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MAGNET FAILURES AND HAZARDS TO THE PUBLIC

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Summary

The superconducting toroidal field coil system of a fusion reactor will have large amounts of energy stored both in its magnetic field and as enthalpy of the helium coolant. Magnet failure may take the form either of a quench, which should be regarded as an abnormal operating condition, or of a genuine accident. Failures of either class may act as initiators for accident sequences which localize and release the stored energy. Some such sequences lead to the release of tritium and activation products into the primary containment and provide a mechanism by which the containment may be breached. The release of radioactive material to the environment following such a breach would present a hazard to the public and it is vital, therefore, that the construction of the containment is such that the probability of such a breach is minimal.

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1. INTRODUCTION

The superconducting magnets conceived for fusion reactors represent a considerable increase in size, stored energy, reliability and operating time from existing superconducting magnet systems.

The scale of the magnet systems may be seen by reference to the STARFIRE reactor design (1), which has a smaller system than several previous designs. The toroidal field system is a twelve element array of D-shaped coils with a characteristic envelope radius of about 14 metres. The coils generate a field of 5.8 T at the 7 m plasma radius and a peak field of 11 T at the coils. The toroidal bore is about 13 m high by 8.5 m wide and the total stored energy is about 50 GJ. The design field is produced by a current of 24 kA per turn, whilst each coil has 705 turns and hence the total number of ampere-turns is about 2×10^8. Each coil has a cross-sectional area of about 2 m^2 and is a complex composite of superconductors, insulators, stabilizers, reinforcements, glues, etc interspaced with many cooling channels containing liquid or gaseous helium. Niobium-tin is used as the superconductor in the high field region (9-11 T) and niobium-titanium in the low field region. The coils are contained in a cryostat with high vacuum thermal insulation and inner and outer pressure vessels.

The high capital costs of fusion reactors will require that all reactor subsystems should have good availability. For instance, an outage of 3% for magnet components corresponds to one year down-time over a 30 year reactor life-time. Existing superconducting magnet systems have experienced a large number of failures due to hot spots, lead overheating, operator error, etc (2,3,4,5). The duty required of the superconducting magnets of a fusion reactor is particularly arduous owing to their size, shape, field, cyclic duty and radiation environment.

The large volume of fusion magnets, typically 1000 m^3, implies a large liquid helium capacity and a large energy associated with its enthalpy, whilst the high magnetic field results in large forces to be supported by the structure, as well as a high electromagnetic energy storage. Sudden thermalization of this energy following failures can in some circumstances cause damage to magnet parts and may even initiate accident sequences leading to the release of radioactive material.

Current fusion reactor design concepts assume that some kind of containment building will be used to minimize the consequences to the environment of the release of radioactive materials. The public will, therefore, only be endangered if an accident sequence leads to a breach of the containment.

A number of modes of magnet failure are identified and the mechanisms by which they can lead to serious accidents are considered. The hazards presented to the public are discussed.

2. MAGNET FAILURES

For the purposes of safety analysis a distinction is made between "abnormal operating conditions", which cause a temporary shutdown of the magnet system without damage, and "accident situations", which may result in permanent damage.

An abnormal operating condition is considered first, followed by a number of possible accident situations.

2.1 ABNORMAL OPERATING CONDITIONS

The quench, which is the best known superconducting magnet failure, is the only "abnormal operating condition" to occur.

A quench involves the sudden transition of a part of the superconductor to normal conductivity. The normal conducting zone then either propagates through the winding or remains stationary without the chance of a short-time recovery. The magnets will be designed for "cryogenic stability", which means that the heat associated with a local disturbance, even the formation of a normal conducting zone, can be transferred to the coolant, so that the zone disappears again within a short time. For this purpose the superconducting wire must be in very good thermal contact with the coolant.

