JOINT EUROPEAN TORUS

JET–P(95)59

Many Authors

JET Papers presented to the 2nd lEA International Workshop on Beryllium Technology for Fusion (6 September 1995, Jackson Hole, USA)

JET Papers presented to the 2nd lEA International Workshop on Beryllium Technology for Fusion (6 September 1995, Jackson Hole, USA)

Many Authors

JET-Joint Undertaking, Culham Science Centre, OX14 3EA, Abingdon, UK

Preprint of Papers to be submitted for publication in the proceedings of the
2nd lEA International Workshop on Beryllium Technology for Fusion.

November 1995

JET Papers presented to 2nd IEA International Workshop on Beryllium Technology for Fusion
(6 September 1995, Jackson Hole, USA)

Contents

Operational Aspects of Using Beryllium -

Safety and Decontamination

M. A. Pick and A. D. Haigh

JET Joint Undertaking, Abingdon, OX14 3EA, UK

Abstract

After more than six years of operational experience working and handling beryllium, JET is now in a position to work efficiently and easily with the imposed procedural, organisational and facility-wise requirements associated with the large scale use of beryllium. It is, however, clear that the use of beryllium requires a large additional commitment both in the form of additional facilities as well as man-power, ultimately leading up to a substantial additional financial burden. This paper outlines this additional effort and what impact it has on the design, operation and maintenance of a large scale machine such as JET or ITER.

1. Introduction

As beryllium and most of its compounds are considered toxic, their use is governed by a number of statutory instruments, regulations and recommendations. These are associated with the control of the work place; storage; control of discharges; personal protection of the work force; medical supervision of the work force; reporting of injuries, diseases and occurrences; classification, packaging, labelling and shipment; insurance. Many of these requirements are to be seen simply as additions to those regulations already implemented in an industrial site such as JET. JET, as any future large fusion machine site, already implements the requirements associated with the Ionising Radiation Regulations due to the induced radiation and the use of tritium. Although there are differences in the regulations throughout the countries of the world, the example of JET and the impact the use of beryllium has had there, serves as a good example. The requirements will differ only slightly were the experiment to be sited elsewhere. The application of the appropriate regulations brings with it the setting up of a variety of facilities, installations and procedures. It is these areas which will be discussed in some detail below.

2. Implementation of Regulations

2.1 General

At JET the implications and recommendations have been formulated in an internal document entitled: Code of Practice for the Safe Use of Beryllium at the JET Laboratory (1).

According to the Code of Practice beryllium should be manipulated in enclosed areas only. Where this is not possible, a local exhaust ventilation system equipped with filtration of a specified high standard is provided for processes likely to generate dust or fumes. Areas in which beryllium is manipulated are clearly marked as **Beryllium Controlled Areas** and access to these areas is strictly controlled. There are large Beryllium Controlled Areas at JET where routine work is performed on beryllium or beryllium contaminated equipment. If beryllium is manipulated in an area not normally designated a Beryllium Controlled Area then a temporary Beryllium Controlled Area is established. Local Rules to regulate work activities, personnel entry, exit and discipline, are associated with each of the Beryllium Controlled Areas. All the possible hazards associated with each separately identifiable job, normally laid down in the form of an Assembly Procedure, are assessed by way of a Safety Assessment which is circulated to a series of prescribed Safety Assessors and attached to the Procedure.

Any person expected to manipulate beryllium at JET must become a Beryllium Worker. To obtain that designation the person must undergo a full medical examination and be declared medically fit for beryllium work. He must attend an induction course in beryllium safety at JET and be trained in the use of all applicable safety equipment including being trained to operate in a full pressurised suit.

2.2 Exposure Limits and Standards

The principal risk associated with the use of beryllium is the inhalation of dust or fumes. These may be generated by processes in which beryllium is manipulated or they may be re-suspended from contaminated surfaces. For these reasons limits have been set on the airborne dust concentration and the surface concentration of 2 mg m^{-3} and 100 mg m^{-2} respectively. This airborne dust concentration limit was first adopted by the American Atomic Energy Commission in 1949 and is recognised throughout the European Union and other western countries. These are the Occupational Exposure Limits (OEL) in use in the UK (2,3).

In JET a Beryllium Controlled Area (BeCA) is set up whenever a Safety Assessment of a job to be undertaken states that 0.2 mg m^{-3} airborne contamination or 10 mg m^{-2} surface contamination is likely to be reached or exceeded. A Respiratory Protection Zone (RPZ) is established at JET whenever the airborne beryllium concentration is expected to reach or exceed 1mg m^{-3}. No person is allowed into these areas unless they are wearing the type of respiratory protection equipment prescribed by Health Physics. A

Beryllium Controlled Area may be an entire room or the inside of a piece of equipment such as the JET torus itself, a temporary enclosure such as a PVC tent or 'Isolator' or even a barriered off area.

2.3 Monitoring

The monitoring of the above outlined limits on airborne and surface contamination is performed by the Health Physics group.

As there is as yet no reliable and legally accepted form of real-time beryllium monitoring, this is carried out by drawing measured volumes of air through a filter paper over a known period of time and measuring the amount of beryllium on the paper by using an Absorption Spectrometer.

