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SAFETY ASPECTS AND APPROVALS OF THE FIRST JET TRITIUM EXPERIMENT

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ABSTRACT

The first tritium experiment was carried out successfully in the JET machine in November 1991. A new gas introduction system was constructed and an existing cryogenic pumping system was modified to permit collection of tritium in the exhaust gas. The total amount of tritium handled was 0.24 g.

This paper describes the essential safety features of the modifications to the machine and how the safety and other approvals were obtained. The standards which were required to be met are discussed, and it is shown that the risk to employees and members of the public arising from the experiment was negligible. In addition, the measures taken to identify potential operational problems and to respond to incidents which might have occurred are described.

1 INTRODUCTION

The JET plasma was fuelled for the first time in November 1991 by deuterium and tritium resulting in the production of more than 1MW of fusion power. Although JET had operated with small concentrations of tritium already as a result of tritium production by D-D reactions, this was the first time that tritium was processed and handled. The first tritium experiment, as well as giving important physics information, has provided valuable experience of the behaviour of tritium particularly in terms of its retention in the tokamak and in vacuum components, which will be important for the full D-T operation of JET.

The modifications to the machine consisted of a gas introduction system, a gas collection system (including an exhaust detritiation system), and changes to the vacuum pumping system to ensure that direct discharges of tritium to the environment were minimised. These are described elsewhere [1,2,3].

Planning for the initial tritium experiments has been carried out in parallel with that for the main D-T experiments which are due to be performed at the end of the JET Project. Because of this, much of the preparation for tritium operation was already underway when the format of the PTE was finalised early in 1991. This included the installation of a comprehensive Radiological Protection Instrumentation System, completion of routine and accident dose assessments and many relevant safety assessments.

This paper describes the essential safety features of the modifications to the machine and how the safety and other official approvals, which were required for the experiment, were obtained. In addition, it describes the measures taken to identify potential operational problems and to respond to incidents which might have occurred.

2 DESIGN SAFETY ASPECTS

Three main safety issues were considered in the planning for the experiment:

(i) Radiation exposure to staff from anticipated operations should be minimised.

(ii) The risk from radiation exposure from accidents to staff and to the public must be as low as reasonably practicable.

(iii) "Best Practicable Means" (BPM) must be used to limit the environmental impact of the experiment.

This last point was fundamental to the design of the modifications to the machine. The quantity of tritium planned to be used in the experiment was of the order of 0.25g. Calculations carried out in connection with routine discharges during the full D-T phase had shown that the public dose arising from a discharge of this magnitude would be acceptable [4]. However BPM requires that options other than direct discharge had to be considered and led to the requirement for collection of as much of the tritium as possible using the technology of cryogenic pumping and absorption of hydrogen isotopes on Uranium (U) beds. This was achieved using the Gas Collection System (GCS) constructed for the experiment [5] . This then left open the option of future separation of tritium by cryodistillation in the Active Gas Handling System (AGHS). The design of the system permitted limited processing of hydrocarbons but was unable to process tritium oxide diluted in large quantities of air or other reactive gases. The system was expected to give a clean-up efficiency during the main processing of gas from the machine of about 99.9%.

Continuing evolution of tritium from the torus was expected to occur up to and including the start of the shut-down. This was expected to be primarily deuterium mixed with impurities, some of which could be unprocessable. It was recognised that at some stage in the clean-up process, a decision would need to be made to stop processing as the effort of preparation of U-bed storage capacity, the shift manning required to operate the plant, and the risk to the individuals involved would not be in accordance with BPM.

Because of the small quantity of tritium in use, the risk to the off-site population was insignificant. Nevertheless it was considered prudent to provide a method of collection of the injected tritium in case a major repressurisation accident or water leak occurred in the machine. In these cases the GCS would be largely inoperable. Two alternatives were available; the Exhaust Detritiation System

(EDS) in the Active Gas Handling plant or a "mini-EDS" in the GCS. The use of either of these systems would have required the disposal of solid or liquid tritiated waste, but the ultimate impact of this would be lower than the acute exposure of individuals under adverse weather conditions.

The main sources of risk to operational staff were identified as through inadvertent release of tritium into working areas and through exposure to γ or neutron radiation from the machine. The latter point was essentially covered by the existing shielding and access restrictions. As a means of minimising tritium diffusion into operational areas in the event of a tritium release into the Torus Hall, the Torus Hall ventilation system was operated under depression [5].

Two basic precautions were adopted to minimise the operator risk from tritium releases:

(i) All components handling tritium were to operate at sub-atmospheric pressure.

(ii) As far as practicable the systems for injecting and recovery of tritium would be enclosed in such a way that any leakage of tritium would be collected and discharged to a stack. This would also enable discharges to be monitored.