The conditions for cryogenic stability are determined by the heat transfer to the helium (influenced by temperature, pressure, cooling channel dimensions, flow velocity, surface conditions, etc.), the maximum energy of possible disturbances and the amount of stabilizing normal conducting material (eg. copper or aluminium) in the conductor. Hence a quench can only be initiated if these conditions are disturbed by either sudden local heating, eg. caused by a sudden movement of a sufficiently large part of the winding and ac loss heating of this part due to the field change, or a lack of cooling, eg. caused by a sudden loss of helium, a blockage of cooling channels or the evaporation of helium following a vacuum breakdown.

The stored electromagnetic energy of the magnet should be discharged into external resistors in a period of typically a few tens of seconds, following the initiation of a quench. The design of the discharge circuits should be coordinated with that of the coils and power supplies to ensure that the system is not damaged by:

(i) heating of the winding;
(ii) high discharge voltage;
(iii) helium pressure increase due to evaporation;
(iv) asymmetric mechanical forces;
(v) inductive current increase in mutually coupled neighbouring coils.

If any such damage were to occur, it would constitute an "accident situation".

2.2 ACCIDENT SITUATIONS

2.2.1 Electrical Arcing

Electrical arcing is a frequent cause of superconducting magnet failure (4,5). Arcing may occur between the current leads or between a lead and a ground component, especially where the intermediate space is filled with helium vapour, which has a very low dielectric strength. It may also occur between turns, where the intervening insulation exhibits imperfections or has been damaged by overheating, overstressing or radiation.

In a fusion reactor environment the superconducting magnets are exposed to appreciable neutron and gamma fluxes. Such radiation fields are potentially capable of significantly reducing the unirradiated electrical breakdown potentials of helium (6). This effect favours the use of forced-flow cooling rather than pool boiling and may prove to be the limiting factor in the magnet shielding criteria rather than nuclear heating or chronic radiation damage as assumed in the design of UWMAK-III, STARFIRE, INTOR, FED, etc. If this is indeed so, then there may be insufficient space to install adequate shielding.

If organic materials are used as glues and spacers, hydrogen will be generated by radiolytic decomposition reactions. This hydrogen will remain frozen in place during normal operation of the magnet but it may migrate quickly into the helium coolant during a quench or accident. Parts per million of hydrogen in helium can reduce its breakdown strength by an order of magnitude (Penning effect (7)). This effect, combined with continuing ionization in the helium coolant, from residual radiation released by reactor activation products, may cause electrical breakdown with low internal voltages in the magnet, during an emergency dump. The use of inorganic insulators is to be preferred in this respect.

2.2.2 Electrical Shorts

Electrical shorts can be caused either by arcing or by contact between conductors. Both turn-to-turn and turn-to-ground shorts can occur. Turn-to-ground shorts are less likely to happen, and a single turn-to-ground short is not serious if the coil is otherwise ungrounded or grounded only through a fuse.

Contact shorts between turns have little effect on a superconducting magnet during steady-state operation. However, during the charging or discharging of the magnet, the shorted turn can have a large current induced in it by the change in flux linking the magnet. In this way the turn can be driven to the normal state, which can lead to overheating of the conductor.

2.2.3 Current Leads

Probably current leads have been responsible for more superconducting magnet failures than any other cause. Each lead generally consists of two parts: a normal lead from room temperature to liquid helium temperature, and a superconducting lead from the normal lead to the magnet itself. The leads experience the magnetic field of the magnet and so undergo a force, but their location makes them difficult to support. Because of their location outside the coil, they are also subject to excess heat input and hence arcing.

Failure of a current lead means a discontinuity of current, with all the safety consequences that entails. There will be high voltages and possible arcing, both at the lead that failed and throughout the magnet system. Large transient forces and eddy current heating are likely. High thermal stresses, overpressurization and magnet destruction may occur.

2.2.4 Conductor Joints

Conductor joints are always potentially a safety concern in a superconducting magnet. They can be in danger of mechanical failure, as well as serving as a resistive heat input; at least they are mechanically an irregularity in the coil structure.

Intra-coil joints, made during coil winding, include joints between different grades of conductor. Inter-coil joints, made during coil assembly, include joints between coils or between pre-assembled portions of coils, eg. pancakes. Intra-coil joints can be made under almost ideal conditions in the winding line, with whatever space is needed for forming and inspecting the joints; while inter-coil joints must be made and inspected in the process of assembling the coils.