Both routine and special air monitoring programmes are undertaken. The routine samples provide information on the general conditions in all areas and indicate whether the performance of all control procedures and facilities is adequate.

Surfaces are monitored by taking dry smear samples of the surface and determining the amount of beryllium in the smear, as with the airborne beryllium samples.

The chemical analysis work on the samples and the absorption spectrometer are carried out in the **Analysis Laboratory.**

2.4 Personal Protection

When working with beryllium all personnel must wear some degree of personal protection. This ranges from the minimum requirement of disposable coveralls, overshoes and gloves, through a range of intermediate levels of protection using different ori-nasal or respiratory protection, to the maximum protection of a full pressurised suit. The respiratory protection to be used is specified by Health Physics.

All respiratory protection equipment is worn only once. If not of the disposable type this equipment is subsequently cleaned and sanitised. This is done in a specialised **Suit Cleaning Facility**.

2.5 Waste Management

The disposal of solid beryllium waste, solid radioactive waste, mixed waste and the disposal of contaminated liquids is covered by a series of formal JET Waste Management Procedures.

The Environmental Protection Act and the Radioactive Substance Act impose a legal duty on the operator to ensure that waste materials are appropriately classified and disposed of by authorised disposal routes. JET deals with a variety of authoritative bodies including the National Rivers Authority, Her Majesty's Inspectorate of Pollution and the local District Council. JET is periodically inspected by the disposal authorities and final recipients of JET waste, and also makes its own visits to the recipient sites.

Solid beryllium is sent either for controlled burial at an authorised land fill site, or, if radioactive, it is disposed of at the UK national radioactive waste repository in Sellafield, Cumbria. The Waste Management Group collects, sorts, samples, processes and dispatches waste using the JET **Waste Handling Facilities**, Fig 1.

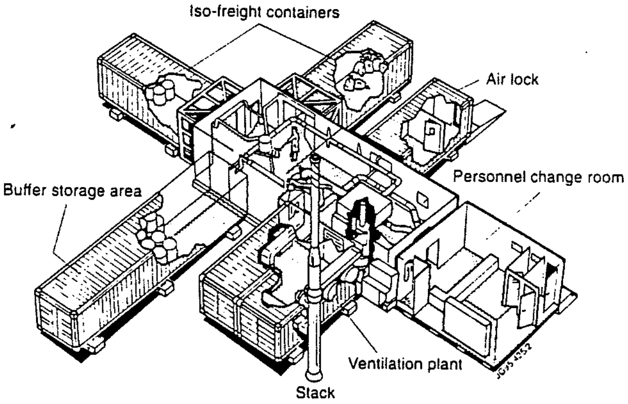

Fig.1: The JET Waste Handling Facility

2.6 Procedures

A very large number of Procedures and Working Rules have been developed which govern all aspects of the work with beryllium. They include, amongst others, the following:

Procurement, Receipt and Issue of Beryllium
Work Permit and Safety Assessment

Packaging, Labelling And Transport of Beryllium
Storage of Beryllium
Beryllium Controlled Areas and Local Rules
Respiratory Protection Zones
Removal of Temporary Enclosures (Isolators and Tents)
Cleaning
Transfer of Materials from Beryllium Controlled Areas
Waste Disposal
Incident Procedures i.e. Accidental Release, Injury, Fire etc.
Radioactive Beryllium

3. Facilities

The following is a list of the main facilities which have been required to be established at JET. The list shows the equipment associated with each of the facilities as well as the number of staff required to man the units during shutdown periods.

3.1 Torus Access Cabin

This Cabin, Fig 2, allows entrance to the JET vessel through the main horizontal port at the 6m level. It contains all the support and communications equipment required for pressurised suits as well as the dressing and washing facilities. It also contains all the services required to enable the in-vessel work.

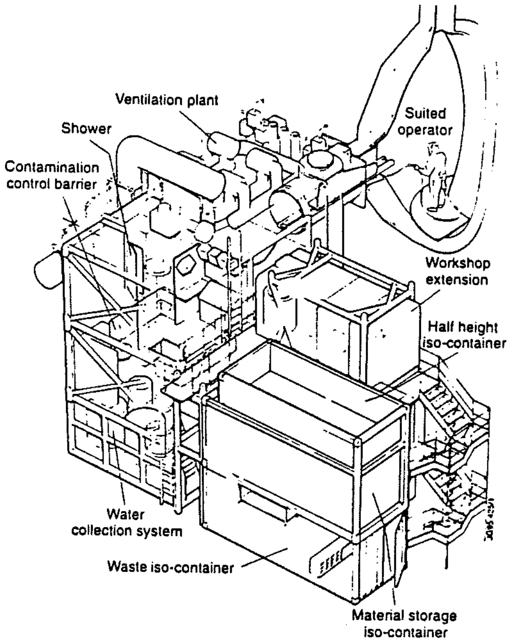

Fig.2: The JET Torus Access Cabin

Equipment:

Contamination control barrier
Ventilation system
Breathing air supply system
Pressurised suit dressing room
Shower
Ex- to in-vessel communications systems - audio\video
JET access and operations box, extensions to storage and workshop areas
In-vessel services -
power distribution
welding power supply
compressed air
water
hydraulics
cryogenic CO_2 blasting
boron carbide water jet grit blasting
Posting facilities
ISO-container docking

Staffing (assuming 2 shift operation):

In-Vessel Operators in suits 12 to15
(3 entrances x 4 or 5)
Engineers/Supervisors 6
Suit support staff 7 to 8

3.2 Boom Access Facility

This facility permits access to the vessel for the boom as well as for personnel at the Octant 5 main horizontal port.

