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ABSTRACT

The introduction of a cryopump into the interior of a large tokamak raises several technical problems related to the thermal stresses, eddy current forces and choice of materials. The JET divertor cryopump has been optimised in terms of stresses, flow stability and operation - the liquid nitrogen cooled chevron structure in particular having to fulfil conflicting requirements at cryogenic temperatures. These requirements include good thermal conductivity in order to minimise thermal gradients (to reduce the radiative heat load onto the liquid helium circuit), high electrical resistivity (to minimise eddy current stresses), high mechanical strength and good mechanical formability.

This paper reports on the materials selection based on measurements of properties at cryogenic and elevated temperatures and the development of an optimised thermal treatment combining solution heat treatment, brazing and precipitation hardening. It also reports on the successful development of various manufacturing technologies which have been employed including (a) techniques for brazing of the chosen copper alloy onto inconel and stainless steel, (b) surface blackening of the copper alloy with plasma sprayed ceramic coatings that are vacuum compatible and able to withstand temperatures between 70K and 1135K and (c) plasma spray deposition of copper onto stainless steel in order to produce an anisotropic composite material with improved thermal conductivity, high strength and high electrical resistivity for use at temperatures between 70K and 650K.

1. INTRODUCTION

Research into controlled thermonuclear fusion is directed towards the demonstration of the scientific and technical feasibility of the fusion of deuterium and tritium nuclei as an economic source of power. One of the major activities in this field is the study of the confinement of high temperature plasmas by magnetic fields. The most successful magnetic configuration is based upon the so-called tokamak principle in which the plasma is confined inside a toroidal vacuum vessel using a combination of magnetic fields generated by external field coils and a high current which is induced to flow in the plasma using a transformer. The JET device is one of the largest and most successful machines of this type[1,2,3]. Values of the critical parameters of plasma density, temperature and confinement time relevant to those ultimately required for a fusion reactor have been obtained in separate experiments using deuterium. In November 1991 the first experiments using a (non-optimum) mixture of deuterium and tritium were successfully executed and produced in excess of 1MW of fusion power[4].

However, the high performance phases of experiments in JET (and other tokamaks) are transient in nature (~1s) and are limited by the influx of impurities from the vessel wall which both cool the plasma due to radiation losses and also dilute the hydrogenic fuel. The reduction and control of the impurities produced by the plasma-wall interaction is one of the major goals of the future JET programme. This will be studied using the divertor concept shown in Fig 1 in which the power and particle exhaust from the main plasma is channelled by the magnetic configuration to appropriate target areas and subsequently, the resulting neutral gas can be pumped by the cryopump[5,6,7,8,9].

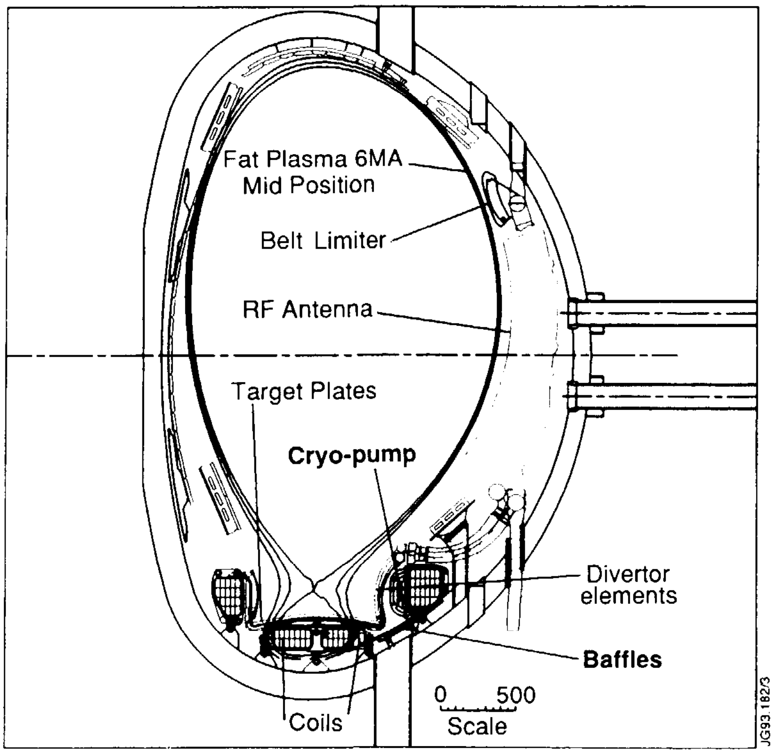


Figure 1. The key elements of the JET Vacuum Vessel in the Pumped Divertor Configuration (post 1993).

