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The following notes cover a discussion held on 24th June 2008 between representatives of JET and representatives from the National Institute for Fusion Studies (NIFS) and relate to interest in running their Large Helical Device (LHD) with deuterium.

JET neutron budget and activation

The original JET requirement for design of components (year 1980) was that all the equipment should be able to withstand irradiation arising from a lifetime total of 10^{24} D-T neutrons.

This figure of 10^{24} neutrons corresponds approximately to the safe limit of irradiation of the epoxy insulation in the TF coils (10^{8} Gray) This was the original radiation-life-defining feature of the JET design. The specification could not be greater than 10^{24} neutrons without vastly increasing the cost of the machine, i.e. by building it with resin-free ceramic insulated coils.

The intention that JET might produce 10^{24} neutrons had consequences for the design of JET:

- Activation of the machine would mean that personnel access to the Tokamak for maintenance would not be possible after about 10^{23} neutrons, and would be very restricted after 10^{22} neutrons. So all systems in the Torus Hall were originally designed for Remote Handling maintenance using robots. This included vacuum flange joints and welded joints.
- Materials close to the ports of the vacuum vessel had to be resistant to radiation damage at 10^{7} Gray.
- Electronics were banished from the Torus Hall.

In the 1980s, theoretical predictions of the activation of JET were done by A Avery of UKAEA Winfrith. He used MCBEND Monte-Carlo computation for the neutronics and a mixture of ORIGEN code and hand calculations for the activation. Hand calculations were used for materials where reaction data was sparse. This work calculated separately the activation from 10^{20} D-D neutrons and 10^{24} D-T neutrons. They covered the structure of the Tokamak, the structure of the building containing the Tokamak (Torus Hall), cooling water, cryogens, vessel bakeout gas and the atmosphere within the Torus Hall.

From 1983 to 1992, JET was operated mostly with D-D plasmas. Early operations were with H-H, during which activation of in-vessel nickel containing components occurred from photo-neutrons arising from run-away electron discharges during plasma disruptions. Two D-T pulses were run in 1991.

By 1989, preparations were underway for a major upgrade to the Tokamak; the installation of a divertor. The shutdown to install the divertor took place in 1992 and 1993. This involved constructing four coils inside the vacuum vessel, a job that involved people working inside the vessel for prolonged periods. Knowing that this was going to happen, with a small but finite risk that JET might never operate at the same performance levels again, the decision was taken to do the ‘Preliminary Tritium Experiment’ (PTE) in 1991. This was restricted to just two pulses. Otherwise the divertor construction would be jeopardized by the in-vessel activation.

By 1990, the TF coils were developing faults. These were associated with water leaks from within the coils that resulted in severe breakdown.
Octant 3 was removed and a faulty TF coil replaced around January 1990.
After reassembly of the Tokamak, a much smaller fault was discovered in a TF coil in octant 4.
The cooling fluid was promptly changed from water to an electrically insulating coolant: Freon (R113) in April 1990. After this, it was thought that the smaller fault in octant 4 could be left as it was.
Freon 113 contains Chlorine, and so becomes quite heavily activated under neutron bombardment, (P-33; $t_{½}$ =25days and S-35; $t_{½}$ =87days).

A consequence of the new divertor design was that it would no longer be possible to remove sectors of the Tokamak and replace faulty Toroidal Field coils, because they would now be intertwined with the divertor coils.
By 1992, when the divertor was about to be installed, the fault in the octant 4 TF coil (4.2) was viewed as too serious to leave alone, because the new divertor coils would prevent any chance of future repair. So octant 4 was removed at the start of the 1992 ‘divertor’ shutdown and the faulty TF coil replaced.
After refitting the octant, the adjacent TF coil, (4.3) was found to have a fault (previously masked by the larger fault in the adjacent coil) and so octant 4 was removed again and coil 4.3 replaced. These coil replacements were made easier by the attention to the remote-handle-ability of the original JET design.
After this, the divertor construction started inside the vessel.
The new divertor coils shared the Freon coolant with the TF coils

The Freon 113 was replaced with Galden 55 in 2001 for ‘greenhouse gas’ environmental reasons. Galden is a per-fluoro-poly-ether, containing no chlorine. The long term activation problem is also much reduced, the only difficult long term activation product in Galden being tritium.

JET operations since 1993 have been mostly D-D plasmas, but a substantial D-T campaign was undertaken in 1997. There is still an activation legacy in 2008 from those experiments due to the Cobalt-60 induced in the vacuum vessel.
A ‘trace-tritium’ campaign was undertaken in 2003, employing tritium-in-plasma concentrations typically around 1%.

