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JET Experience in Recovery from Large Air Leak Incidents

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Abstract

Since July 1990 JET has experienced three occasions where air leaks greater than 10^4 mbar.1/sec happened at a time when the JET vacuum vessel has been under operational conditions at 300°C. Recovery after these incidents to a point at which plasma pulses are successful have involved a bake to high temperature (350°C) followed by a prolonged period of glow discharge cleaning (circa 120 h) to remove the oxygen present as a result of the air ingress and then a beryllium evaporation to finally getter any remaining impurities.

Plasma performance before and after conditioning is compared and an understanding of the mechanism of oxygen removal presented. It will be shown that, after an air leak of the magnitude under discussion, vessel conditioning by glow discharge cleaning is essential for the successful resumption of plasma operation and that any future large fusion machines will need such a facility.

1. INTRODUCTION

JET is the largest nuclear fusion experiment in the world where plasma conditions close to those necessary for a fusion reactor are studied.

Leaks on JET have been described in a previous paper [1]. The aftermath of large air leaks of the magnitude of 10^4 and 10^5 mbar.1/sec which have occurred during operations when the JET vacuum vessel is at a temperature of 300°C required extensive use of the vessel conditioning facilities of baking and glow discharge cleaning (GDC) followed by a beryllium evaporation to return to successful plasma operation conditions.

The objective of vessel conditioning is to achieve a partial pressure or gases other than Hydrogen and Deuterium of < 3.0×10^{-8} mbar at a temperature of 300°C for beryllium evaporation to take place.

Comparisons are drawn between vessel conditioning after a normal cooldown and vent and a large air leak. The removal of oxygen from the large amount of graphite present will be discussed based on mass spectra taken before, during and after each process in the cleaning cycle.

A comparison in plasma performance after minimal conditioning and after the full cycle is made with reference to plasma purity in the form of Z_{eff}.

2. ACCIDENTAL AND NORMAL VENTING

2.1 Accidents

Since the start of the JET operation phase, there have been 48 leaks of a magnitude sufficient to preclude subsequent plasma operation. The consequence of three of these leaks which caused an uncontrolled air venting of the JET vacuum vessel are discussed. A weld leak of $5.0 \times 10^{+5}$ mbar.1/sec occurred on 16th July 1990 and bellows leaks occurred on 2nd September 1991 and 21st January 1992 of $2.0 \times 10^{+4}$ and $3.0 \times 10^{+4}$ mbar.1/sec. respectively. The leak rates were assessed by the rate of pressure rise.

2.2 Normal Venting

For a planned vent the vessel is cooled over a 24 hour period to less than 50°C before inflating with dry nitrogen if access inside the vessel is not required or venting to 100 mbar with dry nitrogen before venting to air if access is needed.

3. BAKING CYCLE

After all work is completed the vacuum vessel is pumped down [2] before the commencement of the bake cycle and a mass spectrum is taken. Figure 1 shows the difference between a scan after a normal vent and large air leak where CO and CO_2 are much higher due to the effect of the oxygen on the six tonnes of hot graphite inside the vacuum vessel.

The JET baking system [3] heats the vessel to 350°C as a first stage in the conditioning process. During this period regular mass spectra are taken and an estimate of the number of monolayers of H_2O, CO and CO_2 removed is made from the increase in the relevant peaks.

Table 1 shows the results of baking cycles following leaks compared to those following normal vents. As is seen the H_2O and CO removed differed little between the bake cycles following normal and accidental vents but more CO_2 was removed after normal vents than leak incidents. A possible reason is that accidental venting of a hot vessel leads to extensive reaction of oxygen within the hot carbon leading to formation of CO_2 which then is more tightly bound. A normal cold vent is not so reactive so the CO_2 is loosely bound to the surface and easily removed.

In all cases the GDC is started when the partial pressure of H_2O has dropped to around 5.0×10^{-6} mbar when the thermal outgassing for H_2O is less than achieved by GDC and the vessel is held at 350°C for the time GDC is carried out.

