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ABSTRACT.

The downstream exit aperture of the JET Neutral Beam Injector Box defines the edge of the profile of each beam as it enters the drift-duct region. This aperture is fitted with a *Box Scraper* assembly comprising high heat-flux hypervapotron elements mounted in a picture-frame arrangement in order to intercept the peripheral part of the beam profile, representing up to 20% of the transmitted power. In order to cope with the enhanced power resulting from upgrading the Neutral Beam Injection Systems at the JET Facility, in which the deuterium neutral beam power from a single box has been increased from 7.5MW to 15MW, it has been necessary to re-design the Box Scraper assembly completely. The design has utilised the original JET hypervapotron concept for the heat flux components, but the internal geometry has been further optimised in order to achieve an increase of peak power density to 13 MWm^{-2} at the hypervapotron element's surface. Comparisons between the old and new designs with regard to geometry, front surface operating temperature and cooling water velocity are presented. Design constraints of the Box Scraper assembly due to the limitations imposed by the available space envelope within the Injector system are discussed. The adopted design has an optimised arrangement of a pair of hypervapotron elements side by side inclined at different angles of attack to match the gradient of the power density at the beam edge, giving a design figure of 400kW power handling per beam. This satisfies the further power increase. The paper also describes the first operational experience with the new Box Scraper on the JET beamlines and results of the power handling tests carried out on the new Box Scraper prototype assembly at JET Neutral Beam Test Bed operated with new high power 130kV/60A Positive Ion Neutral Injectors. Finally, the problems of installing such an assembly into a tritiated neutral beam system and the methodology adopted are reviewed.

1. INTRODUCTION

An EFDA funded enhancement has been undertaken to upgrade of the Octant 8 Neutral Injection system on JET [1] and will result in 15 MW of injectable neutral beam from 8 160kV sources. An analysis of the resulting increase in loading on the Neutral Beamline components highlighted the Box Scraper as having insufficient power loading capacity to accommodate this increase. The previous design utilised a three channelled hypervapotron element, rather than the JET standard two channelled hypervapotron element, that operated on the hairpin flow principle with the return legs sharing the flow. Whilst this allowed the system to operate without the need for thermal expansion compensation, the return legs of the hairpin layout were cooled with preheated water from the first channel which limited its performance. The power levels that had to be accommodated called for single pass hypervapotrons to allow the operating limits to be maintained, a maximum allowable water temperature increase of 50ºC is imposed to ensure that sufficient subcooling is maintained.

The single pass hypervapotrons with their expansion compensation have to fit within a small space envelope defined by the Cryogenic pumps, Central Support Column (CSC) and Neutral Injection Box (NIB) exit aperture. This space restriction imposed the need to further enhance the power handling capacity of the Hypervapotrons from 10MW/m^2 to 13MW/m^2. This increase was achieved by the combination of changes:

- A reduction in the front face thickness, from 6mm to 4mm, so that the over ageing temperature limit of 450°C [2] was not exceeded;
- a reduction in the cooling channel depth, from 10 mm to 8 mm, giving higher water velocity without a significant increase in pressure drop or reduction in mass flow;
- the reduction of the fin height, from 8mm to 4mm, giving better heat transfer by improving fluid flow at the root of the fin [3]; and
- the inclusion of a 1.5 mm slot at the central web of the hypervapotron to reduce the limiting front face temperature immediately above the central web [4]. The improved flow in the region reduces the front face temperature to levels seen at the sidewall where a similar geometry is employed.

These changes were tested one by one, prior to the series production of the new hypervapotron elements, by tests on sections of modified hypervapotrons. Once the contribution of each design change had been quantified a full-scale hypervapotron element was manufactured, with all the design changes included, for a final confirmation test on of the geometry. Once the suitability of the new geometry was established the procurement of the high heat flux elements, the supporting structure and coolant feed was undertaken for final assembly and testing of the new Box Scrapers on the JET site.

