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MAGNET OPERATING EXPERIENCE REVIEW FOR FUSION APPLICATIONS

L. C. Cadwallader

EG&G Idaho

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ABSTRACT

This report presents a review of magnet operating experiences for normal-conducting and superconducting magnets from fusion, particle accelerator, medical technology, and magnetohydrodynamics research areas. Safety relevant magnet operating experiences are presented to provide feedback on field performance of existing designs and to point out the operational safety concerns. Quantitative estimates of magnet component failure rates and accident event frequencies are also presented, based on field experience and on performance of similar components in other industries.

EXECUTIVE SUMMARY

This report is a continuation of magnet operating experience summaries conducted in the 1980's. Several fusion researchers and designers have already pooled pertinent magnet failure events into several documents. This report cites these past studies, provides excerpts from lesser known studies, and adds information on recent events and on operating experiences for medical technology magnetic resonance imaging magnets. Review of earlier studies may be valuable for evaluation of design alternatives or for detailed examination of magnet failure events.

Past work, while thorough, has only supported fusion risk and safety analysis efforts in identifying failure events and failure mechanisms. To determine probabilities of component failures and catastrophic events, more information would be needed about all of the cited magnet facilities, such as the number of magnets built and operated, the time frame of operation, and the operating modes employed. Since such information is not readily available, this report presents suggested magnet component order-of-magnitude failure rates for normal-conducting and superconducting magnets. Magnet support systems, such as electrical power and cooling systems, will be treated separately. Magnet component failure rates can support safety analysis, risk assessment, design failure analyses, and facility availability studies. Accident initiating event frequencies have been collected from the literature and presented here for use as guidance in initial risk or safety analyses.

Table S-1 gives a summary of operating experience information derived from existing superconducting and normal-conducting magnets, broken down by initiating event (IE) categories; that is, the initial event that leads to a facility being in an off-normal condition that could threaten facility workers or the general public. To evaluate these events, order-of- magnitude failure rates, assigned mainly from industrial experience with similar components, have been set in Chapter 4. The initiating event frequencies of occurrence used in other studies are reported in Chapter 5.

TABLE S-1. SUMMARY OF MAGNET OPERATING EXPERIENCES FOR INITIATING EVENTS

Superconducting Magnets

Loose ferrous objects in the magnetic field	An IE, could puncture a vacuum shield
Electric arcs Damaged electrical insulation Magnet turn-to-turn short circuit Electric arc between magnet leads Pancake-to-pancake short circuits due to foreign material intrusion Diagnostic lead short circuit	Chapter 5 references 5-4 to 5-8 recognize arc events
Electrical fires Power supply short circuiting Helium compressor motor short circuit	This IE should be treated
Magnet quenches Magnet quenches induced from plasma disruptions	This event is treated as IE
Helium vent piping failures	This event could help propagate an accident
Insulating vacuum jacket rupture or breach Liquid helium boil and overpressure release from gas recovery system Cracked welds on magnet cases, leading to helium admission to vacuum insulation space Vacuum thermal shield leaks	This IE is treated in reference 5-6 as Loss of Insulating Vacuum
Cryogenic helium leaks	potential IE, Loss of Coolant
Bolt loosening from vibration and thermal cycling	possible IE if breaches system or becomes a missile
Human left in the experiment vault just prior to fusion pulse operations	Personnel hazard only
Unsoldered magnet inter-turn splices Niobium-Titanium superconductor strand breakage	IE, Rupture of a winding
Poor cryogenic system performance to keep magnets cool	--
Magnet training	--

TABLE S-1. SUMMARY OF MAGNET OPERATING EXPERIENCES FOR INITIATING EVENTS (Continued)

Normal-conducting Magnets	
Electrical fires Industrial fires	This IE must be treated
Loss of cooling water into the building Failure to provide adequate cooling water Magnet overheating by connection to incorrect power supply Magnet overheating due to inadvertent switch of cooling water lines	This IE is treated under Loss of Coolant Accident
Loss of cooling water flow Foreign material intrusion in cooling water	This IE is called Loss of Flow Accident
Loose wrench in the magnetic field causing a short circuit in buswork	This IE should be treated
Short circuits due to improper epoxy insulation Electrical power transients causing magnet short circuits Inter-turn insulation failure Electric arc because of ground fault	Short circuits and arcs are IEs treated by safety work
Plasma electromagnetic forces generated damaging current in an unused PF coil	This IE needs further treatment
Bolt loosening from vibration and thermal cycling	possible IE if breaches system or becomes a missile
Sabotage (two accelerator events during US-Vietnam Conflict)	--
Cooling water temperature fluctuations	--
Support system instrumentation faults - flowmeters	--