Equipment:

Contamination control barrier
Ventilation system
Breathing air supply system
Pressurised suit dressing room
Shower
Ex- to in-vessel communications systems - audio/ video
JET access and operations area, extensions to storage areas
In-vessel services -
power distribution
welding power supply
compressed air
water
hydraulics
Posting facilities
ISO-container docking

Staffing (assuming 2 shift operation):

In-Vessel Operators in suits 9
(3 entrances x 3)
Remote Handling Boom Operators 4
Suit support staff 7

3.3 Beryllium Handling Facilities

These facilities, Fig 3, are designed to enable decontamination, assembly, inspection and repair work to be performed on components.

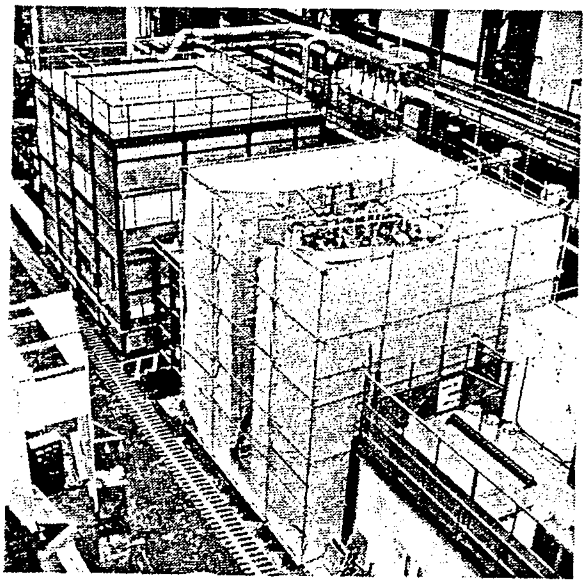

Fig.3: Two of the main JET Beryllium Handling Facilities are shown located in the Assembly Hall of JET. The upper one is a fixed, permanent facility with an in-built 5 m^2 access port in the roof. The lower facility is a temporary facility which is basically a large supported tent. This also permits large components to be entered whilst supported from the roof crane

Equipment:

Contamination control barrier
Ventilation system
Breathing air supply system
Pressurised suit dressing room
Shower
Communications systems - audio/ video
Small beryllium workshops
Decontamination systems -
water wash (high pressure)
boron carbide water jets
ultrasonic cleaning baths
Services -
power distribution
welding power supply
compressed air
water
ISO-container docking
5 m^2 bagging port in roof
Monitored discharge stack

Staffing (assuming 2 shift operation):

Suit support staff 6
Operators in suits 8 (2 x 4)
Non-suited staff 5

3.4 Beryllium Suit Cleaning Facility

This facility is used to clean and disinfect and inspect used pressurised suits and respirators and to keep a stock of clean equipment ready for use in the various facilities. The full stock includes 350 full suits, 80 half suits, 150 respirators and several thousand disposable suits. The throughput of the facility allows 18 to 20 full pressurised suits to be cleaned per day. This is the usual number of suits required for use during a normal working day in the JET vessel.

Equipment:

Contamination control barrier
Ventilation system
External decontamination bath for suits
Internal disinfection bath for suits
Ultrasonic baths for respirators, etc.

Staffing:

Suit cleaning 4
Inspection and issue 3

3.5 Waste Handling Facility

Designed to collect, sort, sample, process, pack and dispatch Be contaminated and radioactive waste, Fig 1.

Equipment:

Contamination control barrier (emergency shower)
Ventilation system and monitored discharge stack
ISO-container docking stations for waste in, waste out

Waste drum compactors
Glove box inspection station
cutting/size reduction room
Buffer store

3.6 Beryllium Analysis Laboratory

Designed to quantitatively measure beryllium contamination of swabs and filters.

Equipment:

Contamination control barrier
Ventilation system
Fume cupboards
Atomic absorption spectrometry
Chemical laboratory facilities

Staffing:

8 on shifts

3.7 Isolator and Tent Manufacturing, Suit Repair Facility

PVC cutting and welding and test equipment
Staffing: 3 Operators

3.8 Transfer and Storage Facilities

ISO container park with ventilated extracts
Standardised transfer and docking facilities using ISO containers
Liquid effluent holding and discharge tanks

3.9 In-Vessel Training Facility

In 1994, an In-Vessel Training Facility was built as a realistic full-scale replica of four octants of the inside of the JET vessel and all of the important aspects of the in-vessel components, Fig 4. This facility has three main uses:

- The provision of adequate training for in-vessel workers. The work in the vessel, in which the background radiation levels is increasing as the number of high performance plasmas increases, is performed by workers wearing pressurised suits with limited visibility and three pairs of gloves. To remain within JET's self imposed radiation exposure limit, a large number of trained fitters, engineers, welders and inspectors are required. The facility is used to train in-vessel personnel in the conditions that await them and to allow them to practice the procedures just prior to their actually going into the vessel. This ensures that all in-vessel work can be done correctly, safely, efficiently and with the absolute minimum of radiation exposure.