2. HYPERVAPOTRON DEVELOPMENT

The evolution of the hypervapotron at JET is directly coupled to the increasing requirement for higher heat flux interception. The semi-optimised geometry employed in the previous Box Scraper is shown, alongside the enhanced version, in Figure 1. Experience has shown that the stepwise approach is the surest route to improvements. This methodology was used to produce the design enhancements, described in the figure above, and now included in the Box Scraper hypervapotron elements. Test sections were produced from old hypervapotron elements that were then tested, to a standard format, in the JET Neutral Beam Testbed.

These tests, basically a power and water flow scan, explored the effect of changes to the various geometrical features in isolation. The contribution of each design change varies and a full description of the tests has been reported [5]. The overall effect is that for similar flow velocities, 3–4 m/s, and when operating at the maximum surface temperature of 450°C the limiting power density is increased from 11MW/m^2 to 13.5 MW/m^2. Figure 2 indicates the gain in limiting power density with increased coolant velocity. The cooling system is presently operating below its maximum performance to reduce vibration, if full flow were restored a velocity of some 4–5 m/s could be achieved increasing the limiting power density even further. The tests indicated that further reduction in the cooling channel cross-section giving higher velocities in the order of 6–8 m/s would increase the limiting power density and that > 15 MW/m^2 might be achieved, according to the extrapolation.

Table I

Element	*Distance to beam centreline (mm)*	*Beam power density at this position (MW/m^2)*	*Power density normal to element's surface (MW/m^2)*
10°	71	32	5.6
20°	85	22	7.5

3. BOX SCRAPER GEOMETRY

The new Box Scraper uses a pair of single pass vertical hypervapotrons in each quadrant of the Neutral Injector Box (NIB) to intercept the peripheral part of the beam profile of a pair of Positive Ion Neutral Injectors (PINIs). The position and angle of attack of these hypervapotron elements is shown in Figure 3. The beam power densities at the leading or innermost edge of the hypervapotrons, where instrumented calorimeters are positioned, are shown in Table I. The figures for power density are derived using a beam simulation program to model a 2MW upgraded PINI and have been validated by experiment during the characterisation and conditioning of the new 160 kV sources [6].

The layout shown in the figure was chosen for two reasons:

1. To ensure that the hypervapotron elements are subject to similar surface power densities so that they both reach the operation limit, the values of surface power density are well below the 13 MW/m^2 operational limit of this enhanced hypervapotron design.
2. Surface temperature is not measured directly. Thermo-couple instrumented copper fingers, 104 in total placed along the leading edges of each element, are subject to a limiting rate of temperature rise. The thermal response of the fingers is inertial on the 10 second timescale of the beam pulse. The maximum allowed rate of rise of temperature corresponds to the limiting hypervapotron element surface temperature of 450°C for a 10 second pulse. The adopted geometry allows this limit to be uniform, simplifying operating procedures and, hence, increasing operational safety. The rate of temperature rise of the fingers is monitored after each pulse and used to predict future pulse power densities. The array of fingers also allows the estimation of beam profile shape and vertical alignment to be made.

The total intercepted power, predicted by beam simulation code, is 220 and 210 kW on the 10° and 20° elements respectively. These values, scaled to the power density limit of 13 MW/m^2 become ~380 kW. This is a 52% increase in total power handling capability over the previous Box Scraper design and is comfortably within the limit of 625 kW that corresponds to the water differential temperature limit of 50°C. This increase is due to the higher mass flow rate of the new design that, in turn, is due to its increased share of the total flow in the multiple parallel loops cooling system.

The original Box Scraper employed curved corner hypervapotron elements, the loading and limit of which was extremely difficult to predict. The new design employs straight hypervapotron elements of the same enhanced internal geometry. These are inclined to the beam to produce scrapers that can cope with the required duty and have predictable loading and limits, copper fingers are also placed on the leading edge of these elements to add another dimension to the diagnostic finger array.

4. BOX SCRAPER TYPE TEST

To verify performance of the new Box Scraper design, a full scale model of the Box Scraper's 2 vertical hypervapotron elements was tested at the JET Neutral Beam Test Bed.

The aim of the test was to establish operational parameters for the new Box Scraper, intercepting the edge of the neutral beam extracted from an upgraded 130kV/60A PINL. Tests have confirmed that, within the limitations of the present cooling system, up to 0.5MW per element (1MW per quadrant) can be handled by the new components, while maintaining the surface temperature below 450ºC and water temperature rise below 50ºC (see Figure 4).