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I wish to thank several people who helped me with this report. Steve Piet and Doug Holland offered valuable advice, editing, suggestions, and extra time to complete the report when I found out how much information was actually available. Steve Herring helped me understand magnet design through numerous sketches and he gave me a great deal of technical support while I wrote the chapter on failure rates. Rolf Buende kindly sent me the proceedings of the Garching workshop on fusion device reliability. Also, Bruce Montgomery and Dick Thome of MIT served as outside reviewers. Since they are subject matter experts, and since they have the largest magnet failure event data base in the US, their comments were very valuable.

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CONTENTS (Continued)

NOMENCLATURE

AGS	Alternating Gradient Synchrotron
ASME	American Society of Mechanical Engineers
cm	centimeter
DOE	United States Department of Energy
FMEA	Failure Modes and Effects Analysis
FTU	Frascatti Tokamak Upgrade
IE	Initiating event
IEEE	Institute of Electrical and Electronics Engineers
ITER	International Thermonuclear Experimental Reactor
IV	Intravenous
JET	Joint European Torus
JT-60	Japan Torus - 60
KfK	Kernforschungszentrum Karlsruhe, in Germany
kg	kilogram
kW	kiloWatt
LCT	Large Coil Task
LN2	Liquid nitrogen
m	meter
MHD	Magnetohydrodynamic
MPa	MegaPascal
MRI	Magnetic Resonance Imaging
NET	Next European Torus
OH	Ontario Hydro
PF	Poloidal field
RFX	Reverse Field Experiment
T	Tesla
TESPE	Toroidal Energy Storage Experiment, in Germany
TEXT	Texas Tokamak
TF	Toroidal field
TFTR	Tokamak Fusion Test Reactor
TMX-U	Tandem Mirror Experiment - Upgrade
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States
Vdc	direct current voltage

MAGNET OPERATING EXPERIENCE REVIEW FOR FUSION APPLICATIONS

1. Introduction

This report outlines magnet operating experiences for use by fusion magnet designers and safety analysts. I mention several improvements in designs and significant problems originating from existing designs. I also discuss operating experiences from magnets in particle accelerators, magnetohydrodynamics, and medical technology applications. While magnets used in medicine are not exposed to the harsh operating environment of fusion magnets, there are still some small issues of interest to fusion magnet designers, so I reviewed medical magnet operations. Examination of operating experience from a variety magnet uses is also helpful to safety analysts because the broad inclusion of magnet events from these other research and technology fields helps ensure a level of practical completeness in initiating event identification.

Magnet reliability is a strong concern for future fusion devices. Each of the three largest fusion experiments in the world, the Tokamak Fusion Test Reactor, the Japan Torus - 60, and the Joint European Torus, have suffered from magnet coolant water leaks that were severe enough to halt experiment operations for repairs.[1-1,1-2,1-3] One case even resulted in tokamak disassembly to replace the coil with a spare.[1-2] Forced experiment outages for repairs to any magnet type, due to any number of reasons, will become more cumbersome when remote maintenance must be relied on because of high radiation fields around the tokamak machine. Magnet replacement would cost a great deal in time and funds.

There have been several reports on fusion and accelerator magnet reliability and operating experiences to date.[1-4,1-5,1-6,1-7,1-8] Readers seeking detailed knowledge of magnet failure events to either evaluate design alternatives or postulate magnet failure events might need to review the past reports. This report does not reproduce the findings of all of these past reports, but instead augments those reports for usefulness to designers and safety analysts. This report also gives recommended magnet component failure rates from analogous components in other industries, and some limited statistical information from present fusion magnet operating experience. These data support design reliability analysis as a check or review of the design, facility safety or risk analysis, or fusion availability analysis.

