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ITER relevant outgassing and leakage from different types of in-vessel cabling

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Abstract

On ITER the electrical connections to most in-vessel diagnostics, in particular the magnetic diagnostics, will require cables to be routed through the main vacuum vessel. The total in-vessel cabling requirement is predicted to be of order 80 km. Due to the large quantity of cabling, the JET experience shows that the cabling has the potential to cause issues for the ITER vacuum and hence operability. Findings are presented from extensive tests to assess experimentally the outgassing of different types of mineral insulated cable, in damaged, undamaged and deliberately perforated conditions. Experience with using metal braided fibre insulated cable which has been used in-vessel on JET is given. Key points are concluded for the necessary manufacturing and installation techniques required for in-vessel cable to be used successfully on ITER.

Keywords: ITER; JET; Vacuum; Insulated; Cable; Outgassing

1. Introduction

On JET there is approximately 8 km of in-vessel cabling serving magnetics and other diagnostics. This is split between two main types, namely solid metal sleeved mineral insulated cable (MI) and metal braided fibre insulated cable. On ITER the electrical connections to most in-vessel diagnostics, in particular the magnetic diagnostics, will require cables to be routed through the main vacuum vessel. The total in-vessel cabling requirement is predicted to be of order 80 km. The surface area of the in-vessel components of ITER is approximately four times that of JET, whilst the current reference design [1] has an available vacuum pumping speed which is approximately half that of JET. In addition the current ITER reference design

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has reduced conditioning capability when compared to JET, in particular the vessel baking temperature is limited to ∼200 °C in comparison to JET's 320 °C limit [2]. Outgassing and leakage from ITER cabling, has the potential to cause issues for the ITER vacuum and hence its operability.

2. Level of outgassing acceptable for ITER operation

At present there is no specific design figure for the outgassing of ITER in-vessel components. A base pressure is defined in the ITER Project Integration Document (PID) [3] of $<10^{-7}$ mbar for hydrogen isotopes and $<10^{-9}$ mbar for impurities at the planned operating temperature of 100 °C. The target on JET is similar, where at 200 °C, prior to starting tokamak plasma operations the aim is to achieve a total pressure in the 10^{-8} mbar region and impurities in the 10^{-10} mbar region. Obtaining this level of vacuum does not guarantee trouble free operation as the condition of the plasma facing surfaces is more significant than base pressure and not necessarily fully represented by the measurement of gas in vacuum.

The first consequence of poor vacuum or surface conditions is failure to maintain plasma breakdown as a result of too much gas entering the initial poorly confined plasma. Tokamak plasmas, once established, are an effective way of cleaning impurities from surfaces, in which they make contact, but will also load these surfaces. Hence, outgassing of hydrogen isotopes will be higher after plasma pulses and require time to reduce before the next pulse. ITER is aiming to achieve a total pressure of 5×10^{-6} mbar prior to each pulse hence the target hydrogen isotopes base pressure from the PID of $<10^{-7}$ mbar could probably be relaxed. The second consequence of poor vacuum or surface conditions is from impurities entering the plasma radiating as they ionise hence counteracting the alpha particle heating required in a self-sustaining fusion reaction. JET can operate without noticeable problems with a leak of 1×10^{-5} mbarl/s. At 1×10^{-4} mbarl/s operations is possible but there is an increased requirement for conditioning. At 1×10^{-3} mbarl/s operations becomes non-viable. If it is assumed that the ITER NIB pumps are open to the torus to assist the torus pumps with the current pumping duct configuration a total pumping speed of around 100 m^3/s is possible. The ITER target of a base pressure of $<10^{-9}$ mbar for impurities is in line with that required from JET experience and but not conservative.