3 OFFICIAL APPROVALS REQUIRED

3.1 UK Government

Nuclear sites in the UK, such as reactors and reprocessing plants, are regulated by the UK Nuclear Installations Inspectorate (NII) which is part of the Health and Safety Executive (HSE). The NII have determined that JET is not required to be licensed by them but would be subject to the normal regulations governing the use of radioactive materials. This is consistent with the situation in the tritium light source industry which handles comparable amounts of tritium (ie several tens of grams on one site).

The statutory requirements which apply to JET are summarised below:

(i) Radioactive Substances Act 1960

Under this Act, JET is legally required to be registered by Her Majesty's Inspectorate of Pollution (HMIP) to keep or use tritium and other radioactive substances. The storage and disposal of tritiated and other radioactive wastes is also required to be authorised by HMIP. The Act does not specify numerical limits for discharges and the onus is on JET to show that the discharges are (a) necessary, (b) "as low as reasonably practicable", and (c) result in acceptable public dose. HMIP judge the acceptability of public dose against the annual limit of 0.5mSv recommended by the National Radiological Protection Board (NRPB).

(ii) Ionising Radiation Regulations

These Regulations set limits for occupational and public exposure amongst other things, and are implemented by the HSE. There are many specific requirements, some of which require explicit approval including those dealing with registration for the use of radioactive materials, dosimetry service approval, measurement of losses and contingency planning. The latter requires a contingency plan to be drawn up to deal with any incidents which may result in exposure of any person to doses in excess of the legal limits (50mSv for JET employees, 5mSv for any other person, per year).

3.2 JET Statutes

JET has a duty under Article 4.1 of the Support Agreement to "satisfy the Host Organisation in advance of any radioactive operation taking place, that the arrangements ..... conform to whatever standards may then be in force within the Host Organisation". The Host Organisation is the UKAEA which, since October 1990, has been licensed by the NII. Therefore, in effect JET must conform to the standards required under a licence.

A consequence of this was the establishment of a Fusion Safety Committee (FSC) to examine the safety of proposed operations. This committee was analogous to Nuclear Safety committees on sites licensed under the Nuclear Installations Act and included several members from outside the JET Project.

The Safety and Reliability Directorate (SRD) of the UKAEA performed a dual role. As well as membership of the FSC, and through this route providing advice to the UKAEA Director of Safety, SRD performed independent "peer reviews" and audits of safety.

4 DOSE ASSESSMENTS AND DISCHARGE AUTHORISATIONS

4.1 Routine

Submissions had been made to HMIP to justify the discharge authorisations for the full D-T phase. The critical group doses for discharges of tritium, activated air and dust to atmosphere and tritium and activation products to the River Thames were calculated.

Atmospheric discharges were modelled using a modified Gaussian plume dispersion model using local meteorological data. Discharges to the river were modelled using a multi-compartment model which enabled differing usage and behavioural patterns to be taken into account.

For tritium, a specific activity model was used and the original submissions assumed that the critical group dose from unit discharge of elemental tritium would be 10% of the equivalent HTO discharge. New calculations based on the ETMOD code [6] will show that this assumption is conservative.

The discharge authorisations granted to JET, which cover the requirements for the full D-T phase are shown in Table 1. The total dose, summed across all the critical groups for the annual authorised discharges in Table 1, is 17μSv. This compares with the JET design target of 50μSv established at the beginning of the Project.

Collective doses were also calculated for tritium. The collective dose for unit discharge to the river was, in contrast to the case for critical group doses, several times higher than that for atmospheric discharge. This has meant that in the case where the hypothetical critical group individual dose is negligible, the application of BPM is weighted towards atmospheric discharge.

To avoid making staged applications for progressively increasing amounts and throughput of tritium, and to permit flexibility in case of the termination of the Project at the end of 1992, JET applied to HMIP for discharge authorisations for the full D-T phase using up to 90g of tritium with 30g in circulation between the torus and the AGHS. Although these have now been granted, the application of BPM, as mentioned above, meant lower limits were appropriate for the experiment. The limits were scaled to take account of the lower quantity of tritium in use, to set a JET management limit of 10 GBq/day, above which a special BPM justification would be prepared for submission if requested by HMIP.

4.2 Accidental

The radiation dose to persons on and off the site which would result from the accidental release of radioactive materials had also been calculated for the full D-T case. A Gaussian plume model was used, modified to take into account building wake effects. For a release of tritium as HTO from the top of the torus building under class F weather conditions, the maximum dose on-site was 11.3μSv/TBq and off-site 0.59μSv/TBq.