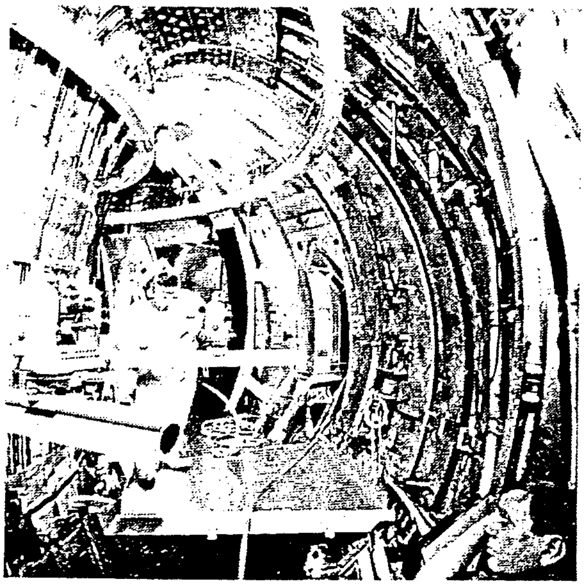

Fig.4: The In-Vessel Training Facility showing an inspector wearing a pressurised half-suit being trained in the use of a theodolite to position in-vessel components

- To check the details of new components, develop and test all new installation procedures, handling and installation tools, new in-vessel flooring, and interface problems in order to ensure that the Mark II divertor can be installed to the desired accuracy and within the boundary conditions prevailing.

- For remote handling operations trials. The preparation of equipment and operators for the fully remote exchange of the tile carriers includes the fullscale testing and proving of each individual task both under normal operating conditions and under failure case conditions. All of these trials will be performed within the facility. The facility has incorporated into it a full-scale space frame representation of all in-vessel components considered to potentially offer a manoeuvring, viewing or access constraint under fully remote conditions.

Equipment:

Suit training facility
In-vessel mock-up of all hardware
Configuration control
Installation trials
In-vessel procedures training
Remote handling trials and procedure tests

4. Decontamination

A detailed examination of a wide variety of possible decontamination techniques was carried out to identify a method which; could be used to safely remove beryllium containing layers from the surface of the inside of the JET machine; would be compatible with subsequent plasma operations i.e. would not introduce unwanted high Z impurities onto the material; would not damage the surface, and would cause little waste disposal problems. Such a method was identified in the wet abrasive blasting using boron carbide grit (4). The method uses a high pressure water jet and a separate vacuum recovery and hydro cyclone system to recover the grit. The method was used successfully to decontaminate the inside of the JET vessel from a layer of tritium containing beryllium and to thereby allow the vessel to be reclassified from a Class 3 Respiratory Protection Zone where the use of pressurised suits is mandatory to a class zero Respiratory Protection Zone where no respiratory protection at all is required, Fig 5. This method of decontamination can be applied to particular smaller components which either require to be worked on or which need to be disposed of easily. It has therefore been included in the equipment available in one of the fixed Beryllium Controlled Areas.

A second method, blasting the vessel walls with a cold jet of carbon dioxide pellets, was successfully investigated and employed in the vessel The mechanical and thermal shock of the blast embrittles and dislodges a contaminating film, which can then be removed by vacuuming (5).

Fig.5: An in-vessel operator wearing a full pressurised suit and using the 100 bar boron carbide grit water gun to clean the JET vessel

5. Conclusions

The use of beryllium in a large fusion device implies a substantial effort in terms of infrastructure, facilities, organisation and manpower. Many, but not all, of the requirements can be regarded as an extension of the requirements already necessary for a facility operating with tritium. This paper describes the situation at JET where beryllium has been used on a large scale and very substantial work has been performed on heavily beryllium contaminated components both inside and outside the JET vessel. Any future machine in which beryllium is planned to be used should consider integrating the requirements into the organisation and the design of the facility and buildings right from the start.

Acknowledgements

The authors wish to acknowledge the contributions to the work by a very large number of members of the JET Team, Special emphasis is made to the contributions of the Health Physics and Safety Group, the Waste Management Group, and the First Wall Installation Group,

References

(1) Code of Practice for the Safe Use of Beryllium at the JET Laboratory, JET-SR(89)02

(2) EH40, Occupational Exposure Limits, Health and Safety Executive, HMSO Publication ISBN 0-11-88-20-80 Annual

(3) EH13, Beryllium - Health and Safety Precautions 1977 HMSO, ISBN 0-11-88-30-38 4

(4) Decontamination of the JET Vacuum Vessel from Beryllium and Tritium, S M Scott et al. 17th Symposium on Fusion Technology, Rome, September 1992

(5) Decontamination of the JET Vacuum Vessel Using the CO_2 Pellet Blasting (cold jet) Technique. S M Scott et al. International Symposium on Decontamination & Decommissioning, Knoxville, April 1994