Using the PID base pressure requirements, a rough 'allocation' of outgassing limits can be made for each of the main in-vessel components based on surface area. The surface area of 80 km of cabling could total half the surface area of the vacuum vessel (850 m^2). Hence a reasonable allocation of outgassing would be 20% for the vacuum vessel 40% for the blanket modules, 20% for the divertor, 10% for diagnostic cabling, and 10% for other in-vessel components. The cabling should on average have an outgassing rate of less than 10^{-8} mbar l/(s m) for hydrogen and 10^{-10} mbar l/(s m) for other impurities at 100 °C. Currently ITER is planned to operate at ∼100 °C but be conditioned at ∼200 °C. Generally the experience on JET shows approximately an order of magnitude reduction in thermally induced outgassing for a 100 °C temperature reduction when an item is conditioned at the higher temperature. This then gives a target outgassing at 200 °C for cabling of 10^{-7} mbar l/(s m) for hydrogen and 10^{-9} mbar l/(s m) for impurities.

3. Metal braided fibre insulated cable

Metal braided fibre insulated cable (Fig. 1) has been successfully used on JET. Due to the ease in achieving high packing density and tight bend radii, it is under consideration for some in-vessel applications on ITER. The main disadvantage, over MI cable, is in nuclear heating due to the difficulty in achieving good thermal contact of the cable with its surroundings. Due to its high surface area outgassing is generally higher than intact MI cable. The vacuum policy on JET is to confirm that such cables meet an outgassing criteria at 200 °C of $<1 \times 10^{-9}$ mbar l/(s m) at 200 °C (cable diameters < 5 mm) for hydrocarbons and

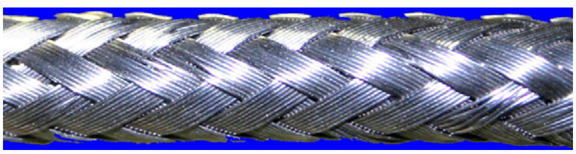

Fig. 1. Metal braided fibre insulated cable.

volatiles before installation. This check is by baking the cable in an instrumented high vacuum oven. To achieve this level a period of baking above 300 °C is required.

The original cable used on JET was manufactured by a company with good understanding of high vacuum practice. When this company ceased manufacturing further cable was made, to similar specifications, by another supplier. A number of batches of cables when tested were found to give outgassing rate some seven orders of magnitude high than the acceptance level. Fig. 2 shows the result of vacuum baking such cable on what was a clean high vacuum flange. Analysis of the deposits showed that they derived from stearic acid ($C_{18}H_{36}O_2$) a lubricant commonly used in drawing wires. Had such cables been installed in JET then operation would have been impossible without major intervention and innovation to find a method to clean the vessel and all installed components. Many methods and solvents were tested to find a way to clean the contaminated cables. The only method which was reasonably successful was prolonged cleaning (7 days) in a hot ultrasonic bath of trichloroethylene followed by 10 days baking at 300 °C after which an outgas rate of <1×10^{-8} mbar l/(s m) at 200 °C, for hydrocarbons was achieved.

If such cable is to be used successfully on ITER the manufacturing processes has to be tightly controlled to ensure low vacuum outgassing including:

- Vacuum outgas testing of the constituent parts of the cable prior to assembly.

Fig. 2. High vacuum flange after baking cable contaminated with stearic acid ($C_{18}H_{36}O_2$).

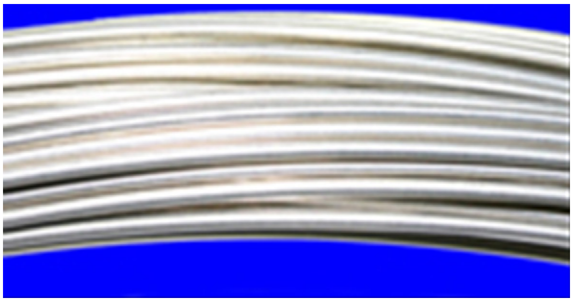

Fig. 3. Section of reels of MI cable.