5 SAFETY APPROVAL

Safety approval was a staged process starting with a review within the internal JET management system to determine the level of risk. At this stage it was established that a submission to the Fusion Safety Committee would be required. This took the form of a preliminary report setting out the overall risk and identifying hazards, a Safety Analysis Report analysing the risks of the proposed experiment compared with standards, and finally a peer review of the submissions. An audit of the safety management system was also carried out by SRD.

5.1 Hazard Assessment

JET systems, which involve extensive use of cryogenic and vacuum systems, differ significantly from normal radioactive material processing plants. The identification of hazards was therefore greatly dependent on the operating experience of JET and on the results of safety studies carried out for other fusion devices. In addition, formal HAZOP (Hazard and Operability) studies had already been carried out for some JET systems, particularly for the Active Gas Handling System. Because of the novel nature of JET, and the existence of several documents identifying hazards, the Fusion Safety Committee requested a summary to be produced. The main hazards identified and a summary of their assessment are listed in Table 2 .

The majority of hazards were adequately protected against by the facilities already built into the JET machine and the experimental building. For example the radiation dose external to the Torus Hall shielding was negligible as this had been designed for the full D-T phase. Access control was provided by a Personnel Safety and Access Control System, the performance of which had already been assessed as satisfactory by SRD.

As the full remote handling equipment was not able to be used, personnel access to the torus for operational and emergency reasons was necessary. This required an assessment of radiation dose rates during the period after pulsing.

Other aspects of radiation exposure considered were releases of freon and activated air, the activation of uranium beds and doses during the forthcoming shutdown.

The main hazard identified however, was release of tritium and this dominated the risk to individuals.

5.2 Overall Risk Assessment

Plant on UKAEA sites are categorised in terms of the overall risk to workers and members of the public and this determines the level of safety justification required. There are four categories [7] ranging from no hazard to an off-site hazard.

The quantity of tritium used for the experiment was 0.25g (about 90 TBq) which, if it were all released as HTO under adverse weather conditions, would lead to maximum short term doses of about 1mSv on-site and about 50μSv off-site. This assumes that the tritium would be released from the top of the torus building. Even if there were a ground level release, doses would still be below statutory occupational and public doses. The overall risk category was therefore "C", a hazard only within the building.

However, because of the novel nature of the experiment, SRD raised the level to "B" (equivalent to an on-site hazard) to prompt a wider review of safety.

5.3 Safety Analysis Report

The Safety Analysis Report (SAR) had three main functions: to describe the final design configuration for the machine and ancillaries; to specify the accident sequences which could lead to a release of tritium (this having been identified in the preliminary analysis as the major hazard) and perform a probabilistic analysis; and to compare the public and worker risks against standards.

The SAR highlighted the safety-related features of the design such as the hard-wired overpressure and overtemperature trips on the gas introduction U-beds which were designed to ensure that the pressure in the system could not exceed atmospheric. Operational constraints required to meet probabilistic and deterministic safety requirements were also described. These included a limit on the Neutral Injection Box (NIB) cryopump tritium inventory and a 15mb pressure limit on the gas regenerated from the GCS cryopump. This latter limit was necessary to ensure that if there was any undetected air leakage into the system, there was no risk of a hydrogen explosion. This limit was found to impose severe operational constraints when dealing with large batches of gas from the NIB and, because of the time delays involved, tended to increase the risk of air leaks. A change to the procedures was made to permit the use of the NIB pumping ducts as a larger buffer volume and ultimately a revised safety case was presented, based on limiting the pressure in the vessel in a hydrogen deflagration to less than atmospheric. This permitted the total pressure after regeneration to be raised to a limit of 110mb.

Many JET machine sub-systems used in the D-D phase are not suitable for use with tritium. For example, diagnostics which discharge into the Torus Hall; radiofrequency (RF) heating systems containing SF6, which could prevent tritium processing if it leaked into the torus and hence into the GCS; and systems such as the pellet injector, in which tritium contamination could cause maintenance difficulties. The SAR specified that these systems should be positively valved off.

Faults on the JET machine such as vacuum leaks were reviewed and the steps taken to mitigate against their effect were discussed. From this and the other accident sequences identified from the hazard assessment, a number of accident sequences, which required fault tree assessment to demonstrate their acceptability, were selected. These events are shown in Table 3 and a typical fault tree in Fig 1.

The criterion for the acceptability of the design for JET tritium systems, agreed with SRD, is that for any single accident sequence, the product of the frequency and the amount released is less than 0.37 TBq/year. This has been applied through the design safety review of the AGHS as a means of ensuring that the overall risk targets are likely to be met. In addition to the frequency of the event, this required a knowledge of the time dependent tritium inventory at risk. This was assessed for each condition as in the example shown in Fig 2. The events are plotted in Fig 3 showing that the SRD design criterion was met.