5. INSTALLATION OF THE BOX SCRAPERS

Two identical Box Scraper assemblies were installed during the last major JET shutdown in a sequence that best suited the overall shutdown programme and satisfied the safety requirements. To gain access to exchange a Box Scraper it was necessary to remove the tritium contaminated CSC from the NIB [7], a cross-section of which is shown in Figure 5. The CSC had to be stored in an area that provided constant ventilation, during the exchange work. This being more critical for the more highly contaminated CSC from the NIB that injected the tritium beams during the JET Deuterium Tritium Experiment, which had to be constantly ventilated by the Exhaust Detritiation System (EDS) of the Active Gas Handling System [8]. Due to logistical problems, namely insufficient suitable storage area's, this work could only be completed consecutively. To gain access into the NIB the surrounding services were removed and a substantial platform built. Contamination was minimised, during transportation of items to the storage area, by the use of custom-made isolators. The NIB Access Cabin (NAC), a contamination containment airlock, was lowered and secured over the NIB. This was then connected to the EDS to provide the depression and ventilation in the NAC during the necessary full-pressurised suit [9] operations. Once access was established a survey was completed and important datum positions transferred to targets installed in the beam duct prior to removal of the redundant equipment. The majority of the surveying carried out on the Box Scrapers was by photogrammetry, a NASA developed survey technique that has proved invaluable during these enhancements.

As the new Box Scraper internal pipe work was to be welded into existing services it was necessary to fully dry the system before welding and subsequent leak testing took place. Drying internal pipe work with space heaters and blowing hot air through the external ports achieved this. This heating, however, caused a five-fold increase in the tritium content of air samples from the NIB. These levels returned to normal a few hours after completion of the drying phase. Once dry the coolant supply pipes were cut and the old Box Scraper removed. This was also transported in an isolator to a ventilated area for storage. A lifting frame, that allowed the point of lift to be varied with respect to the centre of gravity, was designed for the new Box Scraper to simplify full suited installation and alignment where access and mobility are restricted. After the new Box Scraper had been lowered vertically through the NAC and bolted to the NIB wall a photogrametry survey was performed to check the alignment of the new installation to the datum's in the duct. Intermediate connecting pipes were fitted to the Box Scraper using jigs that had previously been manufactured to dimensions taken from the initial photogrametry survey. Difficult access required the use of modified orbital welding heads using parameters that had been determined during weld trials on a full-scale mock-up of the installation that was constructed to develop the installation methodology and techniques. Since full suited access required trained staff radiography was considered impractical and production proof sample welds were produced, tested and accepted before each production weld was completed. To confirm the quality of all the welds and the correctness of the installation the system was pressure and vacuum leak tested. The procedure was then repeated for the other Neutral Injection System. The installation of both Box Scrapers took 49 days requiring 168 man-days of effort and generated 6080 litres of low level radioactive waste. The highest radiation dose to a person was 6 microSv and the collective dose for the 19 people involved in the work was 22 microSv.

6. OPERATIONAL EXPERIENCE WITH THE NEW BOX SCRAPER

Two beams impinge on each hypervapotron assembly, Figure 6 shows an example of the vertical profile of the beam power density incident on the inner edge of the hypervapotron elements, derived from this new instrumentation. In this case two new high-voltage, high-current PINIs were being operated to produce neutral deuterium beams at a voltage of 114kV, somewhat below their maximum capability. The power density at the edge of the innermost element is seen to be significantly higher than that falling on the outer element. This is compensated by the different angles of the elements. The estimated peak power density per unit area on the surface of the hypervapotrons is about $5\mathrm{MWm}^{-2}$ in this case, well within the capability of the component. This early experience suggests that the new Box Scraper is compatible with operation of very high power beams.