The vacuum vessel of JET is an extremely hostile environment for a cryopump. Not only does the pump have to be shielded from thermal radiation from the walls of the torus which are at 300°C but provisions have to be made to withstand large mechanical stresses resulting from electromagnetic forces generated by rapidly changing magnetic fields of up to 100 Tesla s^{-1} which induce large eddy currents. In addition, the pump must be able to be baked to 350°C and also to withstand the stresses due to uncontrolled cool-down and/or loss of the liquid nitrogen supply during operation.

The axisymmetric chevron type divertor cryopump for JET is a circular ring 20m long and 0.4m high. It has a pumping speed of 500,000ls^{-1} for deuterium at 300K and is designed for a peak heat load of 180kW in the LN_2 loop and 5kW in the LHe loop for 10s[7] The cryopump is protected from the hot vacuum vessel (300°C) by a water cooled chevron baffle, and from the plasma by the water cooled supports for the high heat transfer elements in an optically tight arrangement.

2. DESIGN

Figure 2 gives a 3-dimensional view of the cryopump. It consists essentially of two 180° half-circular assemblies to form a ring 6.4 metres in diameter. Each assembly incorporates a stainless steel back-panel, the front screen which is fabricated from blackened copper alloy chevrons and the cryo condensation surface consisting of corrugated stainless steel tubes which have a wall thickness of only 0.3mm in order to minimise the heat load by the high neutron flux. The tubes in the back-panel and chevrons are connected in series to form the liquid nitrogen circuit and a forced flow of supercritical helium is used to cool the pumping surfaces.

The whole structure is supported by clamps attached to one of the divertor coils and the liquid helium pipes are supported by pre-tensioned wires from the back plate. The clamps are electrically and thermally isolated from the coil by ceramics whilst the wires result in a thermal input to the liquid helium circuit from the liquid nitrogen system of no greater than 0.2W.

The support system is designed to withstand forces of up to 8KN resulting from eddy currents generated by magnetic field changes of up to $110Ts^{-1}$. The thermal stresses under normal operating conditions are relatively low- ~20MPa.

Thermal analysis of the total structure during transient conditions generated by uncontrolled cool-down or warm-up indicates that temperature differences of up to 200K can develop between the low (0.1) emissivity back panel and the chevron structure which has a high emissivity (~0.85). Sufficient mechanical flexibility has been incorporated within the assembly to accept these extreme conditions.

Provision has been made to provide cryosorption pumping of He gas using pre-condensed argon on the liquid helium cooled surfaces. Based upon previous experience with this technique, it is estimated that up to ~0.3 barl can be pumped during a 10s pulse using 6 barl of argon on the $4m^2$ of liquid helium cooled surface. The pressure drop in the argon feed pipes is ~20mbar to stay well below the vapour pressure of argon at 77K (~230mbar) in order to prevent freezing of the argon.

Due to space restrictions, the connection between the cryo feed and the cryo pump proved somewhat difficult. Thermal input to the liquid helium is minimised using shields consisting of multi-layer stainless sheet riveted to the liquid nitrogen system. These are designed to withstand both the thermal stresses and those due to eddy currents and yet provide the necessary thermal insulation. The cryo pump is designed to withstand internal pressures in the cryogenic cooling loops of up to 30 bar in order to meet adverse accidental conditions inside the vacuum vessel. The manufacturing and quality control has to be of the highest standards because of the virtual impossibility of in-situ repair after installation in the torus.

A separate water-cooled chevron baffle reduces the heat load from the hot wall of the torus to the liquid nitrogen system of the cryo pump from 50kW to ~2.5kW. During the plasma pulses this load to the LN_2 structure is expected to increase to a maximum of between 5 to 10kW.