5.4 Compliance with Risk Targets

The AEA standard for public risk is that the total risk of premature death to the member of the public most at risk from all fault sequences on the whole site should not exceed 10^{-6} per year, and the risk from any particular fault sequence should not exceed 10^{-7} per year. If the products of release and frequency in Fig 3 are summed and multiplied by the dose per unit release ($0.59\mu Sv/TBq$) and by the risk coefficient ($3x10^{-2}$ per Sv), a value of $1.4x10^{-8}$ per year is obtained. Even with the pessimism arising from the use of non-average conditions and hypothetical members of the public, this is well within the above target. The risk from any accident sequence which fell on the line on Fig 3 is $7x10^{-9}$ per year thus ensuring that the individual accident sequence risk target above is complied with.

The NII also impose public risk targets which are based on the acceptability of accidents related to dose bands. As a release of all the inventory for the experiment would result in a dose to the most exposed individual less than the lowest band, the experiment would not need to be considered according to the NII criteria.

An assessment of worker risk was also performed against the UKAEA criterion of 10^{-5} per year. Using the probabilistic analysis for tritium releases into the working area and assuming a 30 minute evacuation time, gave a risk almost 2 orders of magnitude lower.

6 OPERATIONAL SAFETY

Before the first tritium experiment could proceed, many operational safety issues had to be addressed:

(i) Under the Ionising Radiation Regulations 1985, the JET Project was required to prepare contingency plans in respect of any reasonably foreseeable accident or incident. The "JET Emergency Plan for Accidental Releases of Radioactive or Toxic Materials in the D-T Phase of Operations" was prepared and submitted to the Fusion Safety Committee for approval. The document describes the basic principles and main arrangements for the response on-site to an incident which may lead to a release of radioactive or toxic materials; the implementation of monitoring off-site to determine the extent of any release; and the alerting and advising of those external authorities and agencies with responsibilities for the health and safety of the public in the event of such an occurrence.

The details for implementation of the arrangements required by this plan will be contained in the Site Emergency Instructions. For the first tritium experiment these were issued in the form of JET Incident Response Procedures. Because of the limited amount of tritium used for the first tritium experiment, the procedures emphasized the on-site response including health physics assessment. The procedures were such that they could readily be extended to assess off-site conditions. In particular, provisions were made for establishing a site emergency control centre incorporating a health physics assessment area. These procedures took into account specific incidents which could arise in the experiment, eg tritium monitors going to alarm, vacuum system failures or leaks, water leaks into the torus or Neutral Injection Box, ventilation system failures, gas collection system non-availability, neutral beam (NB) tritium gas introduction problems, fire in areas where a potential for a consequential tritium release existed.

(ii) A review of the management of safety for the first tritium experiment was carried out and assessed by UKAEA Safety and Reliability Directorate. This review clarified the management and operations responsibilities of individuals and groups; it documented the safety-related information; it described the organisation and responsibilities of staff dealing with incidents and the on-call arrangements for back-up staff; it described the method of working with tritium in the experiment and the handling of any proposed modification to the machine or operational procedures; and it outlined the auditable training undertaken to ensure all operations staff were properly qualified to safely carry out their duties.

(iii) The training of operations staff took three main forms:

(a) General safety training concerning the hazards of tritium, the principles of radiation protection and a general description of the measures to be taken in the experiment to ensure the safety of personnel.

(b) Specific training of staff for the operation of their systems in both normal and non-normal conditions, eg neutral beam tritium gas introduction, neutral beam glove box operation, gas collection system: operation of gas pumping, sampling and vacuum leak checking, operation of the tritium recovery and exhaust detritiation systems.

(c) Specific training of staff on the nature of the new systems involved in the experiment, and the incident response procedures (including the wearing of protective clothing). In addition, this training detailed the method of working to be employed, eg access control, third-shift (night) working, communications, and the new alarm system on the JET site. The latter is such that all sufficiently important alarms (tritium, fire, plant alarms, combustible gas detection, security alarms) are directed not only to CODAS but to annunciators on a Site Incident Desk. This new desk included displays for wind speed and direction from two measurement units, one located on top of the torus building and the other well away from the JET buildings.

Two incident response exercises were carefully planned, carried out and assessed. As a result, various problems were identified and improvements in the training of staff and procedures were introduced.

A review of staff was made to identify personnel who should be classified radiation or registered beryllium workers. As a result several staff were specifically trained.

(iv) A review of systems was carried out to ensure that:

(a) They were ready to operate safely.

(b) The necessary emergency and incident response equipment for these systems was ready.

As a result, specific action was taken to isolate several systems connected to the torus vacuum (eg certain diagnostics, the pellet injector, the RF antenna vacuum systems, the in-vessel inspection system). To prevent contamination passing through possibly leaking isolation valves, secondary valves were closed. Vacuum pumps not exhausting to the Gas Collection System were either connected to the torus pumping crown (for operational systems) or stopped (non-operational systems).