- Control of cleanliness in assembly, in particular the use of dedicated dry machines.
- A high vacuum standard of handling component parts of the cable.
- Vacuum outgas, testing at temperature prior to cable acceptance.

4. Solid metal sleeved mineral insulated cable (MI)

MI cable (Fig. 3) is planned to be the most commonly used in-vessel cable type for ITER because it can be mounted to give good thermal contact with surroundings so as to reduce the nuclear heating effects. In preparation for ITER extensive tests were performed in the laboratory to assess experimentally the outgassing of different types of MI cable from the same supplier as used on JET, in damaged, undamaged and deliberately perforated conditions. The deliberate perforation of cabling was performed to ascertain if the postulated prolonged gas supply from damaged cable, in the form of virtual leaks, could be mitigated. The tests were performed after exposure to various conditioning environments including ITER fault conditions such as 2 bar steam.

Table 1
MI cable types tested

Cable type	Insulation	Diameter (mm)	Sheath(s)	Core
Coaxial	Al_2O_3	1.5	SS 304 L	SS 304 L
Coaxial	MgO	1.5	SS 304 L	NiCr
Coaxial	Al_2O_3	3	SS 304 L	SS 304 L
Tri-axial	MgO	5	SS 304 L	SS 304 L

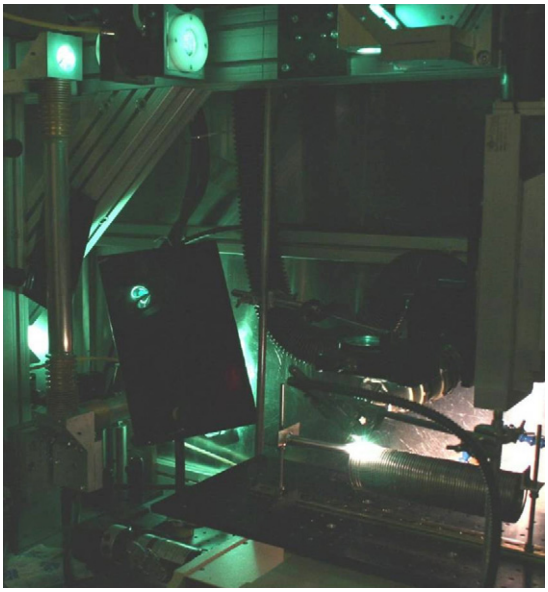

Fig. 4. Perforations of cables using a copper vapour laser.

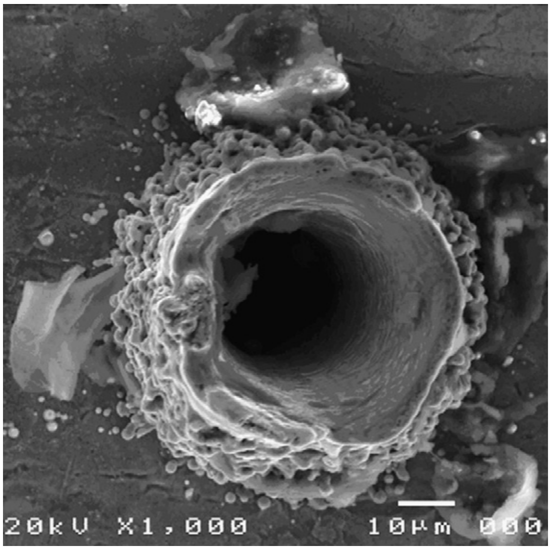

Fig. 5. A 25 μm laser-drilled hole in MI cable sleeve.