A poorly bonded joint or a joint in which one side protrudes out of the coil and can be sheared off when the coil is energized can lead to a current discontinuity. A joint with good mechanical strength but high electrical resistance causes heating and may produce a magnet quench.

2.2.5 Multiple Current Arcing

The arcs previously considered carry the nominal operating current of the magnet and may be termed "single current arcs". More severe damage is caused if, after a single conductor rupture within the winding, adjacent conductors rupture due to the thermalization of energy in the first arc. Each additional rupture of a conductor adds to the current flowing in the arc and the event is therefore termed a "multiple current arc".

Initially the arc is magnetically driven towards the zero-field point in the winding cross-section, acting like an arc welding beam on the conductors in between. Although not all the conductors are immediately hit by the arc, the increasing pressure of its metal and helium plasma distributes the thermalized energy more isotropically and the remaining conductors rupture under the influence of the further heating and added internal pressure. Arendt and Komarek (8) estimated that for UWMAK-III, half the total ampere-turns of the magnet would be carried in the arc after ~ 2s, yielding an arc power of ~ 1 GW, a burnout time of ~ 7s and the vaporization of between 500 and 1000 kg of conductor material.

2.2.6 Stationary Normal Region of Conductor

In a cryostable magnet, a stationary normal zone can arise from a failure of cooling of that region, due to either a massive blockage of the cooling passages to the normal region or the liquid level falling below the conductor region. In either case the region is characterized by good boiling at each end preventing its further growth, but poor cooling within.

The consequences of the stationary normal region depend on the temperature difference which develops. If the temperature difference is hundreds of Kelvin, the electrical insulation can be damaged, permitting turn-to-turn and turn-to-ground electrical shorts, and possibly an overpressurization of the helium vessel. For intermediate temperature differences, thermal stresses can result leading to possible mechanical damage, structure weakening, or insulation destruction.

An additional possibility for the development of a stable normal zone in a toroidal field coil was predicted by Turner (9), whose thermal analysis of a conductor carrying an overcurrent in a nonuniform magnetic field demonstrated that a stable normal zone can develop in the high field region. Such a zone would be cause for operational rather than safety concern, provided that the helium vapourized by Joule heating in the resistive region continued to be adequately replenished. Failure to replenish the helium would lead to continued heating and consequential damage.

2.2.7 Cryostat Rupture and Vacuum Failure

Obviously a cryostat should not rupture; but a cryostat rupture is conceivable through overpressurization, excessive mechanical stress, penetration by an object, burning by an arc or the shearing off of tubing to the cryostat. Cryostat rupture and vacuum failure are interrelated; either can cause the other.

3. ACCIDENTS INITIATED BY MAGNET FAILURE

Energy is stored both as magnetic field energy and enthalpy of the liquid helium or supercritical helium used to cool the magnet. The energy stored in the magnet systems represents an upper limit to the amount of work available from a magnet accident. The toroidal magnetic field system of STARFIRE (1) stores about 50 GJ magnetically and contains about 250 000 litres of liquid helium. The difference in enthalpy between 4.2 and 300 K of 250 000 litres of helium is 84 GJ. These energies are not directly comparable as very different physical mechanisms are involved. One of the main aims of detailed investigations of accident sequences is to assess the efficiency with which the stored energy is localized.

3.1 ACCIDENTS DRIVEN BY THE MAGNETIC FIELD ENERGY

Magnet failures of the types considered in section 2 can initiate accident sequences in which the energy of the magnetic field is released in such a way that a hazard may be presented to the public. Three mechanisms by which the release of the stored energy can result in serious damage are identified:

(i) missile generation;
(ii) arcing;
(iii) collapse of support structure.

The consequences of each are now considered in turn.