CONCLUSIONS

During the recent shutdown two of the new Box Scraper assemblies, equipped with the enhanced hypervapotron elements and comprehensive instrumentation, have been fitted to the JET Facility beamlines. As part of the re-commissioning phase the Box Scrapers performance was assessed as the power was steadily increased. The performance is in line with that predicted from the element test results. The increased diagnostic capability will enable the position of the beams and incident power densities to be fully assessed and indicate where beam re-steering is necessary with greater confidence. The configuration of the present cooling circuit does not allow the full potential of the new Box Scrapers to be utilised. Mass flow was reduced to avoid vibration problems on the NIB, namely, turbo pumps tripping. These pumps will be replaced with more resilient items allowing the flow to be increased in the future, thus allowing for higher powers to be handled or a higher margin of safety to be achieved.

ACKNOWLEDGEMENTS

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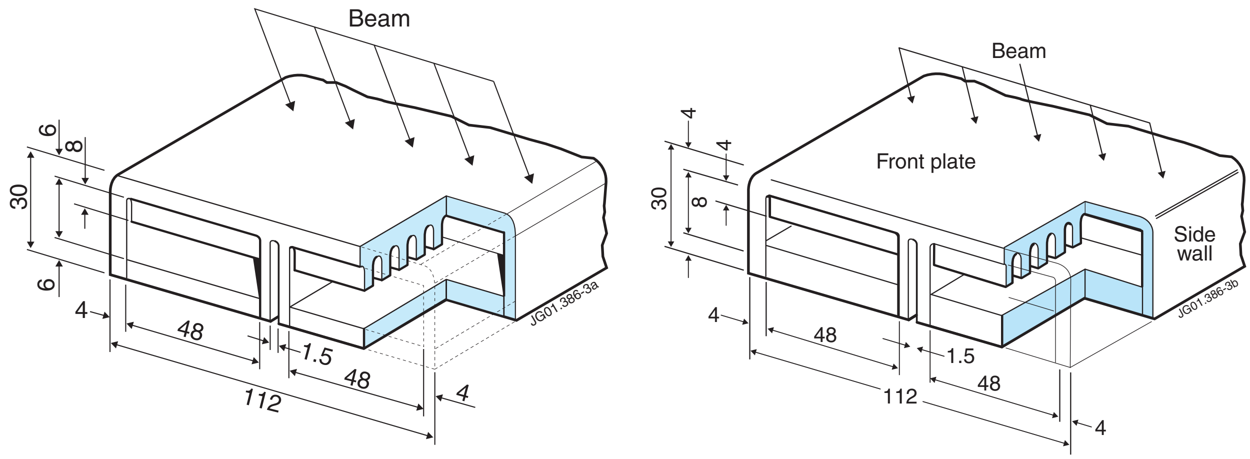

Figure 1: Detailed internal hypervapotron geometry showing changes to the front face thickness, water channel depth, fin height and slot at central web.

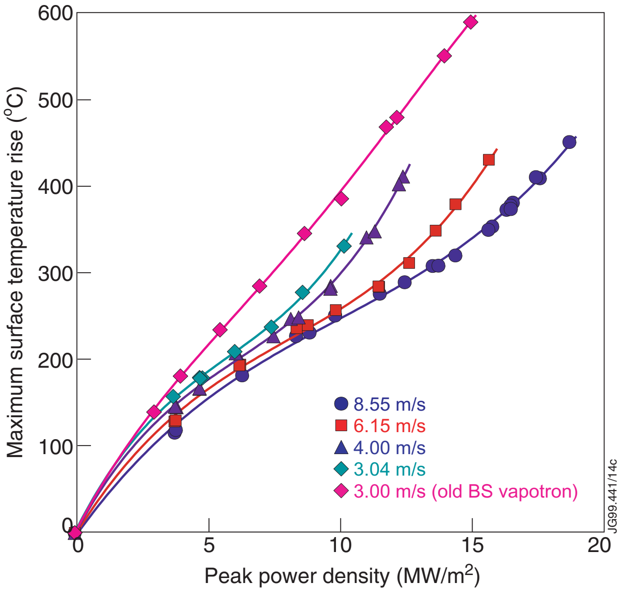

Figure 2: Maximum surface temperature (central web) as a function hydrogen beam peak power density for various water flow velocities. Central web surface temperatures are derived from thermocouple values at the end of 5 seconds long beam pulses. The graph also includes data for old Box Scraper hypervapotron at water flow velocity of 3 m/s for comparison purposes.