Four different cables types (Table 1) were prepared in 10 m lengths and sealed at both ends with a plug weld. Each cable type was tested in three physical conditions; sealed, damaged and deliberately perforated. For all "damaged" cables the damage was produced by mechanically drilling through the sheath(s) with a 0.5 mm diameter drill. All perforations were drilled using a copper vapour laser (Fig. 4). In the case of the co-axial cables, perforations of 25 μm at a spacing of ∼0.5 m were drilled through the outer sheath along the length of the cable (Fig. 5). To produce a perforated tri-axial cable, holes were laser-drilled completely through the cable. Test were then performed on cables which has seen different environmental conditions; new as delivered, evacuated and exposure to a nitrogen, evacuated and exposure to (humid) air, exposed to 2 bar steam. The outgassing from each sample, after each conditioning exposure was determined during a re-conditioning cycle where the cable was baked to 200 °C under vacuum. The outgassing rate over time at 200 °C for all of these tests is given in Fig. 6. The graph illustrates the range of values obtained. Table 2 summarises the outgassing rates obtained for different MI cable groups after 5 days at 200 °C.

All sealed cables reached an outgassing rate in the low 10^{-8} mbar l/(s m) in a relatively short period (2

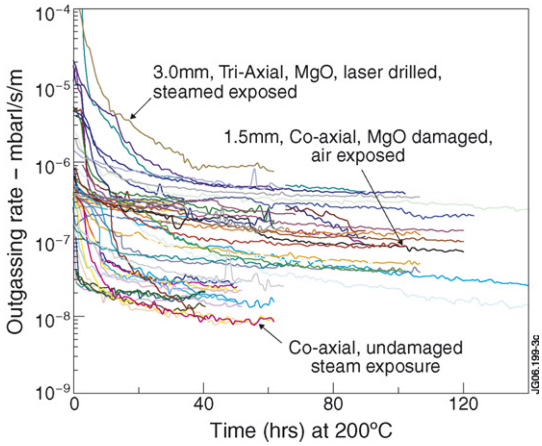

Fig. 6. The outgassing rate over time at 200 °C for all MI cable outgassing tests.

Table 2
Summary of outgassing rates (mbarl/(s m)) obtained for different MI cable groups after 5 days at 200 °C.

Cable condition	Hydrogen outgass rate	Impurity outgass rate
Sealed	$<10^{-8}$	$<10^{-9}$
Laser drilled	$<4 \times 10^{-7}$	$<6 \times 10^{-8}$
Laser tri-axial		$<8 \times 10^{-7}$
Damaged (ex. some 5 mm results)	$<2.5 \times 10^{-8}$	$<2.5 \times 10^{-8}$
Tri-axial damaged		$<2.5 \times 10^{-7}$

days at 200 °C). Improved outgassing was achieved after exposure to 2 bar steam indicating the steam has a cleaning effect. The outgassing was predominately hydrogen with the largest impurity being water at approximately one-tenth of the hydrogen outgassing. This gives water outgassing at 200 °C of $\sim 1 \times 10^{-9}$ mbar l/(s m).

All laser-drilled cables, under all exposure conditions reached an outgassing level $<4 \times 10^{-7}$ mbar l/(s m) after 5 days baking except the tri-axial cable after steam exposure. The tri-axial cable gave prolonged water outgassing at a rate of 8×10^{-7} mbar l/(s m) after steam exposure. Predominately the laser-drilled cables outgassed hydrogen with water being the main impurity at $<6 \times 10^{-8}$ mbar l/(s m).

Damaged cables under all exposure conditions reached an outgassing level of $<2.5 \times 10^{-7}$ mbar l/(s m) after 5 days baking with the exception of 5 mm cable. Different tests on damaged 5 mm cable gave varying results however it was found on some tests to give prolonged outgassing of nitrogen at $\sim 5 \times 10^{-7}$ mbar l/(s m) after 5 days baking. The 5 mm cables which gave higher outgassing were later found but destructive tests to have a large void at one end of the cable from the sealing process. The tri-axial cable outgassing of 2.5×10^{-7} mbar l/(s m) was dominated by water where as the other cables which had an overall lower outgassing rate of 5×10^{-8} mbar l/(s m) consists of 50% hydrogen, 25% water and 25% air.