Sulphur hexafluoride (SF6) was removed from the lower hybrid (LH) waveguides which were refilled with nitrogen, as a precautionary measure, because leakage of Be windows in the LH system could cause SF6 to enter the torus and be pumped to the Gas Collection System. This could disable the Exhaust Detritiation System. In addition the LH launcher was retracted and locked in position.

For CODAS, certain modifications were made to include signals required for tritium accounting and new alarms for the neutral beam tritium injection system.

Most of the draining and refilling system (used for cooling in-vessel components) was emptied of water (eg limiters and gas discharge cleaning electrodes). The active drainage system was made ready to deal with any spillage of contaminated liquid.

(v) Special security and access control arrangements were made. A secure store for the tritiated U-beds was made available and the Gas Collection System area was covered by a system of surveillance cameras, including motion detection, monitored in the JET control room. In addition, a watchkeeper strictly controlled access (24 hours a day) to the building area which included the Gas Collection System and other work in this area was severely restricted.

The Personnel Safety and Access Control System (PSACS), which has been operational since the start of the JET operation in 1983 and which has been assessed by SRD, was extended to provide access control with radiation dosimetry to the Gas Collection System area. The existing PSACS provides for safe access to the main operational areas (Torus Hall, its basement and roof laboratory).

(vi) The formal operation procedures for tritium handling plant were approved through the JET Technical Control System. All operations with this equipment were covered by the JET Safety at Work System involving safety assessments and work permits. The tritium handling plant was extensively tested with deuterium before the introduction of tritium.

After the actual tritium gas introduction experiments were completed, several tasks were performed which required special scrutiny as to their safety:

(a) Initial entry to the Torus Hall following some activation of the machine by the experiment.

(b) Removal of the neutral beam tritium U-bed to the safe store.

(c) Continued operation of the Gas Collection System to remove as much tritium as possible from the torus and Neutral Beam Injector boxes. This included the installation of new U-beds and the transfer of the contents of the original U-beds to the new ones.

(d) Restoration to the normal state of systems connected to the torus vacuum. Checks were made to ensure that there was no spread of tritium contamination to these systems and beyond.

CONCLUSIONS

The standard of safety justification required for the first tritium experiment was higher than would normally be the case for the quantity of tritium used. However, as a result, the preparations for the experiment have provided valuable experience in treating the issues which will arise for full D-T operation of JET. In particular they have highlighted the considerable effort necessary to establish training and emergency arrangements, and the management and QA structure necessary to operate with tritium.

The safety assessment has confirmed that the risk from the experiment was negligible and that the methodology of probabilistic risk assessment is suitable for application to this type of system. However, the fact that the hazard assessment was fragmented between several different documents caused potential delays with the review by the Fusion Safety Committee. A single, more structured, hazard assessment document would have been beneficial.

The dose assessments which had been carried out showed that the impact of routine radioactive discharges would be within the guidelines laid down in the United Kingdom. The application of Best Practicable Means requires careful consideration at all times during design and operation, and the discharges from the experiment had to be justifiable in relation to the usage of tritium and the available technology for its separation.

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[4] A C Bell et al, "Routine Tritium Releases from JET", Proceedings of the Fourth Topical Meeting on Tritium Technology in Fission, Fusion and Isotopic Applications, Albuquerque 1991.

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[6] S B Russell and G L Ogram, "ETMOD: A New Environmental Tritium Model", Proceedings of the Fourth Topical Meeting on Tritium Technology in Fission, Fusion and Isotopic Applications, Albuquerque 1991.

[7] H E Campbell and M D Rowbottom, "The Independent Assessment of Planned Tritium Operations at JET", Proceedings of the 16th Symposium on Fusion Technology, September 1990.

Discharge Route	**Activity**	**Annual Discharge Limit**	**Critical Group Dose**
<u>Aerial</u>	Tritium as oxide	90 TBq	6.3 μSv
	Tritium (excl oxide)	110 TBq	< 1 μSv
	Activated air and coolant	24 TBq total βγ	7 μSv
	Activated dust	1 GBq	<1μSv
<u>Liquid</u> (Aqueous to Thames)	Tritium	10 TBq	0.12 μSv
	Activation products	100 MBq	< 1 μSv