4. GLOW DISCHARGE CLEANING

Glow discharge cleaning in JET [4] is a process whereby an RF assisted glow current is maintained at a pressure of around 5.0×10^{-3} mbar at DC currents of up to 10 amps. Deuterium and Helium are routinely used at JET for GDC. During all GDC operations mass spectra are taken at regular intervals using a differentially pumped mass spectrometer with an 80:1 orifice. The number of molecules (n) of a particular mass (X) removed in the time (t_1-t_2) between each mass spectrum is given by:

$$(P_x - P_o) \times S_{eff} \times (t_1 - t_2)/kT$$

where P_x = average value of mass 'X' partial pressure over the time interval (t_1-t_2).

P_o = Partial Pressure Mass X with Glow Current at 0

S_{eff} = Pumping Speed measured at 6288 ℓ/s

k = Boltzmann's Constant

T = Temperature (^{o}K)

The total number of molecules (N) of mass X is then obtained by the sum of n over the period of that GDC and then divided by the number estimated to form a monolayer, to give the monolayers removed.

4.1 <u>Deuterium GDC</u>

The objective of Deuterium (D_2) GDC is to remove oxygen as CO and the remainder of H_2O. For D_2 GDC the above calculation is made difficult by the cracking pattern of D_2/carbon compounds whereby mass 18, normally H_2O, is a function of mass 20 (CD_4) and mass 28 is not only N_2 and CO but can also be C_2D_2 formed during D_2 GDC.

This is resolved by taking the mass 17 peak as a function of the H_2O magnitude and if no peaks of mass 30 and mass 32 exist which indicate C_2D_2 all of mass 28 is assumed to be CO assuming no leaks.

Table 2 shows the total number of monolayers of CO removed by D_2 GDC for three leak recoveries and two normal conditioning cycles and also illustrates that CO removal is dependant on glow current.

The changeover point from D_2 glow to He glow is decided in one of two ways.

a) If the mass 30 and 32 peaks are of the same height and about one third of the mass 28 peak which shows that most of the mass 28 peak is C_2D_2 and no oxygen as CO exists and only carbon/D_2 reactions are present. This occurs often in the conditioning following a normal vent.

b) If the side peaks of mass 28 are absent or very small then the mass 28 peak is mostly CO and can persist for a long time following a major air leak when the graphite is soaked with oxygen. The amount of residual oxygen may be inferred from the behaviour of the spectrum when the glow discharge is stopped. If no increase in the CO_2 peak occurs, this signifies that the oxygen reservoir has been adequately depleted. In practice recovery GDC in D_2 takes twice as long as conditioning performed without a preceeding air leak. One of the above conditions being satisfied the Helium glow may be commenced.

4.2 Helium Glow Discharge Cleaning

The helium (He) glow is used at JET to remove the remaining oxygen and D_2 which at this point is the major peak. Until recently this process was not monitored but by using the mass 6 peak (D_3^+) it is possible to assess the removal of D_2 by He GDC.

The results of the removal of CO are shown in Table 3 and are similar to the D_2 glow, except in one case, but about one order less than for D_2.

It is simple to match the requirement of 3.0×10^{-8} mbar to the partial pressures obtained during the He glow at 350°C and so when that level is reached then the glow may be stopped, the vessel cooled to 300°C and beryllium evaporation commenced.

5. BERYLLIUM EVAPORATION

Beryllium evaporation [5] has been used at JET to provide a highly reactive layer to getter impurities and improve plasma performance.

The level of 3.0×10^{-8} partial pressure impurities is mainly an empirical number but if beryllium evaporation above this level is carried out it has been found that there is a deterioration in the beryllium evaporation heads caused by the formation of BeO from the residual gas impurities. The mass spectrum is monitored before and after this operation and an example is shown of the spectra obtained (Figure 2) with impurity levels of 10^{-9}mbar at a temperature of 300°C.