3.1.1 Missile Generation

Missiles may be generated if a current carrying part of the winding becomes loose and is accelerated radially outwards in the background field of the other coils by the Lorentz force. Arendt and Komarek (8) estimated the kinetic energies of missiles of various sizes and concluded that the scaling is such that small pieces of conductor that might break off during the burning of a multiple-current arc will not constitute hazards in addition to those of the arc's plasma beam. For a missile to have a high energy, the winding must rupture at two places at least 1 m apart. Even then, the missile's kinetic energy is less than the energy of the multiple-current arcs. Arendt and Komarek concluded that the occurence of missiles is hypothetical since it would require the occurence of multiple-current arcing at two places simultaneously. Another possibility, however, might be the rupture of the winding at one point by multiple-current arcing, followed by the breaking away of a section under the influence of the bursting forces.

A similar analysis was performed by Schneider and Caretta (10) for the FINTOR magnets. Their results indicate that missiles of about 20 kg weight may reach velocities of the order of 100 ms^{-1}. The assumptions adopted for these calculations are such that the velocities obtained constitute upper bounds to those expected in real situations.

3.1.2 Electrical Arcing

An electrical arc may wander under the influence of the prevailing magnetic field and can damage any reactor components which it strikes.

Arendt and Komarek (8) made an assessment of the damage potential of arcs, based on the UWMAK-III reactor design, which has 18 toroidal field coils providing a total stored energy of 108 GJ at a current of 10 kA.

An arc voltage of 200 volts was assumed, which corresponds to a dissipation of 2 MW in a single current arc. The magnet winding was assumed to be driven normal within about 20 s by either an external quench triggering mechanism, the loss of vacuum due to the arc burning through the vacuum tank or a loss of liquid helium. The time-averaged resistivity of the stabilizing and reinforcing materials that cover ~ 60% of the winding cross-section was estimated to be 2×10^{-9} Ω-m, which corresponds to a Joule dissipation in the winding of 20 MW. Thus the energy is dissipated with increasing power in the winding itself at a faster rate than in the arc. It was concluded that single current arcing at a fusion reactor magnet would dissipate some tenths of the stored energy in an uncontrolled way and lead to moderate damage in the region of the arc. The damaging effects would not be enhanced by thermal or mechanical transients due to the long time scale of the event. About 100 kg of copper (or 50 kg of aluminium) would be evaporated and deposited on surfaces in the vicinity of the arc. If a stable single current arc were to burn in the leads, the magnet winding would probably not be affected and could be operated after replacement of the damaged parts.

In the case of multiple-current arcs, the consequences are much more severe. The entire magnet must be replaced with no conceivable possibility of repair. Burning through the magnet cryostat, the plasma from the arc may damage adjacent elements of the fusion reactor such as the divertor, neutral beam injector and refuelling device. The possibility of uncontrolled spilling of tritium from these elements into the reactor containment cannot be excluded.

The analysis quoted infers that the 18 coils each have separate electrical circuits so that they may be discharged independently. A series-connection of coils would, however, allow the total stored energy of the coil system to reach the faulty circuit. In this situation a significantly greater amount of energy would be dissipated in the arc.

In principle an arc provides sufficient thermal power to vapourize radioactive components of the reactor. During the current decay in a faulty magnet, however, the remaining background field of other torus magnets will drive the arc away from the fusion plasma chamber and the blanket.

3.1.3 Collapse of Support Structure

If the TF coils of a tokamak are perfectly aligned, and all carrying the same current, they exert only a centering force on each other, which is withstood by the central support cylinder. The misalignment of the coils expected in assembly introduces out-of-plane forces on each coil, but these forces are smaller than the out-of-plane forces due to the pulsed poloidal field. However, a large current imbalance among the TF coils would lead to very large out-of-plane forces.

If, despite the differences in magnitudes of the coil currents, their directions are unchanged, the radial component of the body force on the coil will continue to be towards the centre of the machine, while the out-of-plane forces will tend to pull the coils together like an accordion. If, however, the current in a coil is reversed, as might happen if it has a short circuit while the system is being energized, then the radial component of the body force will be outwards from the centre of the machine, while the out-of-plane forces will tend to push it away from the other coils.