THERMAL FATIGUE OF BERYLLIUM

E. Deksnis, D. Ciric, H. Falter, C. Ibbott, A. Peacock
JET Joint Undertaking, Abingdon, OX14 3EA, UK

Abstract

Thermal fatigue life of S65c beryllium castellated to a geometry 6 x 6 x (8-10)mm deep has been tested for steady heat fluxes of 3 MW/m^2 to 5 MW/m^2 and under pulsed heat fluxes (10-20 MW/m^2) for which the time averaged heat flux is 5 MW/m^2. These tests were carried out in the JET neutral beam test facility A test sequence with peak surface temperatures ≤600°C produced no visible fatigue cracks. In the second series of tests, with T_{max} ≤750°C evidence for fatigue appeared after a minimum of 1350 stress cycles. These fatigue data are discussed in view of the observed lack of thermal fatigue in JET plasma operations with beryllium PFC. JET experience with S65b and S65c is reviewed; recent operations with Φ = 25 MW/m^2 and sustained melting/resolidification are also presented. The need for a failure criterion for finite element analyses of Be PFC lifetimes is discussed.

Table 1. S65c fatigue tests, flux densities MW/m^2

Series 1

shutter position	peak power density			std	number of		on time per pulse		modulation	
	max	min	average		pulses	cycles	average	std	on time ms	off time ms
1	5.55	3.21	4.61	0.45	112	112	2.40	0.80		
2	12.87	4.62	11.04	0.98	112	1041	0.93	0.17	108	142
3	19.73	13.63	15.00	0.98	86	700	1.00	0.98	110	190
4	21.06	16.35	18.70	0.86	93	827	1.07	1.00	96	231

Series 2

shutter position	peak power density			std	number of		on time per pulse		modulation	
	max	min	average		pulses	cycles	average	std	on time ms	off time ms
1	7.69	4.09	5.39	0.55	98	98	3.60	0.89		
2	12.01	7.75	9.63	0.77	60	1236	2.34	0.75	104	108
3	15.57	9.63	13.43	0.96	51	823	1.86	0.33	107	189
4	19.65	7.91	18.40	1.56	71	800	1.91	0.60	146	273

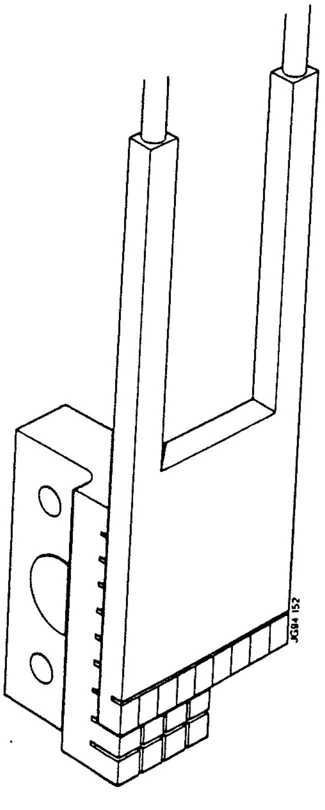

Figure 1: Shadowing of irradiated tile

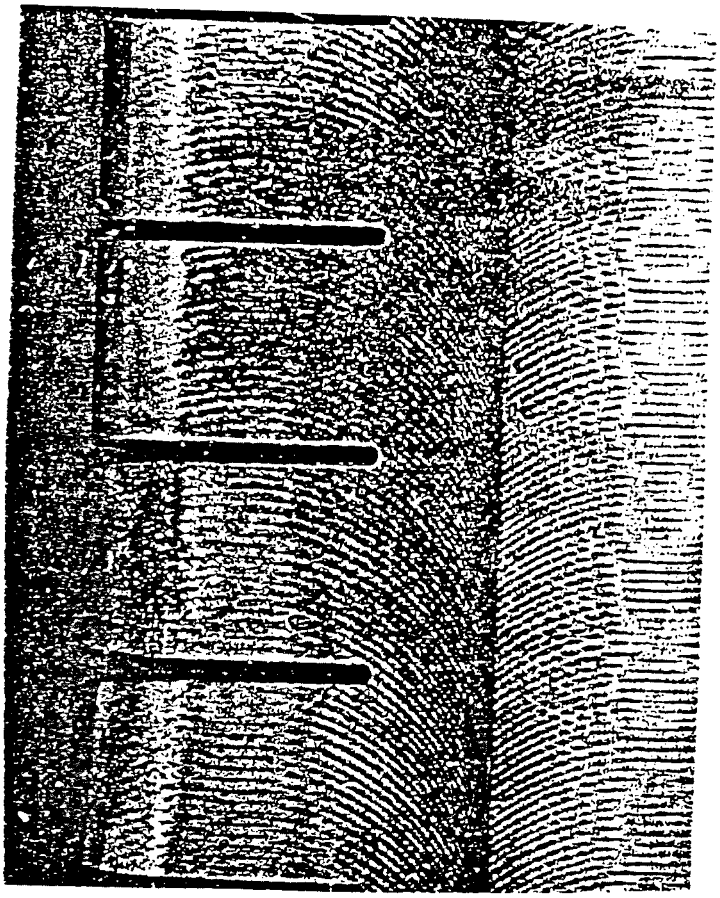

Figure 2: Edge view after irradiation of S65c castellated tiles

1. INTRODUCTION

The requirements for beryllium plasma facing components specify that the beryllium cladding sustain steady heat fluxes of 5 MW/m^2 under normal conditions and steady heat fluxes of 20 MW/m^2 under off-normal conditions. The proposed designs envision a thick cladding of beryllium (6-10 mm) onto an actively cooled heat sink, i.e. a CuCrZr substrate. The stresses in the beryllium part of such a duplex component comprise, in addition to the singular stresses that obtain at the free edge of the brazed joint a concentrated stress field near the irradiated surface and another one near the brazed interface (away from the vicinity of the singularity).