6. PLASMA PERFORMANCE

After the leak on 16th July 1990 the vessel was pumped down and a baking cycle to 300°C performed. A beryllium evaporation was done without a preceeding GDC, before plasma operation was attempted. The maximum plasma current obtainable was 750 kA, far below that required for successful operation, and after 18 attempts with almost 100% radiated power in the form of oxygen with some carbon contribution, other start up scenarios were tried without success.

After this D_2 GDC was run for 20 hours at 8 amps current removing 4.4 monolayers of CO and another evaporation performed after lowering the vessel temperature to 200°C. This time plasma operation was successful. However a disruption required 13 recovery pulses after which beryllium evaporation was done during subsequent nights. The plasma performance then steadily improved with Z_{eff} decreasing to pre-leak levels, but problems were experienced in density control, leading to many disruptions.

However the plasma performance after the conditioning carried out during August 1990 showed a marked improvement. Figure 3 shows the average Z_{eff} before and after this period and a short period of commissioning pulses was required to obtain good high current and power pulses.

7. SUMMARY

Experience on JET has shown that large air leaks, whilst inconvenient, are not a disaster and that by use of baking and glow discharge cleaning followed by beryllium evaporation successful plasma operation may be restored.

The time to condition the JET vacuum vessel after a major leak is of the order of seven days based on the cases described of which two days are needed for the bake cycle followed by four days Deuterium GDC and one day Helium GDC before the required parameters for beryllium evaporation are reached.

Future plans include a glow discharge system capable of 40 amps total current so these recovery times could well be shortened.

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TABLE 1.	Monolayers Removed During Baking Cycle			
Date	H_2O	CO	CO_2	Instance
5/91	46.1	6.3	12.7	Normal
6/91	52.1	4.4	11.8	Normal
8/90	35.4	4.0	6.1	Leak
9/91	34.0	4.7	8.2	Leak
1/92	50.1	4.5	4.7	Leak

TABLE 2.	Monolayers of CO Removed During D_2 GDC			
Date	Number	Max. Current	Instance	Comment
5/89	12.7	5.5	Normal	
6/91	22.6	8.0	Normal	2 Cycles Combined
8/90	25.0	10.0	Leak	Partly Conditioned
9/91	49.8	12.0	Leak	
1/92	35.5	10.0	Leak	

TABLE 3. Monolayers of CO Removed During He GDC

Date	Number	Max. Current	Instance	Comment
6/90	6.67	7.0	Normal	Less D_2 Glow
6/91	0.14	8.0	Normal	
8/90	1.26	8.0	Leak	
10/91	1.02	8.0	Leak	
2/92	1.30	10.0	Leak	

