung function was reviewed. There is also evaluation of fitness to wear RPE, eg pressurised suits. There are no plans for systematic follow-up of the 850 former beryllium workers at Culham. In the USA, widespread use is made of the beryllium blood lymphocyte proliferation test, which measures the reaction of blood immune cells to a beryllium compound. This in principle indicates if the individual is sensitive to beryllium but does not diagnose sub-clinical or clinical CBD. The test has been considered at Culham but is not likely to be adopted until reliability issues are resolved. Medical research has found genetic markers which may play an important role in determining sensitisation [7], and potentially offers means of screening workers, although ethical concerns exist over its use.

CONCLUSIONS

Site procedures are well established for beryllium safe handling, and operational results demonstrate good control with 99.98% of exposures below $2\mu g/m^3$ and 99.83% below $0.2\mu g/m^3$, after allowance for RPE worn. Only occasional exposures have been observed. There are no reported cases of beryllium related health effects in the current workforce, although there is need to be aware of a possible latency period. The modest quantities of tritium used in JET have enabled adequate control of both hazard types, but a larger scale use of tritium and beryllium will be more challenging and require new techniques to be developed. Although remote handling was developed mainly for radioactive environments, it could be equally useful for toxic hazards, eg in maintenance and decontamination tasks prior to manual work in hazardous areas. Exposure control depends largely on engineering controls, which for JET have had to be purpose designed for a range of unique operations. RPE is essential for contaminated in-vessel work, but largely provides a margin of safety and reassurance, especially in new tasks where contamination levels are not known. Retrospective analysis of beryllium monitoring samples has affected safety of operations. Significant effort has been required developing practical work procedures, training of the workforce, continuously monitoring the workplace, providing medical support, and providing rescue and emergency response in case of incidents. Tighter controls have emerged within the beryllium industry, especially with the prospect in reduction of the exposure limit. The policy as developed in the 1980's for JET, of applying stringent exposure controls and standards have proved to be prudent and practicable, and remains consistent with the proposed new exposure limit. This approach is directly applicable to developing safe methods for beryllium work in the future.

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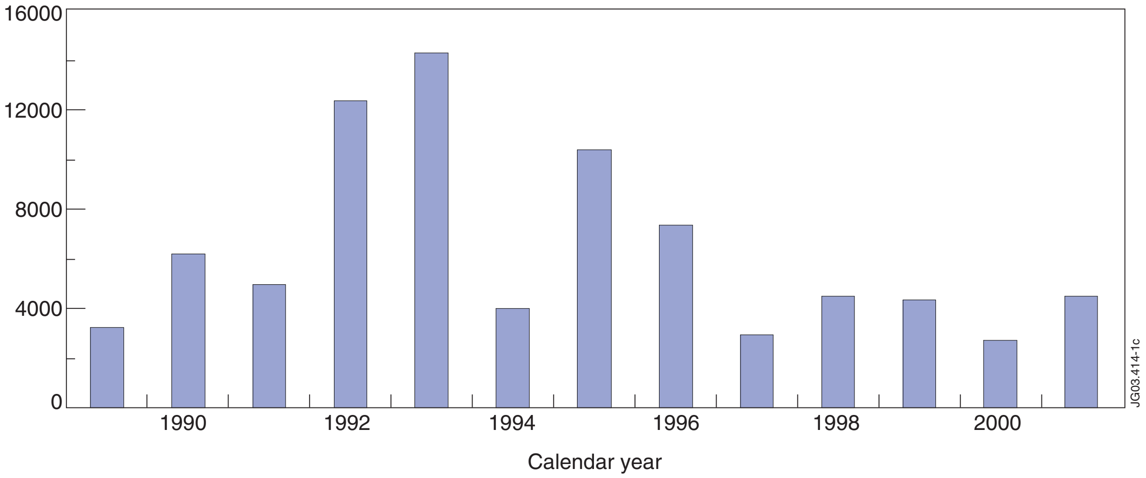

Figure 1. Beryllium Personal Exposure Assessments (1989-2001)