The report can be used to gather a basic understanding of the typical operations problems encountered in magnet operations, not just the major accident events or design basis events that are discussed in safety literature. In Chapter 2, I discuss superconducting magnet operations and the problems encountered in accelerators, medical technology magnets, and fusion magnets. Chapter 3 contains several reviews of water and cryogenic cooled normal-conducting magnet system operations. The end of each of these chapters has a summary table on the typical problems encountered for each type of magnet system. Information from these two chapters supports the magnet component failure rate determinations I give in Chapter 4. The initiating events and their frequencies of occurrence presented in Chapter 5 are taken from the literature, and can be qualitatively understood from the summary tables in Chapters 2 and 3.

Chapter 1. References

1-1. K. Arakawa et al., "JT-60 Operational Experience and Trouble Analysis," Proceedings of the IEEE Thirteenth Symposium on Fusion Engineering, Volume 2, October 2-6, 1989, Knoxville, TN, pages 1072-75.

1-2. J. R. Last et al., "JET TF coil fault - detection, diagnosis and prevention," Fusion Technology 1990, Proceedings of the 16th Symposium on Fusion Technology, September 3-7, 1990, London, UK, pages 1609-1613.

1-3. G. Gettelfinger et al., "Oil as an Alternative Coolant for Use in the TFTR Toroidal Field Coils," Proceedings of the IEEE Thirteenth Symposium on Fusion Engineering, Volume 2, October 2-6, 1989, Knoxville, TN, pages 1181-85.

1-4. J. Powell, et al., Aspects of Safety and Reliability for Fusion Magnet Systems, First Annual Report, BNL-50542, Brookhaven National Laboratory, January 1976.

1-5. S. Hsieh et al., "A Survey of Failure Experience in Existing Superconducting Magnet Systems and its Relevance to Fusion Power Reactors," IEEE Transactions on Magnetics, MAG-13, January 1977, pages 90-93.

1-6. J. B. Czirr and R. J. Thome, Experience with Magnetic Accidents, Minority Enterprise Service Associates (MESA) Corporation, Orem, Utah, March 7, 1985.

1-7. R. J. Thome et al., "Survey of Selected Magnet Failures and Accidents," Fusion Technology, 10, November 1986, pages 1216-1221.

1-8. D. B. Montgomery, "Review of Fusion System Magnet Problems," Proceedings of the IEEE Thirteenth Symposium on Fusion Engineering, Volume 1, October 2-6, 1989, Knoxville, TN, pages 27-31.

2. Superconducting Magnet Operating Experiences

This chapter discusses operating experiences for superconducting magnets from the medical technology field, particle accelerators, and fusion devices. Since the medical nuclear magnetic resonance imaging (MRI) magnets do not operate under the same conditions as fusion magnets, only some notable MRI events will be discussed. Next, notable events and design fixes for accelerator and fusion magnets are discussed.

2.1 MRI magnet experiences

Table 2-1 gives brief explanations of MRI magnet events acquired through the Freedom of Information Act from the Food and Drug Administration's data bank on devices[2-1]. The data sort is from 1981 to 1991, the time span of MRI activity. Magnet manufacturers are not delineated here. Also, the numerous events related to MRI patient problems, such as radiofrequency burn injuries, are not germane to this report and are not given here. If not for the seriousness of the injuries to patients, some of these events could be considered humorous because of the hospital personnel struggling to become aware of the forces generated by high magnetic fields.

An important thing to remember is that these events show how unusual or strange operating experiences can become. Reviewing the table shows that most of the MRI events deal with unsecured ferrous objects in the magnetic field, either by personnel unfamiliar with the precautions needed around high field magnets or by persons simply not heeding warning signs. Several events are due to magnetic field effects on equipment in the rooms, light fixtures, mirrors, and cable tray bolts. The event of unauthorized worker entry is illuminating, since it shows the nearly total disregard some workers have for safe practices in the workplace. It is important to note that most of these magnets are only in the 0.5 to 1.5 Tesla field strength range, and that fusion magnets generally have much higher field strengths. Thus, the severity of magnetic field effects and the volume affected by stray fields will be much greater for fusion experiments. Other MRI events of interest to us are the magnet quenches where the helium was not correctly vented away. This problem appeared in