4.1. MI cable structure and characteristics

The void content of the insulating mineral in a cable will be influential in the amount of gas adsorbed by the cable. Microscopic studies were made on samples of the insulant, both before and after being processed into a cable. Examination of powder extracted from a cable (Fig. 7) shows that the particles do not maintain the original spherical structure. Hammering and drawing of the cable during manufacture, causes insulant to break down into smaller fragments, which then fill the voids thus producing a more densely packed structure overall. An accurate measure of void fraction has not been made but the indication is that for cables tests it is likely to be <5%, significantly lower than the 20–30% reported for some cables [4].

Tests were performed to determine the steady state gas conductance along some of the cables by the measurement of gas flow with cables at atmosphere pressure at one end and high vacuum at the other. As expected cable conductance was approximately proportional to cross-sectional area. The conductance was not found to be fully uniform with length. For a short length a higher proportion of gas flow will be viscous and transitional and hence the conductance per unit length increases with the reduction of test length. Some variation in conductance was found depending on the section of cable measured which could be explained by variations in the insulant packing density. Typically the conductance measured at room temperature of a 1 m long 5.0 mm diameter cable was 5×10^{-7} and 2×10^{-8} l/s for a 10 m length.

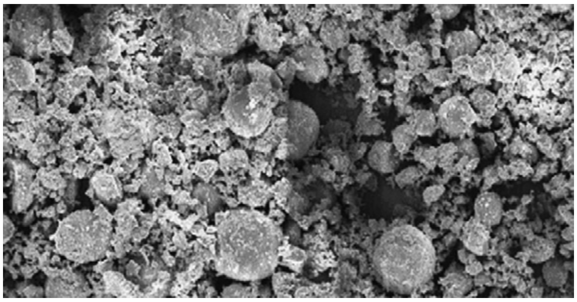

Fig. 7. MI cable insulant.

Generally on JET MI cables are terminated on either side of the vacuum feedthrough or within a private interspace. The philosophy, of ensuring cables did not cross the vacuum boundary was occasionally not followed and resulted on one occasion in an air leak of 1×10^{-4} mbarl/s through the cable. This type of leak is extremely difficult to locate due to the response time to helium leak detection.

4.2. Understanding of MI cable outgassing

The outgassing of a damaged or perforated cable consists of two components, gas originating from voids and gas originating from surfaces. Surface outgassing is dominated by water and hydrogen where as you could expect leakage from voids to be dominated by air or nitrogen depending on exposure conditions. A simple uniform conductance model for a representative damaged 10 m cable gives an e-fold time for the outgassing rate from voids of the order 10 h for all the cable diameters at 200 °C. In the tests performed the component

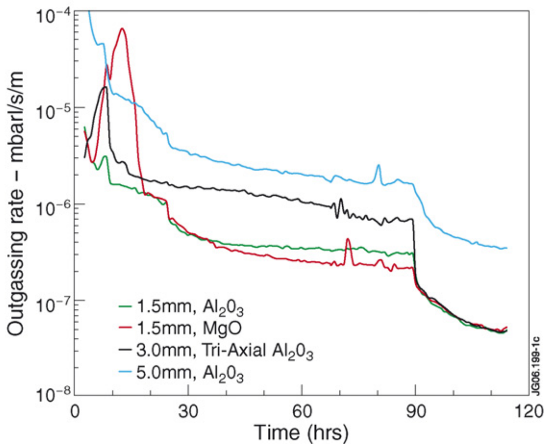

Fig. 8. Total outgassing of damaged steam exposed cables over heating and cooling (30–200 °C) cycle.

of outgassing originating from pumping of the voids is hence dominant at the beginning of the test cycle and its contribution will have significantly fallen off by the time the test system had been fully evacuated and reached 200 °C. The quantity of gas originating from surfaces is very dependent on the outgassing temperature but once at constant temperature for a few days it would be expected to trend towards a fairly constant value. This is generally what was seen in the tests.