3. CHOICE OF MATERIAL AND HEAT TREATMENT

Extensive material screening of precipitation hardenable copper alloys was undertaken in order to achieve the required material properties. Namely high electrical resistivity at 77K and yet good thermal conductivity combined with high mechanical strength.

Pure copper was excluded due to its low electrical resistivity and mechanical strength.

Many copper alloys can provide high strength through precipitation hardening. In this process, fast cooling of the alloy from high temperatures to ambient prevents initially any change in the crystalline structure and reduces the grain sizes. Subsequently heating to modest temperatures results in elements or compounds appearing in the grain boundaries (precipitation) which give relatively high mechanical strength (and electrical resistivity).

JET has extensive manufacturing experience (machining, brazing, welding) with CuCrZr (Cr 1%, Zr 0.1%). This alloy was not used because of its low electrical resistivity at 77K resulting in large induced eddy currents and consequently high mechanical stresses.

The introduction of Ni, Cr or Zr into copper results in high thermal conductivity but again low electrical resistivity at cryogenic temperatures. On the other hand, the introduction of Be into copper will give high strength and electrical resistivity but low thermal conductivity.

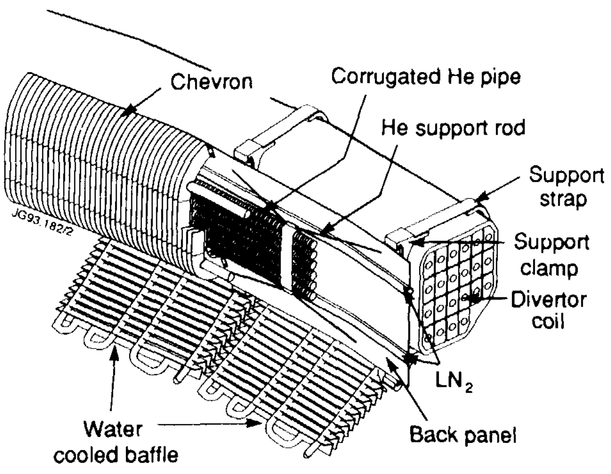
In order to identify the most suitable material, measurements of thermal conductivity, electrical resistivity and mechanical strength at different temperatures were undertaken.

Table 1 shows the results of typical material property measurements for CuCrZr and CuNiSi (2.5% Ni, 0.6% Si). These properties were obtained after the same heat cycle (Fig.4). The effect of the heat cycle was crucial. It can influence the properties by as much as a factor of 3. The high electrical resistivity of CuNiSi (Siclanic), particularly at 77K; its adequate thermal conductivity and high mechanical strength combined with its good formability when annealed, resulted in its use for the cryopump and baffle chevrons.

Table 1: Material properties of CuCrZr and CuNiSi

Material	Property	Temperature (K)	Result
CuCrZr	Thermal Conductivity W cm^{-1} K^{-1}	300	3.5
CuNiSi		300	2.2
		77	0.85
CuCrZr	Electrical Resistivity $\mu \Omega$ cm	300	2.42
		77	**0.70**
CuNiSi		300	4.6
		77	**2.9**
CuCrZr	0.2% strength MPa	300	298
		77	306
CuNiSi		300	426
		77	460

Figure 3 shows the equilibrium diagram of CuNiSi. During the fast cooling from the brazing temperature, the change in the crystalline structure type α is initially blocked. Subsequently, during heating to $475^{o}C$, Ni_2 Si is precipitated in the small grain boundaries resulting in high mechanical strength and electrical resistivity.