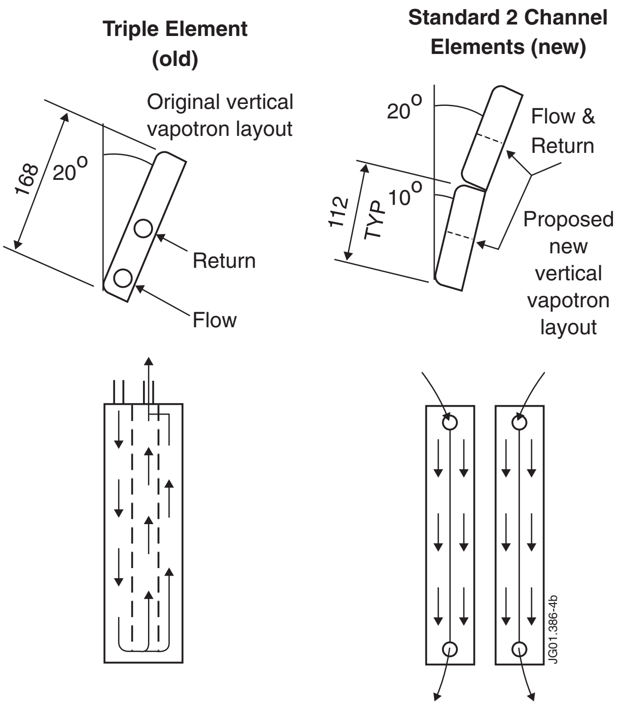

Figure 3: A comparison of the geometry of the old and new Box Scraper designs showing the single pass and hairpin flow techniques. The isometric sketches show the change from one hairpin flow element to two single pass hypervapotrons inclined at 10 and 20 degrees to the beam centreline. Note also that the curved hypervapotron elements have been replaced with straight elements reducing the beam transmission slightly but accommodating the higher powers.

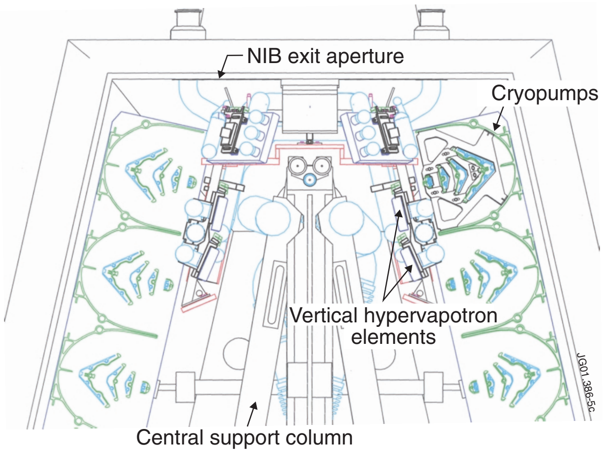

Figure 5: The space envelope defined by the central support column, cryo panels and the N.I.B. exit aperture limit the freedom to expand the Box Scraper as a means of reducing incident power.

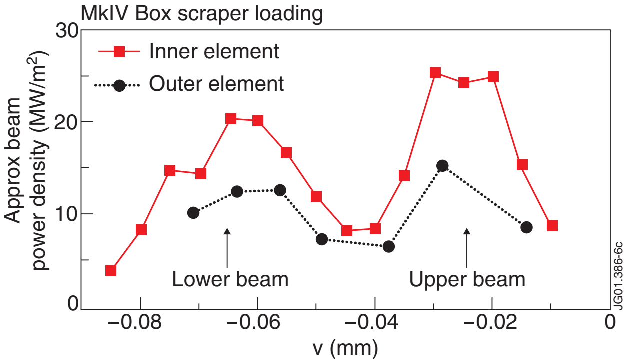

Figure 6: A plot of power density against vertical position showing the beam profiles on the vertical hypervapotron elements derived using the thermocouple temperature measurements from the newly installed copper calorimeter fingers.