It can be seen from Fig. 8 at 90 h that on cooling from 200 °C to room temperature the outgassing drops for all four cables. The largest reduction is for the tri-axial cable for which the outgassing was dominated by water outgassing. This change in thermally induced outgassing is in line with that which is generally observed with vacuum compatible materials. In this test outgassing from the damaged 5 mm cable was different and showed a dominance of nitrogen. It is thought that in this case the gas was from a large void, produced in sealing the cable, at the opposite end to the damage. (Further test runs a different piece of the same cable type did not give this result.)

Damaged or laser-drilled tri-axial cable consistently gave the highest levels of prolonged outgassing when exposed to steam. It is thought that the tri-axial cable structure particularly promoted the storage of water vapour during exposure.

The test results show that the steady-state cable outgassing is dominated by the thermally induced surface outgassing. Hence, laser drilling is not beneficial for the overall outgassing rate as it increases the exposed surface. Generally the single point of damage to a cable is more tolerable than multiple laser-drilled holes.

4.3. Compliance with ITER outgassing requirements with MI cable

The outgassing of many ITER in-vessel components will contribute to the pressure inside the ITER vacuum vessel. A philosophy to meet the ITER pressure requirements is to allocate outgassing limits for all in-vessel components. Allocating 10% for diagnostic cabling gives on average a cable outgassing rate limit of 10^{-8} mbar l/(s m) for hydrogen and 10^{-10} mbar l/(s m) for other impurities at 100 °C. Such an approach would put very demanding requirements on the outgassing of impurities from MI cable, but with all cable undamaged it is possible to meet this type of allocation limit.

The laser drilling of cables increases outgassing of both impurities and hydrogen and if all proposed cables for ITER diagnostics were laser drilled then the outgassing limits would not be met for either hydrogen or impurities, being around 4 times and 50 times too high, respectively. The laser-drilled tri-axial cable gave prolonged water outgassing at a rate of 8×10^{-7} mbar l/(s m) after steam exposure, 800 times too high if all installed cable was of this type.

Generally the outgassing of damaged cable was lower than that of laser-drilled cable and acceptable for hydrogen outgassing. Excluding the tri-axial cables and some anomalous result on 5 mm cable then 4% of cable could be damaged before the impurity outgassing allocation would be used. Tri-axial cable was then worse by a further factor of 10.

Overall the outgassing MgO and Al_2O_3 insulated cable was found to be very similar.

4.4. Recommendations on the use of MI cable on ITER

Based on the tests, observations made at cable manufactures and experience on JET the following are recommended for ITER:

- Cables should be terminated within the vessel or an inert gas filled, dedicated private vacuum interspace and not pass across the vacuum vessel boundaries.

- Cables should be sealed and vacuum leak tested, by helium bombing, prior to installation.
- The use of triaxial MI cable should be very limited.
- The routing and trunking scheme should be such as to offer good protection against damage to cables.
- Cables should be proven to achieve outgassing rate limit of 10^{-8} mbar l/(s m) for hydrogen and 10^{-10} mbar l/(s m) for other impurities at 100 °C.

The manufacturing process of the MI cable should also be tightly controlled to give

- A high vacuum standard of cleaning and handling of the constituent parts of the cable.
- A high and defined packing density of insulate so as to limit the void fraction ideally to <5%. This could be achieved by using preformed insulant rather than powder and in manufacturing specifying a hammering operation after each drawing operation.

5. Conclusions

The ITER vacuum requirements necessitate that outgassing and leakage from in-vessel components are adequately considered in the design and specification of in-vessel components. There are a number of different cable types which can be compatible with the ITER vacuum requirements, but to ensure compatibility then controls as outlined in this paper are required in manufacturing and testing prior to installation. Assuming these controls, then damage to a few % of cable sleeves would not breach the impurity targets for ITER operations. Overall perforation of MI cables is not beneficial and if performed on many cables could jeopardise ITER operations.

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