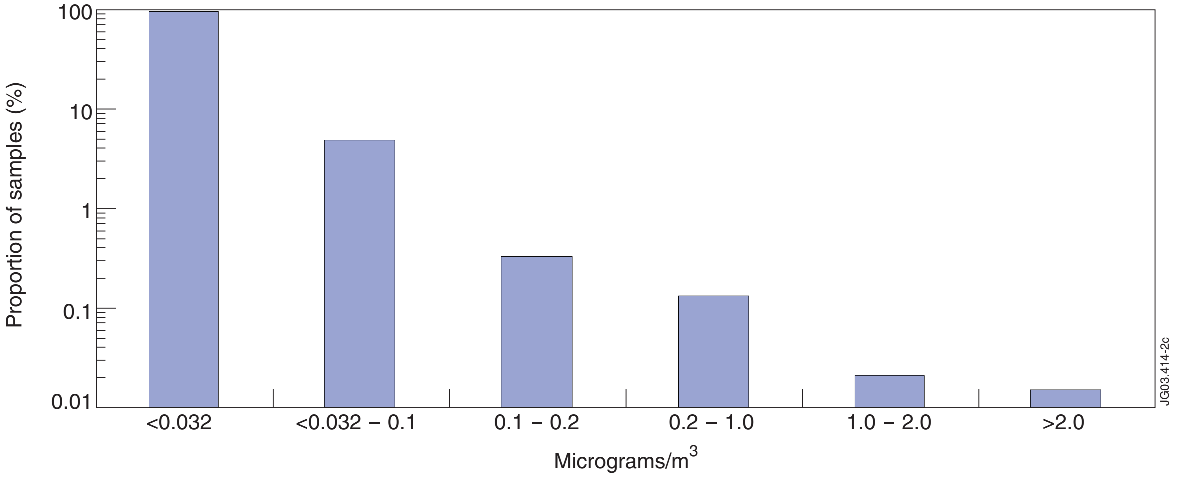

Figure 2. Beryllium Exposures (1989-2001), as 8-hr Time-Weighted Averages, RPE Adjusted

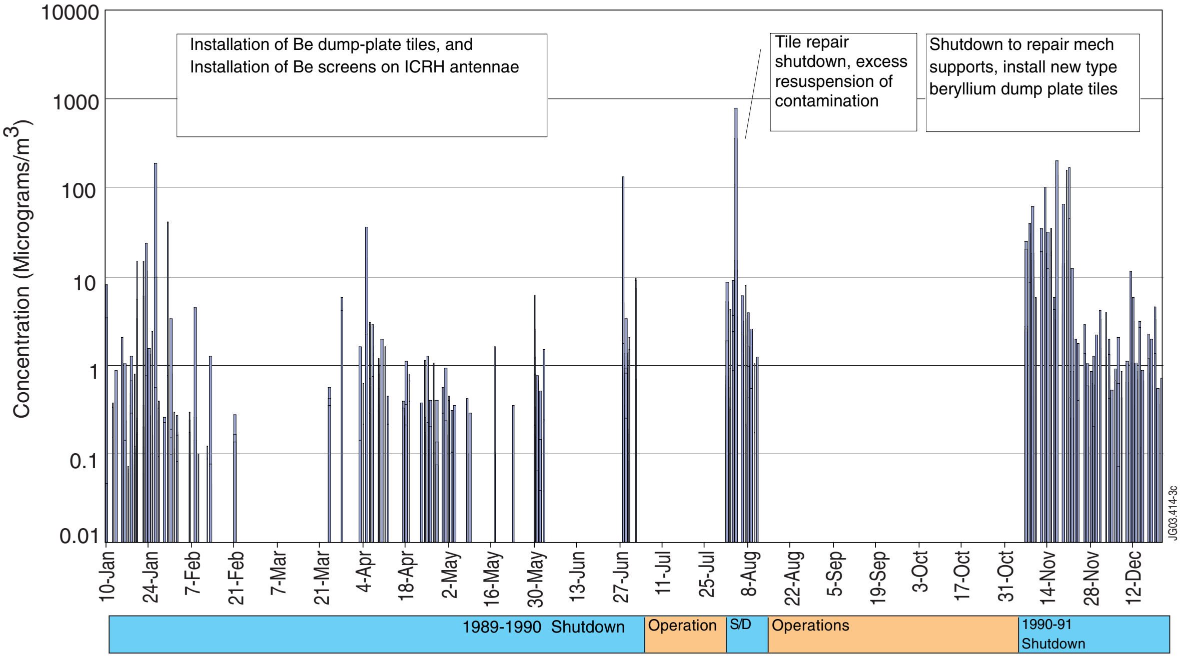

Figure 3. In-Vessel Beryllium Concentrations by External Personal Air Sampler - 1990.