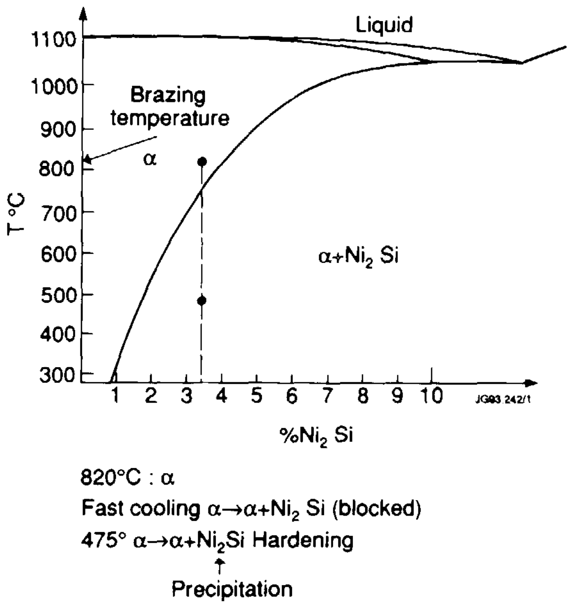


Figure 2. 3-Dimensional view of the JET Pumped Divertor cryopump.

Figure 3. Equilibrium diagram of Siclanic.

4. SURFACE COATINGS

4.1 Blackening

In order to minimise the heat load on the low emissivity cryo condensation surface, the chevron assembly requires a high emissivity coating.

The chevrons are blackened by vacuum plasma spray which provides an emissivity of 0.85. The coating remains bonded to the Cu alloy during a thermal cycle of -200°C to 860°C, it is vacuum compatible and acts as a brazing stop-off.

The process involved

- Grit blasting (pure white fused aluminium oxide, grit size 0.063-0.150mm)
- Ni-layer of 10μm (Kanigen industrial electroless Ni plating)
- Grit blasting (as above, but grit size 0.180-0.355mm)
- Air spray of Ni-Cr (40μm ± 10μm) underlayer for brazing at 820°C or of Ni-Al underlayer for brazing at 860°C

and

Al_2O_3-T_iO_2 final layer (50μm ± 10μm) by vacuum plasma spray.

Following the spraying process, the black coated chevrons could be cut by wire erosion, or diamond cutting without damaging the coating.

4.2 Aluminium Oxide coating

In the liquid nitrogen circuit, the stainless steel back panel is electrically insulated from the front chevron screen in order to minimise the eddy currents generated.

For this reason, an aluminium oxide coating was used which was compatible with vacuum, remained firmly bonded to stainless steel washers during a thermal cycle of -200°C to 350°C and resisted several kV.

This process involved:

- Grit blasting (pure white fused aluminium oxide, grit size depending on the rigidity of the item)
- Air spray of Ni-Al underlayer (70µm)

and finally

Al_2O_3-layer (0.3 to 0.5mm)

4.3 Cu-spray

In order to reduce the temperature differences between the black chevrons and the low emissivity back panel during baking (350°C) or uncontrolled cooling of the cryopump, a Cu spraying process was developed to deposit 1mm dense Cu strips to the 3mm stainless steel back panel. This process had to be vacuum compatible and the Cu to remain firmly bonded during a thermal cycle of -200°C to 350°C. The Cu strips whilst increasing the conductivity of the heat transfer towards the LN_2 pipes, did not increase significantly the electrical conductivity in the perpendicular direction of the eddy currents.

The process involved:

- Grit blasting (as before, grit size 0.180-0.355mm)
- Cooling of back plate (LN_2 at the rear, water through the tubes)
- Air spray of Ni-Al (0.1mm)
- Cu spray (1mm)
- Shot peaning with glass beads to repair deformation during grit blasting and Cu spray.

The thermal conductivity of the sprayed Cu on the stainless steel plates ($Wcm^{-1}K^{-1}$) was: 1.4 ± 10% (300K) and 0.83 ± 2% (77K). (The accuracy of low temperature measurements is higher due to smaller radiation losses.) While these values were not optimised and were significantly less than for pure Cu; the composite material was more than 5 times more conductive than steel and would result in lowering thermal stresses without increasing the eddy current ones.

In the event, during production and mainly due to time restrictions, the process was not used. The (secondary) thermal stresses which the process should have alleviated are high but acceptable.