Table 1: Discharge Authorisations

Hazard	Causes	Mitigating features	Comments
Loss of containment	Leakage; U-bed overheating	Sub-atmospheric operation; secondary containment for GI and GCS; Exhaust detritiation (for torus system leaks); Overpressure trip	Overpressure and air leakage analysed in SAR
Loss of shielding	Doors left open	Interlocked	Analysed for full D-T
Fire	Various	Fire/smoke detection; automatic extinguishing in certain areas	Radiation dose rate in all areas assessed in case man-access required
Explosion	Hydrogen explosion	Pressure limit following potential air leakage limited to 15mb	
Loss of ventilation	Fan failure	Redundant fans	Analysed in SAR
Loss of electrics	Various	UPS for radiation instruments	Cryogenic systems remain safe; U-bed tends towards safer state
Loss of cryogenics	Various	Pressure relief on cold finger	All tritium systems remain sub-atmospheric on warm-up
External hazards		Robust construction of JET buildings	Covered by bounding case of total release of tritium
Operator error		U-bed overtemperature/ pressure trips; valves and U-bed heaters interlocked by plug arrangements to avoid energising D_2 bed when T_2 requested; multiple tritium alarms	All operators fully trained; key actions require multiple independent checks; independent checking of GCS vessel, isolators and stack is possible.

Table 2: Summary of Hazard Assessment

EVENT DESIGN	EVENT DESCRIPTION	PERIOD
P1, B1 P2, B2 P3, B3	Failure of PINI insulator	Tritium Day 2 Interperiod Post-experimental detritiation
P4, B4 P5, B5 P6, B6	Catastrophic failure of diagnostic window	Tritium Day 2 Interperiod Post-experimental detritiation
P7, B7 P8, B8 P9, B9	Water-leak induced window failure	Tritium Day 2 Interperiod Post-experimental detritiation
P10, B10 P11, B11 P12, B12	Liquid nitrogen leak into vacuum	Tritium Day 1 Interperiod Post-experimental detritiation
U13	U-bed heater cut-out-failure	U-bed reactivation
U14	Amersham U-bed heater cut-out-failure	Tritium Days 1 and 2
E15	Hydrogen/air explosion in the GCS	During cryopump regeneration hydrogen processing
L16	GCS process leakage	Following Tritium Days 1 and 2
L17	Process leakage from neutral beam tritium introduction system	Tritium Days 1 and 2