The extensive JET experience with inertial PFC made out of S65 and S65c Beryllium has produced data for the thermal fatigue of S65c for heat fluxes S-25 MW/m^2, Tsurface up to and including melting. Careful experiments in a controlled test-bed environment on S65c material for JET applications have been carried out by SNLA (1) and partially by JET (2). More recent ITER emergency tasks investigated the fatigue lifetime of S65c beryllium material under pulsed, transient heating conditions. The aim of the study was to understand the effect of peak surface temperature upon the fatigue characteristics of S65c material (3). Somewhat surprisingly there appears to be a temperature threshold of 600-750°C for the development of large invisible permanent thermal distortions @ 10^3 cycles of Φmax ≈ 10-15 MW/m^2.

More recently JET has examined as an ITER task the thermal mechanical response of thick beryllium cladding of a CuCr vapotron. These results are still being examined and will be presented in full in a forthcoming conference (4). However, visual observations indicate that resolidified S65c material under these actively cooled conditions and that looks to be different to the appearance typical of inertial tiles show a markedly different appearance. Finite element results will be presented in this paper to investigate the possible reasons for this difference.

Very recent JET tokamak experience with inertial tiles that have been deliberately melted in tokamak operation (5) shows that extreme events, giant ELM's producing 200-400 MW/m^2 localised heat fluxes, can be sustained without apparent low-cycle fatigue failure. Sustained melting experiments @ 25 MW/m^2 liquified (and displaced) up to 3mm of tile material without apparent prejudice to the mechanical integrity of the inertial tiles.

2. CONTROLLED HIGH HEAT FLUX TESTING

Irradiation of beryllium tiles at flux densities of 5-25 MW/m^2 has been carried out in the past for several design of the JET Mark I beryllium target plates in a dedicated test rig located within the JET Neutral Beam Test bed. For the ITER emergency task only one tile of beryllium was irradiated at a time. Adjacent areas (originally up to four tiles could be tested simultaneously) were covered by copper tiles. A copper shutter, seen schematically in Figure 2, was designed to allow selected areas of the irradiated tile to be exposed to different flux histories.

Initially the shutter was located at its highest position which allowed nearly all of the beryllium tile to be illuminated. As the shutter is lowered the irradiated area became less. The pulse history of castellations accumulated as the shutter was lowered. The design of the shutter did not permit raising of the shutter without a full exchange of the beryllium test-rig. This latter is a time consuming process (of the order of two days), largely due to delays in receiving safety checks for the absence of contamination due to beryllium dust.

The beryllium test rig is a small volume (1 m^3) beam line that is physically disconnected from the main Neutral Beam Test Bed. Control and data requisition are shared between the two facilities. The beryllium beamline is operated without a vacuum pump (i.e. less than $10^3 \ell$/sec) which means that the tank is run at the pressure required for the plasma source. This latter is a standard JET source with a reduced extraction area.

Calorimetry (for diagnostic purposes) of the applied beam was achieved through eleven individual calorimeters located at the lower edge of the shutter, i.e. the copper castellations in the shutter cf. in Figure 2.

Surface temperature of the beryllium component was measured by an AGA IR camera. The emissivity of the surface and transmission factors for the windows is measured by observing the cooldown of the beryllium tile heated to ~200°C. Thermocouples embedded in the tile allow calibration of the IR camera. Heat loss from the tile is principally by conduction to the holders and through black body radiation. A change in bulk tile temperature of ~100°C was found to occur within five minutes. Thus the bulk temperature of a tile under repeated tests, i.e. cycling with intervals of three - five minutes came quickly to an equilibrium value ~50°C.

The testing sequence for both tiles was similar. With the shutter in the top position a flux density of ~5 MW/m^2 was applied over the entire beryllium tile face. For series 1 tests pulse lengths were adjusted for all shutter positions such that the maximum surface temperature did not exceed 600°C. An interlock alarm was set up between the IR camera and the plasma source allowing the source to be switched off (within 50 ms) if the measured temperature approached to within 10° of the set level. For the second series of tests the corresponding set point was raised to 750°C.

3. FATIGUE TEST RESULTS

As part of this study beryllium tiles made of S65c material with overall dimensions 32 x 79 x 49mm deep, T-shaped in cross-section with surface castellations, as shown schematically in Figure 1, were irradiated in the JET neutral beam test-bed (6). In order to maximise the results of this experiment it was decided to (a) consider a pulse train that has a time average flux density of 5 MW/m^2 instead of steady long pulses of 5 MW/m^2 and (b) to shadow parts of the tile under different loading conditions so as to study the evolution of fatigue induced deformations (if any) with the number of applied heating cycles. Two blocks of material were available for the study and the difference between the two series of tests was the end temperature to which the surface was heated, i.e.$\leq$600°C for series 1, $\leq$750°C for series 2 (7).