JET Operator policy now is to limit the neutron production to levels that will allow man-access for maintenance to within one metre of the vacuum vessel ports. This policy has been in force since year 2000. Allocating a total lifetime neutron budget of $2x10^{21}$ neutrons presently ensures this. In practice, a budget of $2x10^{21}$ neutrons per 1/e life of Cobalt-60 (7.6years) would also ensure this.
This is achieved by a strict rationing of neutron production.
It was realised that the versatility of JET to investigate plasma physics depends on the possibility to allow personnel access within the Torus Hall to service and

modify systems. The new budget now means we can now use equipment with lower radiation resistance, 2×10^4 Gray near the vacuum vessel ports.

The maximum possible performance of JET in its present configuration operating in D-T is believed to be about 3×10^{19} D-T neutrons per pulse. In the 2008 configuration of JET, this would require operating near the machine limits of 6MA plasma current and 4 Tesla toroidal field. JET is not usually operated near these limits nowadays, and is only rarely operated with tritium. So the new restricted neutron budget can be fairly easily accommodated by the scientific programme.

Two important points to note for a machine the size of JET if using deuterium:

- Since the D-D reaction has roughly equal probabilities of producing (p+ T) or (n + He3), approximately one triton appears for every D-D neutron. The tritons that do not undergo a secondary fusion reaction should be collected. In JET, most of this tritium is recovered because the tokamak exhaust is processed by the Active Gas Handling plant. (Recovery >95% when operating open cycle and 100% when operating closed cycle). Example: Production of 10^{20} neutrons corresponds to 10^{20} tritons; which represents an activity of 10^{20} / (12.33years / ln2) = 180GBq.
- During D-D plasma operations in JET, about 1% of the tritons produced from the D-D reactions in JET undergo a D-T reaction before being exhausted from the plasma. In D-D operations, activation by reactions with a threshold between 2.5MeV and 14MeV may be strongly determined by these secondary fusion reactions. For example; the short-term activation of the building air may have an impact on the way the building ventilation must be implemented. (Nitrogen-13; $t_{½}$ =10minutes. Nitrogen-16; $t_{½}$ = 7seconds, and Sulphur-37 $t_{½}$ =5minutes; all three of these generate penetrating gammas) For JET, which has building ventilation arrangements already designed to cope with D-T operations, these secondary D-T reactions during D-D operation are unimportant because they a factor $>10^4$ less than during D-T operations.

For large machines ***not*** equipped for D-T, but operating with deuterium, both these points may need to be considered.

Personnel access inside the vacuum vessel is severely restricted because of activation from neutrons, the principal activation products remaining after one month being:

	Reaction	Threshold?	Half life
Cobalt-57	Ni58(n,d)	From D-T reactions	267 days
Cobalt-58	Ni58(n,p)	From D-D & D-T reactions	71 days
Cobalt-60	Ni60(n,p)	From D-T reactions	5.27 years

For this reason, maintenance and upgrade work inside the vessel is mostly done by robot. Only in exceptional cases is manned entry into the vessel allowed. If manned entry is required, it is done near the end of a long shutdown after the shorter-term activation has decayed. The long-term Cobalt-60 activation inside the vessel is still about 100μSv/hour, so one person working in the vessel for 6 shifts each of 4 hours has nearly used up his 3mSv ‘shutdown’ radiation dose allowance from the ‘external’ gamma dose, before accounting for ‘internal’ tritium dose.

Penetrations through the concrete ‘biological shield’

The walls of the Torus Hall are 2.8m thick, the roof 2.25m thick.
The designs of the penetrations and access labyrinths were checked by A Avery and N Davies in the 1980s. They used a MULTISORD code. I believe they also developed their methods with Monte-Carlo sub-modelling.
The Torus Hall was built with many apertures for electrical feeds, cryogenic services, cabling, water cooling, RF transmission lines etc. These apertures were made with stepped sides to stop unnecessary streaming around the edges. They were designed to be filled with high density concrete blocks and sand around the equipment that passes through. The Torus Hall is lined with borated concrete blocks and the intention was that this lining should be continuous, including at the penetrations. The penetrations are also sealed to be gas-tight so that the Torus Hall ventilation system can hold the atmosphere at a slight depression to control the dispersal of contamination. The largest direct line-of-sight apertures to radiation are those for the gas circulation system that is used to bake the vacuum vessel. The pipes for this, where they go through the wall of the pit, are about 1 metre in diameter. Most of these services pass through the basement, which forms a secondary shielding enclosure.

Penetrations for diagnostics in the walls and the ceiling of the Torus Hall require secondary shielding enclosures outside the Torus Hall wall where direct line-of-sight diagnostic beamlines passed through the wall. Some of these enclosures have not yet been completed to the 10^{24} D-T neutron specification. For example, the Thomson scattering optics were constructed with several multiple right-angles in the vicinity of the penetration so that a small concrete blockhouse could then be built around the optics. The blockhouse for this has not yet been built, and will probably never be needed because of the new restricted neutron budget.

In general, the penetrations are now permitted to weaken the effectiveness of the Torus Hall shielding, because of the new restricted neutron budget. The walls are thicker than they need to be for $2x10^{21}$ neutrons divided over 20 years. They were built to shield $5x10^{23}$ neutrons/year.