Table 3: Events Analysed by Fault Tree

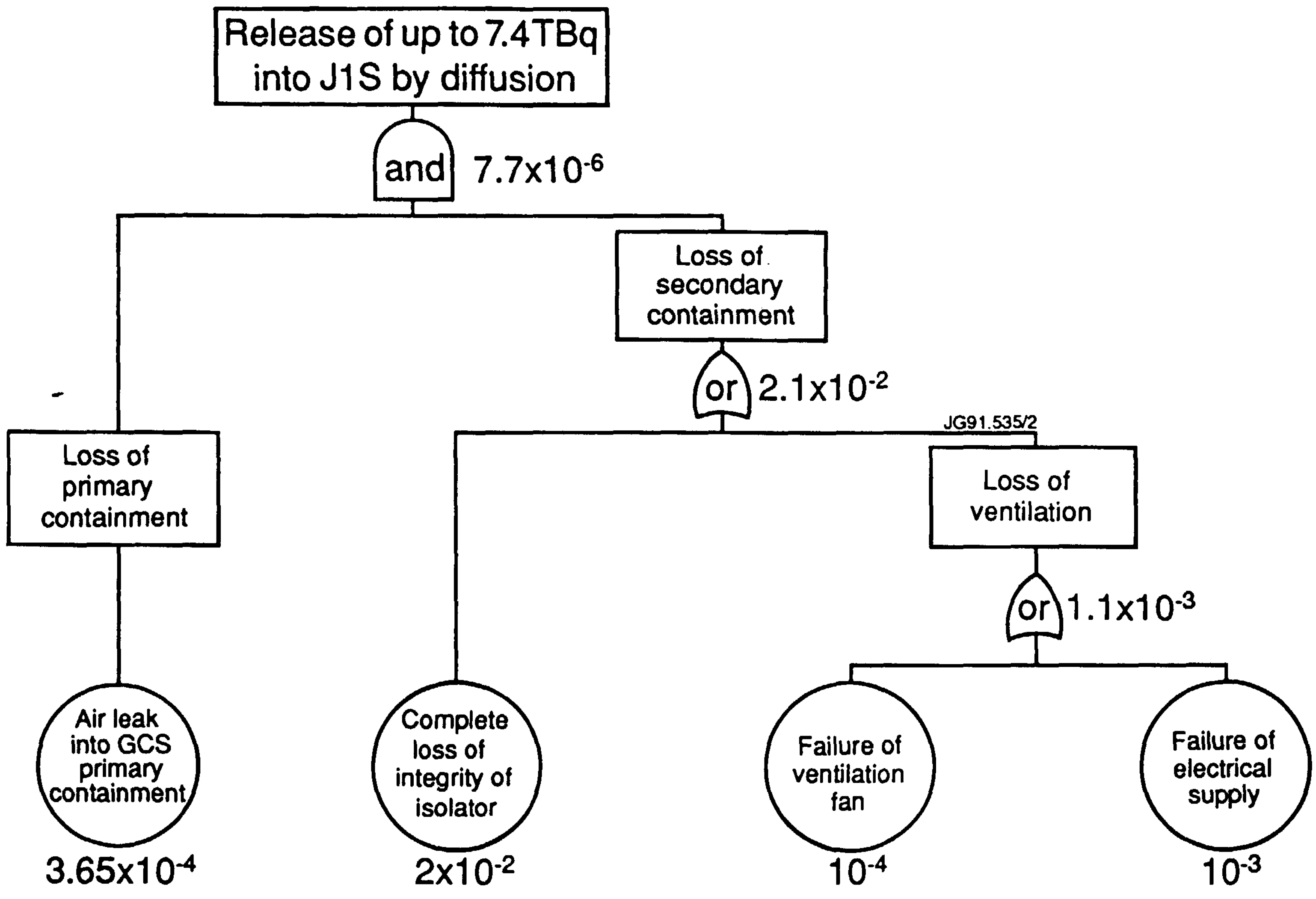
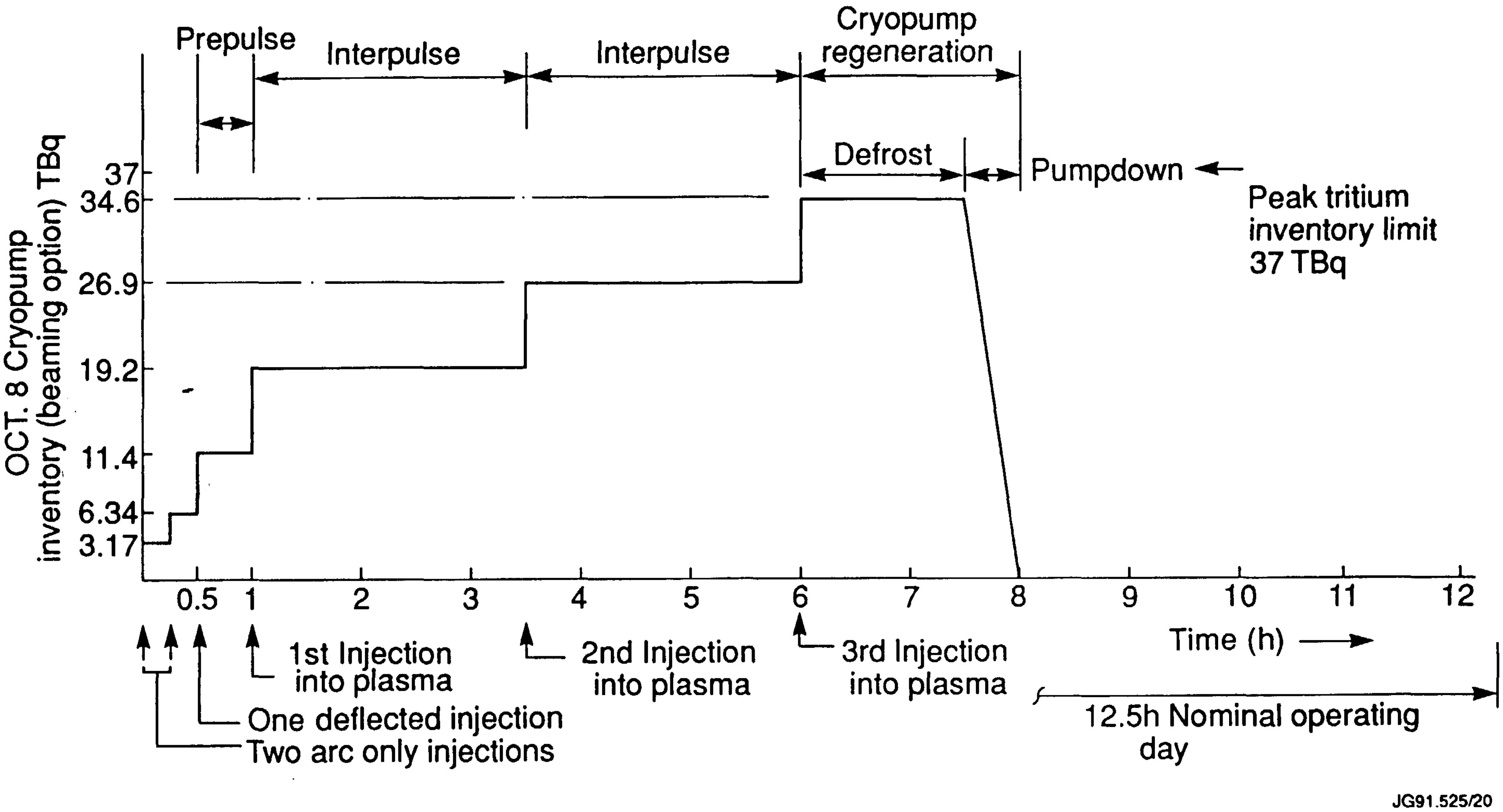