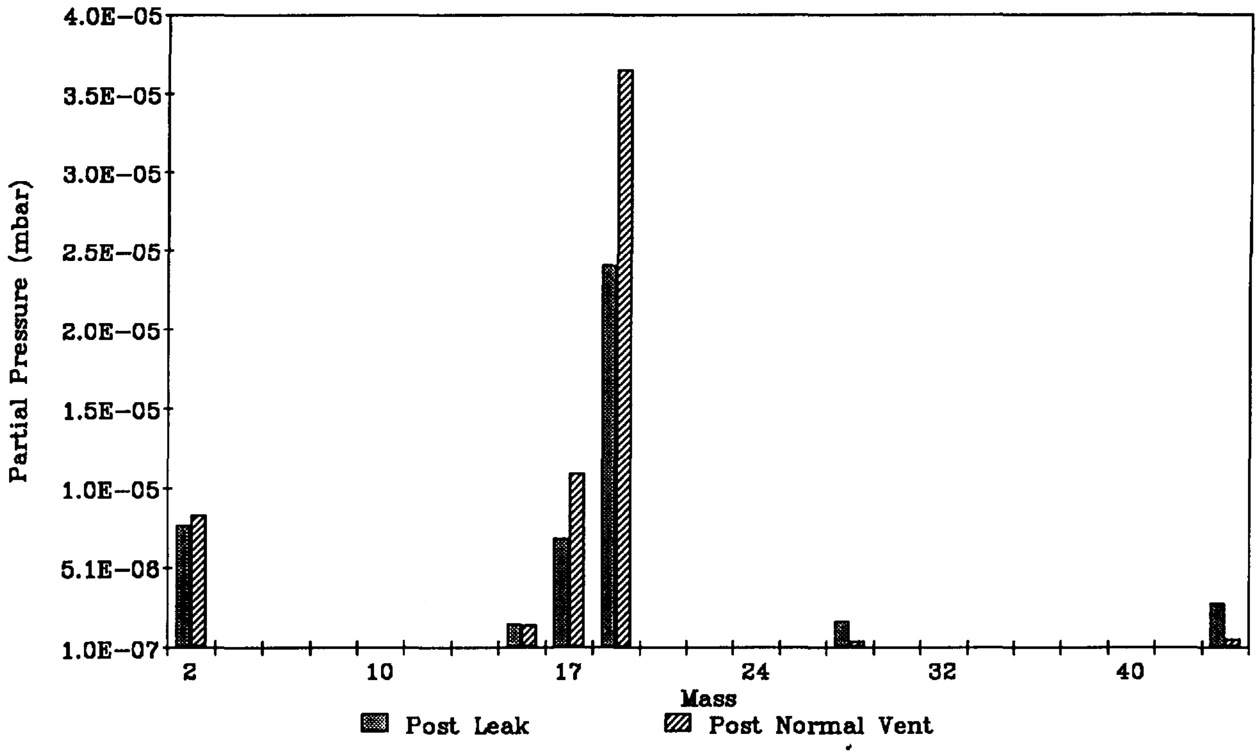

Figure 1: JET Mass Spectra before Bake After Leak and Normal Vent.