The structure may be subjected to large thermal strain during a magnet accident, following rapid local cooling and/or heating resulting from the spillage of helium coolant and the thermalization of the magnetic stored energy.

It is hard to imagine a worse accident in a tokamak reactor than the TF coils collapsing together. Cryostat rupture, vacuum failure and electrical discontinuity would all result, with all their subsequent dangers.

The possibility that the structure will collapse under its normal cyclic loading cannot be excluded. A valid assessment of the probability of such a failure would require data which is not currently available, on the failure rates of the structural materials at low temperatures or preferably of components of the types envisaged.

3.2 ACCIDENTS DRIVEN BY THE ENTHALPY OF HELIUM

There are various possible ways that helium can be released to the primary containment. Abnormal heat generation in the magnet or heat leakage in the insulation system leading to rapid boiling of helium is one possibility. If the vapour relief system is unable to cope with the pressure rise, then a pipe may break or a dewar may even rupture. The dewar can also be burned through by an electrical arc or ruptured by external forces such as those arising from an earthquake. If the dewar ruptures, the helium at first flashes to a two-phase mixture.

A small amount of heat transferred either from the magnet or from the containment structure would superheat the helium.

There is a potential for pressurization of a Tokamak reactor containment due to the release of the helium in the superconducting magnet. Missiles may also be accelerated by the helium pressure.

3.2.1 Containment Pressurization

An assessment of the potential for containment pressurization by helium release was made by Okrent et al (11), based on the preliminary UWMAK-1 design (12) and considering the entire magnet system. The reactor is completely enclosed by the primary containment and the total magnetic energy storage is 350 GJ. The toroidal, divertor and transformer magnets are housed inside double walled, stainless steel dewars. The inner vessel is filled with helium which completely submerges the magnet. The 20 cm vacuum gap between the inner and outer walls is filled with super-insulation material. The heat generated by the magnet during the normal power cycle will boil off part of the liquid helium. The helium vapour is led away from the dewar through the vent pipe. The vent pipe runs through the primary containment walls and feeds helium vapour into the liquefying system. The liquid is then fed into a 200 000 litre storage tank. The cycle is completed when the liquid helium is distributed back to the magnet dewars. The total helium inventory in the proposed 5 000 MW(th) fusion power plant is 450 000 litres with 250 000 litres within the primary containment boundary. In calculating the temperature and pressure inside the containment following a loss-of-helium accident, 250 000 litres of helium, the total volume within the containment, must be assumed to be released. The free volume of the containment is 1.6×10^5 m^3.

Okrent et al. estimated the conditions within the containment for three cases. In the first case one third of the energy stored in the magnet was assumed to be converted into thermal energy by joule heating and in turn heated the helium. For this case, the peak pressure inside the containment was found to be 4.1 atmospheres, and the peak temperature 1027 K. This case should represent a very conservative estimate for the parameters and conditions postulated. For the second and third cases, instead of assuming the fractional release of magnetic energy, a maximum final temperature was assumed. For final temperatures of 300 K and 500 K, the pressures estimated were 1.2 and 2.0 atmospheres, respectively. It is clear from these results that the heat transfer mode could play an important role in the containment pressurization.

Jones and Merrill (13) modelled the transient temperature and pressure fluctuations in the containment building of FED (14), following a TF magnet failure. A break in the magnet coolant inlet line was assumed to occur simultaneously with a failure of the magnetic energy discharge system, which is the condition believed to result in the worst possible pressurization of the containment. The escape of liquid helium into the containment atmosphere was found to decrease the containment temperature and pressure continually, until a minimum pressure of 0.84 atmospheres was reached after 150 s. Subsequently, the containment atmosphere continued to heat-up as a result of natural convective heat transfer between the atmosphere and the containment walls. This gradual temperature rise produced a containment overpressurization of 0.45 atmospheres after 1 hour.

3.2.2 Missile Generation

Failure of the liquid helium containment could in principle involve the generation of missiles, which would threaten the integrity of other reactor components and the containment. No assessment of these effects has been found in the literature.