TABLE 2-1. MAGNETIC RESONANCE IMAGING (MRI) MAGNET EVENTS

Event Date	Description of the Event
March 26, 1986	A patient positioning handwheel handle for the patient table became loose and flew into the magnet bore. The patient was not struck. Engineers redesigned the handwheel.
June 5, 1986	The magnetic field drew part of a forklift into the magnet while the device was being worked on for installation. A workman was injured. While the magnet was being set up in a semi-trailer as a mobile unit, the two steel tines of an approaching forklift (about 36 kg each) dislodged and struck the workman who was in the magnet bore, throwing him about 4.5 m. The doctor had to remove his stethoscope to assist the workman, and a paramedic's scissors flew out of his hands when he tried to cut the workman's trousers open to render medical attention. The workman suffered multiple broken bones and needed a metal plate placed in his arm to recover its use.
August 6, 1986	The patient handling cradle latch release rod became unscrewed from its hydraulic piston due to hydraulic pressure. The rod bounced off a 'demonstration patient' and hydraulic oil sprayed on the person. The piston has been redesigned and modifications are in progress to prevent recurrence.
November 19, 1986	A patient in a full body cast was being scanned. The patient had a fluid-filled head positioner in use on the scan cradle. When the scan began, an arc jumped from the metal head positioner frame to the patient's forehead and to the magnet body coil. The patient was not injured.

TABLE 2-1. MAGNETIC RESONANCE IMAGING (MRI) MAGNET EVENTS (Continued)

Event Date	Description of the Event
July 9, 1987	A ferrous oxygen bottle was carried into the scan room, was drawn to the magnet and lodged in the magnet bore. The 0.6-T magnet's quench switch did not work correctly when used to shut off the field for bottle removal. The patient was injured.
September 23, 1987	A workman came into the MRI control room to perform some work in the magnet room. He was denied access by the MRI operator, since the magnet was in operation. The workman then went to the hospital office, obtained a key to the back door of the room. The back door was clearly marked that a magnet was in the room (in english, arabic, and hebrew). The workman entered the room and a ferrous tool was pulled from his hand. The tool struck the back plate of the magnet, shattering a plexiglas cover. A piece of that plexiglas cut the patient being scanned.
January 13, 1988	A patient with an implanted insulin infusion pump was being scanned. The magnetic field moved the infusion pump. The patient was removed from the MRI machine, but the pump remained non-functional. The device is clearly marked that persons with electrical implants must not be scanned.
November 11, 1988	During a magnet quench, the helium venting system failed and helium began venting into the scan room. The operator hurt his back while evacuating the patient.

TABLE 2-1. MAGNETIC RESONANCE IMAGING (MRI) MAGNET EVENTS (Continued)

Event Date	Description of the Event
November 29, 1988	A patient in traction was brought into the scan room. When the technician attempted to move these traction weights through the magnet bore, they were attracted to the magnet body. The technician's hand was injured.
January 1, 1989	During a magnet quench, the venting system failed, causing helium to fill the scan room. The patient bumped his knee while quickly evacuating the scan room. The vent pipe had separated from the magnet body, causing a helium cloud to fill the room.
February 24, 1989	During a magnet quench, the helium vent system failed and vented the gas into the scan room. The room pressure quickly increased, causing the scan room door to stick closed. The operator broke out a window between the scan room and control room to gain access to the scan room for patient evacuation.
June 7, 1989	The cradle pad on the patient handling device caught fire because the operator had crossed the cables of two surface coils. (induced currents started fire)
September 19, 1989	A patient with a pacemaker was scanned and suffered a fatal heart attack during the exam. The coroner determined the cause of death to be MRI interruption of the pacemaker.
November 15, 1989	A light fixture in a mobile scan room fell from the ceiling and struck the patient when it was attracted to the magnet. The patient was cut in several places.

TABLE 2-1. MAGNETIC RESONANCE IMAGING (MRI) MAGNET EVENTS (Continued)

Event Date	Description of the Event
November 17, 1989	An MRI technician suffered a broken wrist when the ferrous part of a hoyer lift (patient stretcher) was brought into the scan room and was attracted to the magnet.
November 22, 1989	A nurse overlooked changing an IV pole to a non-ferrous type when bringing a patient into an MRI scan room. The nurse suffered bruises, hematoma, and lacerations while trying to retrieve the IV pole from the magnet.
April 23, 1990	During installation of an MRI system, a capacitor inside a gradient amplifier ruptured and ignited. The fire was contained in the amplifier, which is inside a steel cabinet away from the scan room.
April 27, 1990	A defective Balzer cold head (LN2 thimble to cool the magnet insulation space) was making enough training noises to hamper communications with the scan patient.
June 26, 1990	During initial servicing at a new installation site, the field service engineer received an electric shock while performing a calibration procedure. The engineer hit the coil body when recoiling from the shock. He received minor bruises.
December 7, 1990	The installation engineer received a 400 Vdc shock from a dynamic disable switch box on an MRI while performing coil calibration. A failed capacitor in the box resulted in 400 Vdc being applied to the box chassis. The engineer was not injured.