Table 1 above gives a summary of the irradiation conditions for the various positions of shielding plate in both series of experiments.

The power deposition profile can be seen in figure 1 where the isothermes are shown for a tile in test series 2. For technical reasons the line of sight to the central vertical row of castellations was obscured. The maximum temperatures reached there show a continuation of the footprint without any areas of concentrated heat flux. Figure 2 shows two rows of tiles where typically 2 laterally adjacent castellations (nearly identical heat irradiation history) show distinctly evidence for dimensional change.

A elevation view of the areas showing signs of thermal fatigue is seen in figure 3. No signs of melting are evident yet there is substantial vertical growth of the central surface region of a castellation accompanied by anticlastic inwards bowing of material near the tip of the top corners. There is no visible evidence for fatigue cracking akin to that reported earlier, cf (5) and shown for comparison purposes only in figure 4.

Table 2 below shows a compendium of thermal fatigue data for S65c beryllium tiles castellated typically with a groove of 0.5 - 1.0 mm fully rounded bottom. JET operational experience prior to 1994 has been with other forms of S65 material.

Table 2. JET experience with castellated S65c material

Castellation mm	Φ MW/m^2	Cycles
6 x 6 x 8	≤ 20	~ 2 x 10^4
10 x 14 x 6	≤ 18	failed
10 x 12 x 12	≤ 16	failed

The outcome of these investigations is that JET Mark I beryllium tiles were castellated to roughly 7 x 6.5 x 8 mm deep size with a very considerable cost incurred by the requirement of having to hide each corner of each castellation. Typically there are ~ 8000 tiles each of which is subdivided into 55 castellations.

4. CASTELLATION STRATEGY

All of the beryllium PFC components installed on JET have been castellated to improve their fatigue lifetime. In fact all of these components have been partially melted due to accidental exposure (e.g. belt limiter tile edges

JET) or deliberately (ISX-B (7) and more recently JET (5)). It can be said that the castellation strategy has not proved itself to improve JET PFC lifetimes.

Prior to the deliberate melting experiments a series of plasma events, giant ELM's caused localised melting of a small fraction of the MKI beryllium tile surface. Typically 1MJ (total) energy was deposited for ~10ms leading to localised flux densities of 200-400 MW/m^2 onto the surface of castellations. The onset of melting occurs within the time scale of the event itself. Mechanical compulations show that strain rates of 10-100/sec are likely to have been sustained and that the entire top 1-1.5mm of castellations plastified to ~ 2-5% per event. However, this layer at least has been subsequently melted and little trace is likely to be found in detailed metallurgical examinations of these tiles.

The most recent JET experiments with deliberate melting of beryllium have shown that inertial tiles castellated per the results of the JET fatigue tests, i.e. approximately 6.5 x 7mm, up to 8mm deep, of 0.5mm width castellations, 0.25mm radius, have shown no signs of low cycle thermal fatigue at flux densities of ~25MW/m2, 4Hz (swept plasmas). For unswept plasmas severe surface melting obtains at a similar flux density. It is estimated that ~200 cycles have been carried out in recent JET experiments with no evidence for large thermal fatigue cracks under these conditions.

Figure 3 shows a view of the S65c Mark I beryllium tiles in the region where strong melting has been sustained. In fact nearly 3mm of material has been melted and displaced laterally to solidify as large drops of beryllium. The largest of these drops is nearly 8mm in diameter. The character of the melted surface due to tokomak operation is markedly different, cf figure 4 for a view of a thermal fatigue test tile with ~ 10^3 pulses at $\Phi \leq 25$ MW/m^2. Detailed metallurgical investigation of the MKI tiles is to search for lateral cracks hidden by resolidified layers or developed at the root of castellations.