4. HAZARDS TO THE PUBLIC

Magnet accidents are considered to fall into one of three categories:

(i) The magnet would be damaged so that replacement or repair would be necessary, but no radioactivity would be released. Although the reactor could not operate, safety would not be an issue.

(ii) The magnet would fail with some radioactivity released within the containment but the containment would not be breached. This would be analogous to a LWR core damage accident.

(iii) The magnet would fail with a breach of the containment and the release of some radioactive material to the environment.

It is accidents falling into category (iii) which present a hazard to the public. Thus it is necessary to identify the sources of radioactivity which are vulnerable to release by accidents of the types discussed in section 3. The radioactive inventory is in the form of tritium and activation products. The accident potential of each is examined and then the mechanisms by which the containment may be breached are discussed.

4.1 RELEASE OF TRITIUM TO THE CONTAINMENT

The tritium which can be released by a magnet accident is assumed to be that which is held in those components sited in the reactor hall. These components are now considered in turn:

(i) Vacuum pumps contribute significantly to the vulnerable tritium inventory and in the case of the STARFIRE design it is estimated that they may hold ~ 100 grams. Tritium may be released from the pumping surfaces if air (or any other gas) enters the pump chambers or liquid helium cooling to the pumps is lost. The tritium will then be released to the reactor hall if the vacuum seal is lost. Most of the major magnet accidents described could, in principle, cause such a release.

(ii) Fuel injectors. The tritium inventory associated with fuelling will depend on the system employed. In the case of gas puffing, however, which has been assumed in recent reactor designs such as STARFIRE, the inventory is very small.

(iii) Blanket System. The principal source of tritium lies in the blanket modules. For STARFIRE (solid breeder) the inventory is of order 10 kg - approximately 90% of the total inventory. It is claimed that the probability of significant release is low, and the fraction released even under a violent accident would be small. The loss of coolant, however, could result in a temperature rise in the blanket that would cause an increase in tritium release. It is quite possible that a magnet accident would damage both the blanket and cooling system. The tritium inventory in a blanket employing a liquid breeder is more vulnerable since it would be possible for any liquid to drain, at least partially, from the reactor. However, the potential hazard of such events is the principal reason for the selection of $LiAlO_2$ in the STARFIRE design and in the strong current interest in solid breeding materials.

Although some specific reactor studies claim that only a small part of the tritium held within the reactor containment is vulnerable, this is in general not proven and for the purposes of this study, which examines accidents in the generic sense, it must be assumed that the total "vulnerable" tritium inventory of typically 10 kg can be released.

4.2 RELEASE OF ACTIVATION PRODUCTS TO THE CONTAINMENT

While tritium is the only radioactive material intrinsic to a D-T fuelled fusion reactor, other materials will be activated by the reaction-product neutrons. Fluids, such as the coolant and the reactor cover gas, which may contain relatively small quantities of radioactivity, are particularly vulnerable to release.

The structural components of the reactor are much less vulnerable as the release of the radioactivity contained in these materials requires melting and aerosol or vapour transport to the external environment. It is this material, however, which contains 99% of the activation product inventory. Some control of the radioactive inventory can be achieved by a suitable choice of materials.

The choice of reactor cover gas will also largely depend on its activation products. If air were used it would become activated due to the production of ^{14}C, ^{16}N and ^{41}Ar. Carbon dioxide is preferred for STARFIRE (1) principally because its radioactivity concentration decays in a few minutes, whereas that of the other candidate, nitrogen, takes several hours.

4.3 BREACH OF CONTAINMENT

The impact of missiles and the application of excessive pressure can both cause a breach of the containment.

4.3.1 Missile Impact

Missiles may be generated by the influence of Lorentz forces on a section of broken magnet, as described in section 3.1.1.

In discussing the impact of such missiles, Schneider and Caretta (10) estimate that in a baryte type concrete structure of density 3.5×10^3 kg/m^3, missiles have the potential to penetrate 2.5 times their length.