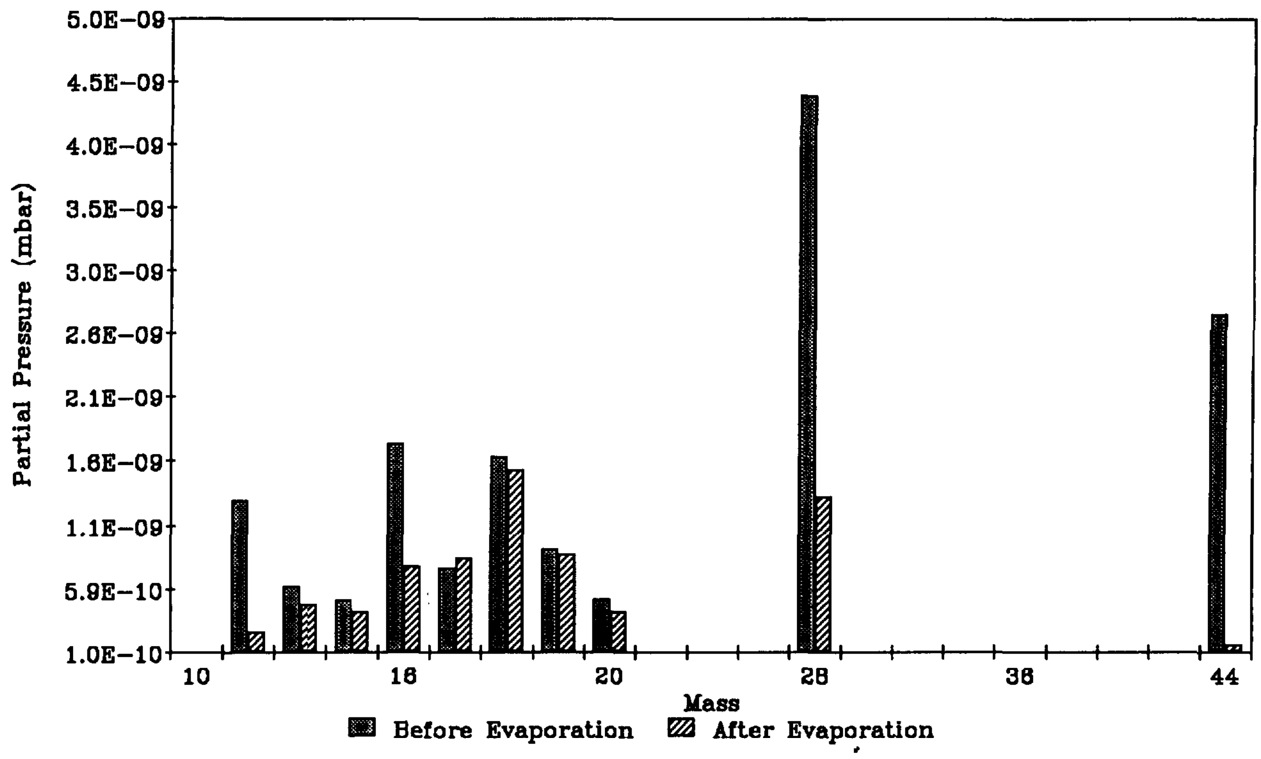

Figure 2: JET Impurity Mass Spectra Before and After Beryllium Evaporation.

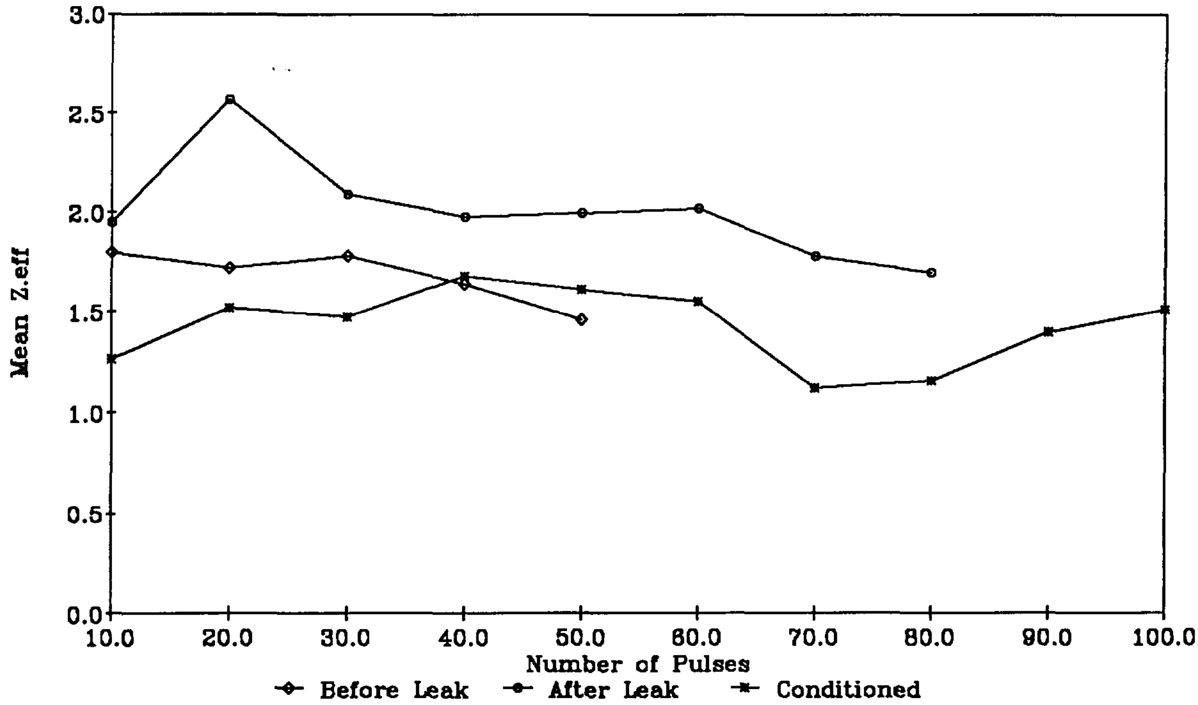

Figure 3: Mean Zeff vs. No. Plasma Pulses Before/After Leak and Conditioning.

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