TABLE 2-1. MAGNETIC RESONANCE IMAGING (MRI) MAGNET EVENTS (Continued)

Event Date	Description of the Event
December 7, 1990	The magnet owner got an oxygen bottle stuck in the bore of an MRI magnet. A respiratory therapist carried the ferrous bottle into the scan room during magnet operation. No one was injured.
February 12, 1991	An oxygen sensor for room atmosphere to protect the patient in case of cryogen release was not mounted correctly and could not read the oxygen level in the MRI room.
March 4, 1991	The bolts that hold aluminum cable drop channels pulled out of the ceiling in the scan room, presumably due to magnetic field effects. There was no personnel or patient injury.
March 6, 1991	The magnet quenched, releasing helium into the magnet room. The venting system was repaired the same day. No one was present during the event.
May 7, 1991	A stabilizing sandbag filled with small, ferrous metal spheres (referred to as "bb's") was brought into a scan room on the patient's gurney. The magnet attracted the bb's, and the bag breached, leaking bb's out. The bb's were retrieved from the surface of the patient's skin, the magnet bore, and the gurney.
May 24, 1991	The oxygen monitor was determined to not have a battery backup. This is specified in safety information, since the oxygen monitor must be operable at all times in case of cryogen release. The monitor will have a backup power source installed.

TABLE 2-1. MAGNETIC RESONANCE IMAGING (MRI) MAGNET EVENTS (Continued)

Event Date	Description of the Event
July 8, 1991	A patient was brought from emergency services with a ferrous oxygen bottle. When brought near the MRI magnet, the bottle was propelled by the magnetic field, and it struck the patient. The patient's first aid included sutures in the genital area.

In summary, MRI magnet events between 1981-1991 include:

Loose ferrous objects in the MRI scan room	15 events
Helium vent system failures	4 events
Electric arcs or shocks	3 events
Electrical fires	2 events
Oxygen sensor problems	2 events
Defective cold head	1 event

more than one magnet unit. Improper venting would be a great safety concern for future fusion facilities, since building overpressure could allow activated cover gases, tritium gas, and/or activated solid aerosols to be released from the confinement building. Electrical fires should be a great design and safety concern for fusion, since there are large amounts and many types of electrical power required to run the machine. We will see that there have been several accelerator magnet and electrical fires and a few fusion facility electrical fires.

Magnet training, a phenomenon in high current density magnets where the conductor shifts position due to Lorentz forces,[2-2] has been observed in compact superconducting magnets for medical applications. Michigan State University researchers heard a metallic pinging noise and a loud ping followed by a quench at under half the rated field strength on their initial coil test. The pinging noise was audible when standing near the magnet on many other tests. The cause was the coil sliding axially on the bore tube. The magnet was modified by inserting shrink fit stretcher rings between the magnet coil and the bore case, which was difficult due to the very close tolerances. Only ten operations were needed after the rings were installed to run the magnet up to rated current without quench.[2-3] Quenching on initial startup seems to be the rule for high current density superconducting magnets.

MRI and other medical technology magnets are typically small units with bores only large enough for a patient. They do experience radiofrequency radiation, but do not see any ionizing radiation fields, electromagnetic effects, or extreme thermal stresses. A discussion with a magnet manufacturer revealed that these units are typically designed for a ten year life.[2-4]

2.2 Accelerator magnet experiences

Particle accelerators use superconducting magnets to confine higher energy particles, just as fusion experimentalists wish to confine more energetic plasmas. There have been several publications discussing magnet operations. First, Table 2-2 gives citations of events from the literature and the US Department of Energy's Occurrence Reporting and