Arendt and Komarek (8) suggest that while the kinetic energy of a missile may be large it is less than the values assumed for aeroplane crashes into the containment structure of fission power stations. Since fusion plants will also have to be designed to withstand aeroplane crashes, the magnetic generation of missiles should not lead to a breach of containment.

4.3.2 Pressurization

The primary containment of UWMAK-1 (12) is constructed of reinforced concrete clad with steel. To minimize the diffusion of the tritium, the containment is to be run at a vacuum. Its design differential pressure load is given as 1.0 atmosphere in the inward direction and 0.68 atmospheres in the outward direction. The free volume is 1.6 x 10^5 m^3.

The containment may be pressurized by the release of helium, as described in section 3.2.1. Although it was clear from Okrent's results that the level of pressurization is strongly influenced by the heat transfer mode, it is apparent that there is a real possibility of the design pressure of the containment, 1.68 atmospheres, being exceeded.

The results of Jones and Merrill indicate that even if it is intended to run the containment at atmospheric pressure, it will need to be designed to withstand inward as well as outward pressures.

Pressurization may also result from lithium-concrete reactions and this possibility must be considered for reactors which use liquid lithium, such as UWMAK-1. While the steel liner on the concrete serves to reduce the opportunity for a lithium spill to contact the concrete containment, the possibility that there will be a partial breach of this cladding material also exists. For example, thermal stresses induced by lithium at 800 K, the coolant temperature in UWMAK-1, on a 300 K steel liner could lead to buckling and the possibility of local failure of the liner. Similarly, seismic events might lead to a lithium spill and failure of the steel liner. A severe magnet accident would also have the potential to initiate such an accident.

Lithium attacks concrete, leading to the release of water and its subsequent reaction to form hydrogen and other products. Okrent et al (11) estimated that, depending on the lithium pool temperature, in excess of 1 TJ of energy may be extracted for each 1% of the UWMAK-1 lithium inventory consumed. The pressure may reach the design level of the primary containment, 1.68 atmospheres, in about 1 hour even if only about 1% of the concrete floor area is active towards lithium. In fact the potential pressures are sufficiently high that overpressurization of the primary containment is a realistic possibility even after reaction product cooling on heat sinks to 400 K.

The containment may also be subjected to overpressure following a loss of coolant accident. STARFIRE for example has the steam generators located within the reactor building for safety reasons, ie. fewer penetrations and a larger building volume. The volume of the containment is 2.55 x $10^5 m^3$ and that of each of the two primary water coolant loops is 250 m^3. It is estimated (1) that if a break occurs in one of the two loops then its entire inventory will escape into the reactor building within 20 to 200 s, causing a differential pressure on the containment walls of 0.68 to 1.0 atmospheres.

5. CONCLUSIONS

Magnet failures do not present a direct hazard to the public but could initiate sequences of events which lead to the release of radioactive material into the containment and/or a breach of the containment. By this indirect route a magnet failure may either contribute towards or be wholly responsible for a release of radioactivity to the environment, thereby placing the public at some risk.

A number of events have been described which could in principle cause the release of radioactive material. As part of the preparation of the detailed design of a fusion reactor, a study of its accident potential will be required which will involve a first stage probabilistic safety assessment. A full probabilistic risk analysis of the type currently made for fission reactors is not possible in the short term, however, owing to a shortage of data on both the properties of materials operating in the conditions expected and the failure rates of components particular to fusion systems.

The need to avoid catastrophic damage to the reactor itself and to achieve the necessary availability will require the development of a sophisticated magnet protection scheme. The diverse natures of possible faults will require that the scheme can identify each type of fault and select the appropriate sequence of actions.

The public will only be put at risk if the containment is breached. A further study may therefore also be warranted to determine whether a containment building can be constructed economically, which will withstand all conceivable accidents. Its design will be influenced by the need to withstand both inward and outward pressures arising not only directly from the release of fluids but also from the internal effects of fire, explosion, electrical arcing, chemical reaction and missile impact and external events such as earthquakes and aircraft crashes.

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