Fig 1: Fault Tree for GCS Process Leakage



$$\text{Time-at-risk average inventory} = \frac{\text{Enclosed area}}{\text{Nominal operating period}} = \frac{183.9\ (\text{TBq.h})}{12.5(\text{h})} = 14.7\ \text{TBq}$$

Fig 2: Time-dependent Tritium Inventory

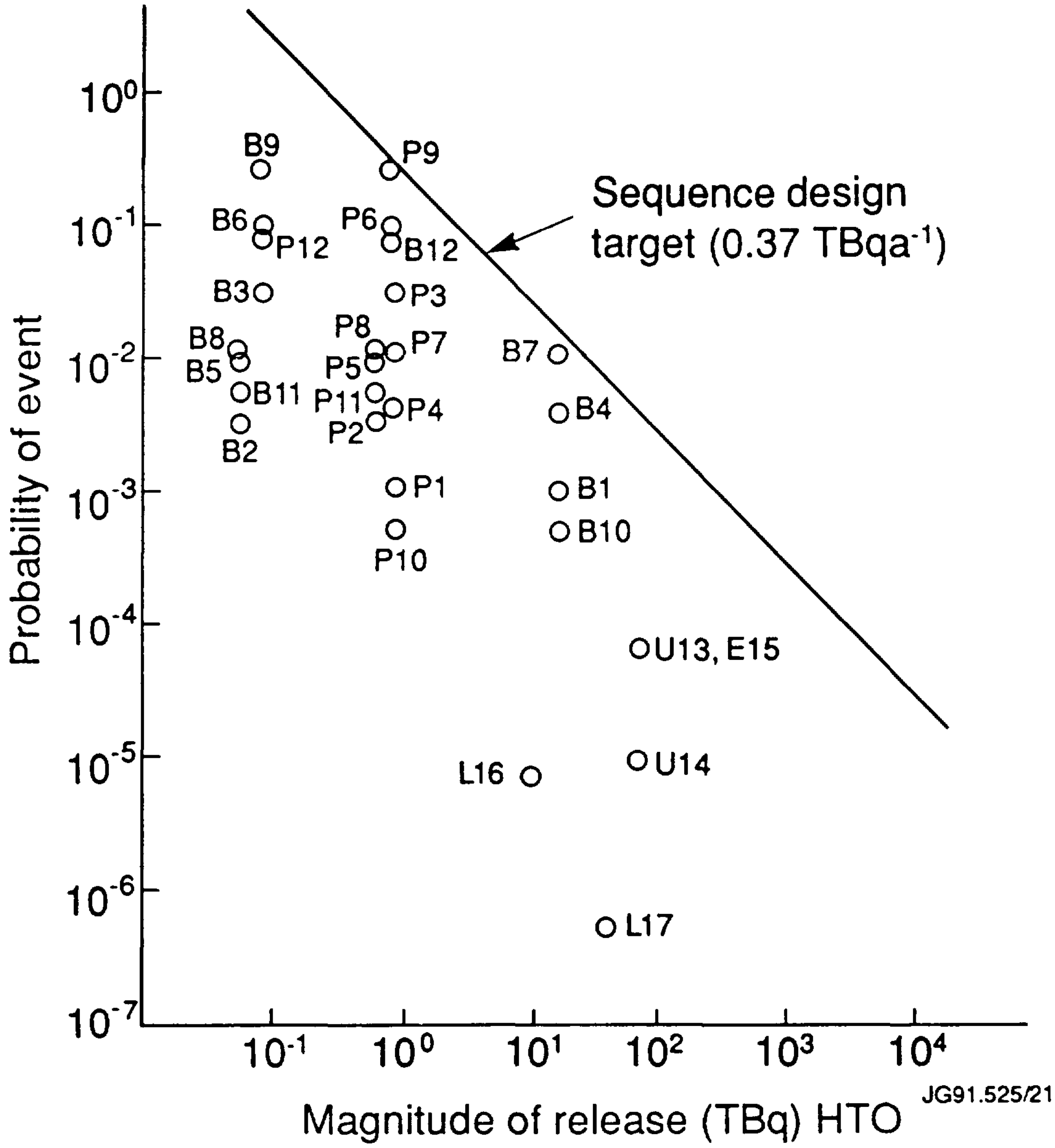


Fig 3: Probability versus Consequences Map

ANNEX

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