TABLE 2-2. SUMMARY OF MAJOR SUPERCONDUCTING MAGNET FAULT EVENTS

Event Date	Description of the Event and Reference Number
July 21, 1964	An explosion occurred in the hydrogen purifier of a bubble chamber expansion system when a valve was inadvertently left closed during purging operations. Precooler and adsorber coils were torn open and the containing dewar bulged. Repairs cost $11,000. Report 64-41B.[2-5]
March 18, 1966	When the main hydrogen flow through the purifier was begun, an explosion occurred at the inlet to the adsorber coil. Immediately, the liquid hydrogen contents of the bubble chamber were dumped to the atmosphere through a safety vent system. Repairs cost $12,000. Report 66-8.[2-5]
February 24, 1986	A plasma physicist worked inside the experiment vault while the fusion magnets and plasma heating units operated, a health and safety violation. The supervisor's sweep of the area missed the physicist, or the person entered after the sweep was completed. The physicist was not injured. Operations procedures will be reviewed to preclude future occurrences of leaving a person inside the vault during operation of the experiment.[2-6]
January 13, 1982	During liquid helium transfer to cryopanels, a valve leading to the magnet dewar spuriously opened and allowed the helium to flow into the warm dewar. The liquid helium boiled and the resulting overpressure caused a helium gas recovery bag to rupture. An overpressure relief type of device will be added to the gas recovery system.[2-7].

TABLE 2-2. SUMMARY OF MAJOR SUPERCONDUCTING MAGNET FAULT EVENTS (Continued)

Event Date	Description of the Event and Reference Number
March 23, 1990	The liquid helium compressor for a superconducting magnet was in operation when there was a site-wide power surge. The compressor contactor failed to break power to the compressor motor during the power dip, which caused the 300 kW motor to short circuit and fail. A technician quickly shut down the system in an orderly manner and discharged a portable fire extinguisher, because smoke was present around the motor. Undervoltage and underfrequency protective relays will be installed. Repairs cost an estimated $6,000.[2-8]
July 19, 1991	An unplanned superconducting magnet discharge was initiated when an isolation amplifier input cable was disconnected inadvertently. Some minor damage occurred to insulation on a current lead-in during an arc to ground. A G-10 insulator disc melted in the arc that passed through a 1-cm distance at the current lead joint. The arc opened a hole in the stainless steel jacket, allowing liquid helium into the vacuum space of the tank. Helium was vented into the laboratory and to atmosphere via pressure relief valves. Water coolant from the damaged current lead entered the magnet, requiring warm up and drying before resuming operations. The magnet coil itself was not damaged. More distance will be provided at the current lead joints. Repairs will be completed by September 24, 1991 and cooldown will begin on October 1, 1991.[2-9,2-10].

Processing System[2-11] for accelerator and fusion events at DOE facilities.

There are two interesting papers describing the TEVATRON accelerator magnet operational experiences.[2-12,2-13] The first paper describes many magnet quenches induced by proton heating from the accelerator beam, five magnet ground faults from superconductor strand breakage due to flexure, and a quench and subsequent power supply run-on event that damaged insulation and ground faulted eight magnets. There were other events, such as a power supply transformer primary to secondary short circuit that damaged five magnets, a power supply failure that placed excessive voltage on the magnets, and a leak of helium into the insulating vacuum jacket with subsequent cryostat rupture. Overall facility outages because of magnet quenches averaged about 4/week, for the 1983 to 1987 time frame (this is roughly 0.003 quenches/magnet-week).

There were also several TEVATRON magnet installation problems: an improperly constructed magnet that had not been detected as faulty during testing, one magnet containing a turn-to-turn short circuit, and two unsoldered inter-magnet splices (only one of which was detected prior to installation). The individual magnet changeout time for the TEVATRON is on the order of five days.[2-13]

Further experiences with the TEVATRON facility indicate that Kapton insulation tape loses its adhesiveness at cryogenic temperatures. The tape must be sealed with some mechanical means, such as tying with Kevlar string, to prevent movement or unravelling from magnet or flow-induced vibration. The niobium-titanium strands continued to break in some magnets, primarily in the earlier magnets where the G-10 conductor holddown block was not smoothed to eliminate sharp edges. Magnet leads are now tied with Kevlar string to stop flexure during power ramping. Coil clearance loss during ramping led to the coils bumping the single phase terminating plates. That situation led to cracked welds on the cases, which leaked helium into the vacuum insulation space. Bolts from the G-10 lead holddown blocks were backing out of the blocks, probably due to vibration and thermal cycling.[2-13]

A surprising TEVATRON facility discovery was a black, greasy material inside several magnets. It was identified as lithium grease from the helium refrigerator expansion engines. The grease would migrate down the cylinder to the bottom of the engine, freeze there, and then be ground up and swept into the helium stream by the reciprocating motion of the pistons. Another black, conductive substance was found on the electrical leads outside the machine that provide power for the correction elements. This substance allowed current leakage to ground. The leads were cleaned and coated with a non-conductive sealer.[2-13] I have seen similar phenomena at a fission testing reactor, where vertical cables dripped out a black, oily sludge from their terminations. That substance was a coating applied to electrical cable insulation for easier assembly. The coating was fire retardant and a very poor dielectric, unlike the TEVATRON black material. It is possible that some material serving in a similar function was seen at the TEVATRON.