5. BRAZING CYCLE

Figure 4 shows the brazing cycle (temperature, pressure versus time) developed for attaching the chevrons to the stainless steel tubes. The tubes were nickel plated (4-10 μm) to assist wetting. The brazing material was CuAg (28% Cu, 72% Ag). It should be noted that during brazing itself, N_2 is introduced to suppress the evaporation of silver. The O_2 content of the oven is kept very low by a titanium shield around the components. At the beginning of the cycle, the oven is purged with N_2 and subsequently pumped to reduce further the O_2 content. Then the temperature dwells at ~400°C so that good vacuum (10^{-4}mbar) is achieved. Prior to brazing itself the temperature is stabilised at 760°C (just below the liquidus of the brazing alloy of ~780°C). At 820°C, the brazing temperature, the alloy is in solution so that precipitation hardening is achieved in the last part of the cycle (Fig.3).

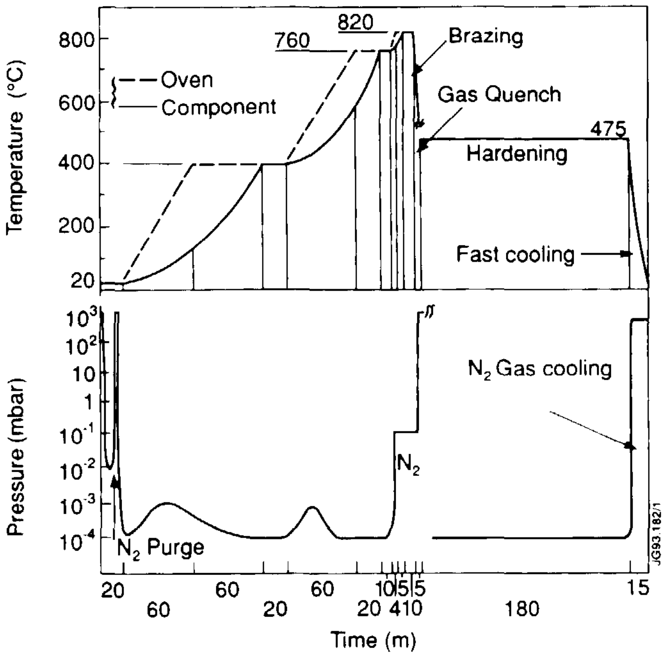


Figure 4. Brazing and Hardening Cycle of Siclanic.

During the development programme for the brazing, several other problems had to be addressed:

- Compatibility of the black coating with the brazing material and the high brazing temperatures (see section 4). It was finally found that the black coating was acting as brazing stop-off.
- A crimping tool was produced to reduce the brazing gap to 0.1mm.
- The possibility of a time lag between the temperature of the black chevrons and the shiny nickel plated pipes, (which in the end was ≈ 1 sec).

In addition to the brazing cycle and material used in production; the following brazing materials and temperatures were also qualified.

Ag 58.5%	Cu 31.5%	Pd 10%	860°C
Ag 56%	Cu 42%	Ni 2%	890°C
Ag 20%	Au 60%	Cu 20%	845°C

The quality of the brazing achieved during production was very high (≥ 90% contact) despite the large size of the pieces being brazed. The quality was checked by peel tests, macro and micro examinations and hardness measurements. In addition a non-destructive detection technique has been developed whereby hot gas is pumped through the brazed assembly and an infrared camera is used to detect cold spots due to lack of brazing contact.

For the water cooled baffles, where the siclanic had to be brazed on inconel (Ni plated) pipes; AgCuPd was used as a brazing material, with a brazing temperature of 860°C and a backing gas of 1mbar 5% H_2 and 95% N_2. Otherwise the cycle was similar to Fig 3 and the material had slightly higher electrical and thermal resistivity. The electrical resistivity reached (μΩcm): 7.7 (300K) and 6.1 (77K). The higher brazing temperature required a different underlayer in the blackening process (section 4).

CONCLUSIONS

A cryopump has been designed and manufactured to be used in the hostile environment of a large fusion vacuum vessel.

The cryopump has been optimised in terms of thermal and eddy current stresses, temperature gradients, relatively high thermal loads and it can withstand extreme conditions like baking to 350°C, loss of coolant or uncontrolled cool down.

Special brazing and surface treatment techniques have been developed so that the Cu alloy used for the manufacture of the pump fulfils conflicting requirements, namely good formability, good thermal conductivity, relatively high electrical resistivity and high strength.

High quality levels were achieved during production despite the size of the components involved.

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