5. BE CLAD PFC

The JET testing programme for thin

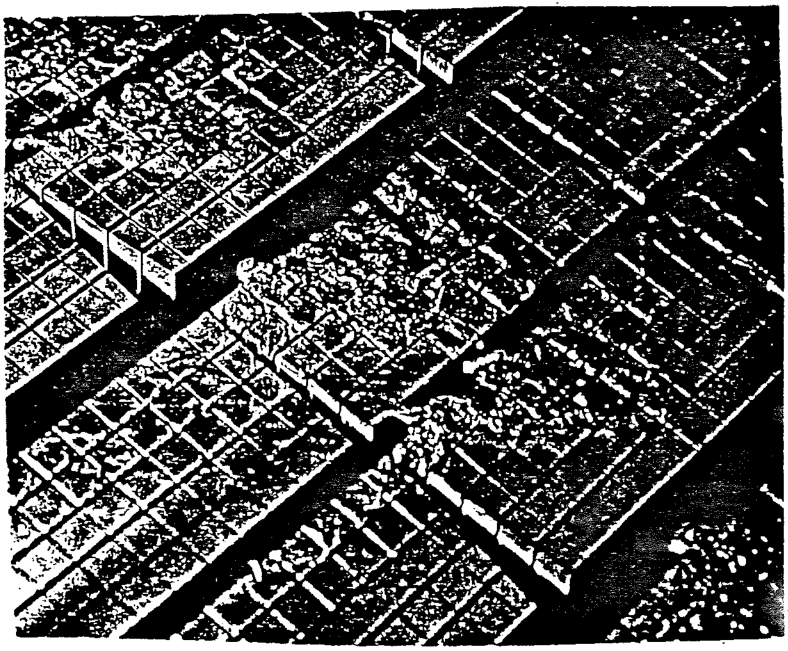

Figure 3: MkI Beryllium tiles

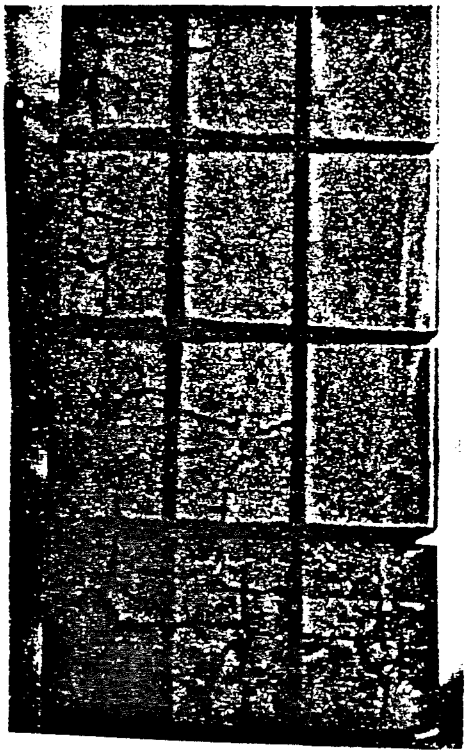

Figure 4: Reference fatigue tests

claddings 2-3mm Be onto CuCr vapotrons, has been extensively documented, (6). All of these tests have relied upon S200, also S200H material. More recently work has been done for thick 10mm layers of S65c clad to a vapotron. Details of this testing are to be presented elsewhere (4). However, the non-destructive part of this work, i.e. avoidance of surface melting showed that for S65c cladding, some 100 cycles at 5 MW/m^2 were sustained with $T_{surface} \leq 600^{\circ}C$ and with no evidence of surface failure. These claddings are 27mm x 27mm. Experience from previous JET testing of inertial tiles would have predicted lateral cracking of the irradiated surface at 5MW/m^2. This was not observed to be the case.

The confirmation of finite element analyses is subject to the lack of a failure criterion for thermal fatigue in Beryllium. It is noted that there is no published data for the fatigue of any grade of beryllium at elevated temperatures (8). Recent results, reported later in this conference (9), suggest that S65c is superior to S200 in terms of resistance to cracking due to thermal shock. Modelling of these latter experiments confirms the need for a model of the plastic behaviour of beryllium under thermal loadings.

6. CONCLUSIONS

The data presented here suggest that there is a substantial reduction in the fatigue lifetime of S65c for temperatures in excess of 600°C. In attempting to model this effect the sparseness of the database on material properties is noted. In particular, in view of ITER requirements, the need is clear for material properties at all temperatures up to the melting temperature of beryllium.

The principal mechanism for the fatigue failure seen in these experiments is anticlastic bending of material along diagonal vertical edges of castellations. Modelling shows that the location of peak plastic strain in finite element analyses is sensitive to the value of Poisson's ratio, particularly the value of this quantity at elevated temperatures. The little data that has been published is contradictory for the temperature evolution of Poisson's ratio for any grade of beryllium (8).

7. ACKNOWLEDGEMENTS

Peter Miodurszewski of Oak Ridge National Laboratory, R.D. Watson of Sandia National Laboratory for transparencies used in oral presentation.

REFERENCES

[1] M.F. Smith et al, Thermomechanical testing of beryllium for limiters in ISX-B and JET, Fusion Technology, Vol 8, July 1985, p 1174-1183

[2] E. Deksnis et al, Fatigue of inertial beryllium elements for JET MKI pumped divertor, Proceedings 17th SOFT, Vol 1, p 242-246, 1993

[3] E. Deksnis, D. Ciric, H. Falter, D. Martin, Report on ITER emergency task, fatigue studies of S65c beryllium, JET report (1994)

[4] H. Falter, High heat flux tests on 10 mm Beryllium tiles brazed to an actively cooled vapotron made by CuCr, to be published (1995)

[5] B. Tubbing et al, First results with JET Beryllium melting experiment, EPS conference, Bournemouth, UK, July 1995 (to appear)

[6] H. Falter et al, Thermal test results of the JET divertor plates, Proceedings SPIE, Vol 1739, pp 167-172, 1992

[7] P. Mioduszewski et al, Joint JET-ISX-B Beryllium Limiter Experiment, Final Report, ORNL, July 1986

[8] D.E. Dombrowski, E.B. Deksnis, M. Pick, Thermomechanical Properties of Beryllium, IAEA Handbook in Properties of PFC materials, Vienna 1995

[9] R.D. Watson, D.l. Youchison, D.E. Dombrowski, R.N. Guiniatouline, Low cycle thermal fatigue testing of Beryllium grades for ITER PFC, 2nd IEA International Workshop on Beryllium Technology for Fusion, Sept 6-8, 1995