An interesting event occurred at the CELLO detector. The CELLO detector has a large solenoid, bath-cooled superconducting magnet system.[2-14] In addition to the typical problems with cryogenic systems, particularly the compressor and turbo-expanders, a magnet lead arc event occurred.[2-15] During a test of the emergency current dump system at 1000 amps, an arc of about 800 kJ energy developed between two current leads. It was apparently caused by gaseous helium passing from one lead to the other through a crack in the bonding between the G-10 fiberglass epoxy insulating plate and the lead tube. After about 5 seconds, the arc extinguished itself. The arc had evaporated about 0.13 kg of copper from the current leads. Several important conclusions were drawn from this event. First, the coil was not damaged by an arc in the leads, and probably would not be unless the arc burns down to the windings themselves. Next, the arc energy went almost entirely to evaporating material at the base points of the arc, and using the enthalpy difference for vaporization gives good agreement with the mass lost in this event. Third, the copper vapor did not remain as an aerosol, but rather it was deposited on various surfaces in the vicinity of the arc.

Work experience in magnet safety at the Toroidal Energy Storage Experiment (TESPE) in Germany showed that less than 10% of the arc energy will actually vaporize the material at the arc location, with the remainder going to heating and melting the magnet material.[2-16]

2.3 Fusion magnet experiences

Past efforts to identify and catalog fusion and other related magnet failure events include work by Hsieh et al.,[2-17] Thome et al.,[2-18] Czirr and Thome,[2-19] and Montgomery.[2-20] Summaries of these efforts are given briefly below.

In 1977, Hsieh et al.[2-17] described costly failure events of hot spots and arcs caused by electrical circuit failures, short circuits between windings, insufficient electrical insulation and mechanical supports, inadequate power lead cooling, incorrect wiring material, and cooling passage plugging; Hsieh also describes gas-cooled power lead failures due to insufficient cooling and conductor movement problems due to inadequate mechanical restraints. These were very early problems with superconducting magnets and are now receiving much closer design attention.

In 1986, Thome et al.[2-18] described many magnet design faults, improper assembly, improper operations, inadequate procedures, and insufficient quality controls. Czirr and Thome[2-19] provide the detailed reference information for the Thome et al.[2-18] paper.

In 1989, Montgomery[2-20] also described magnet events in these same classification terms. While the event tallies are not broken down by type of magnet, Montgomery's overall percentages are: mechanical support related causes, 22%; conductor related causes, 15%, insulation related causes, 25%; coolant related causes, 6%; external systems related causes, 14%, and system performance related causes, 18%. Failure rates for components similar to fusion magnet components included under these categories are addressed in Chapter 4, and some human error rates for operations and maintenance are addressed in Chapter 5.

Unfortunately, information on the total numbers of magnets in use in the surveyed fields (accelerators, physics experiments, and fusion), life spans of the facilities that were operating magnets, and the time spans of the failure data studies themselves are not available to perform statistical failure rate calculations from reference 2-20. However, these events do provide a great deal of qualitative information and guidance for assigning ranges of failure frequencies and assigning initiating event types.

The Large Coil Task (LCT),[2-21] while fortunately not included in these mentioned surveys of major magnet fault events, had results which showed that cryogenic support systems were very troublesome for system performance. Overall, the conductors, the spacers, the magnet cases, etc., performed well for the year of LCT operation. The six LCT coils achieved just over 50% availability for the year of tests. Major problems were in cryogenic leaks, vacuum thermal shield leaks, and the cryogenic system performance. One interesting event occurred to a pool-boiling magnet. A diagnostic lead[2-22] for a temperature sensor shorted across three or four turns of a coil. The shorting wire was found and electrically burned out.

A very interesting event occurred on July 8, 1988 at the Tore Supra facility. While this event is cited by Montgomery[2-20], it deserves attention because of the similarity to an accelerator magnet fault and the magnitude of the Tore Supra repair effort. One of the superconducting toroidal field magnets, coil BT 17, experienced a short circuit between pancakes.[2-23] The coil was run at partial fields in the pulsed mode for almost a year before a shutdown was instigated and the coil removed. Coil replacement took approximately 6 months. Failure analysis indicated that a metal particle in the magnet caused or contributed to the short circuit, but the origin of the metal particle was not discovered. A similar event occurred with an accelerator magnet, in August 1981.[2-24] An iron chip, probably lodged in the accelerator's bore tube during fabrication in 1978, caused a short between the bore tube and the ultra-pure aluminum that surrounded the superconductor. Thin, inadequate ground plane insulation was credited for the event. This is a case of accelerator magnet experience acting as a precursor for fusion magnets.

Duchateau et al.[2-25] briefly discussed another Tore Supra event that occurred in December 1989. After a very severe plasma disruption, TF coil BT 4 quenched from an 'important irradiation', challenging the magnet safety system. The system responded correctly, discharging the coil. We do not know what the important irradiation was, perhaps it might have been runaway electrons. These have been known to cause heating damage in other fusion devices.[2-26]

2.4 Tips for designers

There are several good documents published on superconducting magnet design tips to enhance magnet availability.[2-20,2-27,2-28] Henning[2-27] suggests many easy, practical ideas, such as overlapping mylar sheets to protect against pinholes that could allow arcing. For accelerators, Tollestrup[2-28] suggests that twice the amount of calculated refrigeration should be provided, since liquid helium is rapidly consumed when removing heat, and other troubles - vacuum leaks, contamination, heat leaks, human mistakes, and ignorance - can quickly mount up. A slow cooling facility is subject to much downtime, and can take days to cool after minor repairs.

Operators must be aware of unsecured ferrous objects near magnetic fields. There have been two such events at fusion facilities. Magnet vibration, leading to loose bolts and other failures, seems to be a problem for superconducting accelerator magnets as well as the normal-conducting ones. Vibration must be well treated in the design. Operations experiences are briefly summarized in Table 2-3.

Manufacturing can allow many faults to occur. Machining chips left in the coil have probably been the cause of two expensive magnet problems. This is a latent type of failure event; that is, it appears only after the magnet has operated for some time. The chips slowly abrade insulation and then cause a failure at some years into machine operation. Very strict specifications must be given to manufacturers, and tests to determine the cleanliness of finished units must be performed to guarantee that a short-lived magnet is not being installed in an expensive fusion experiment, such as the $5 billion ITER machine.

TABLE 2-3. SUMMARY OF SUPERCONDUCTING MAGNET OPERATING EXPERIENCES RELEVANT TO FUSION DESIGN AND SAFETY

Loose ferrous objects in the magnetic field
Electric arcs
Helium vent piping failures
Electrical fires
Magnet training
Magnet quenches
Damaged electrical insulation
Power supply short circuiting
Insulating vacuum jacket rupture or breach
Human left in the experiment vault just prior to fusion pulse operations
Liquid helium boil and overpressure release from gas recovery system
Helium compressor motor short circuit
Magnet turn-to-turn short circuit
Unsoldered magnet inter-turn splices
Niobium-Titanium superconductor strand breakage
Cracked welds on magnet cases, leading to helium admission to vacuum insulation space
Bolt loosening from vibration and thermal cycling
Electric arc between magnet leads
Cryogenic helium leaks
Vacuum thermal shield leaks
Poor cryogenic system performance to keep the magnets cool
Diagnostic lead short circuit
Pancake-to-pancake short circuits due to foreign material intrusion
Plasma disruption induced magnet quench

Stringent pre-operational testing of ITER magnets should be undertaken to spot these latent faults, such as machining chips left in the magnet case. More rigid tests should be devised to ensure that all possible faults of that type have been eliminated before taking the ITER machine into tritium operation.

2.5 Risk-based design for magnets

Chapter 4 gives some estimated failure rates from analogous equipment to allow for more thorough safety assessment work on fusion magnets. Failure Modes and Effects Analysis (FMEA), a systematic look at each major component to determine its failure effects on its system, can be prioritized using these failure rates. System fault tree analysis can also be performed on those events found to be important by the FMEA. These are the tools of risk-based design, which is a good practice to follow as a design check. When dealing with such expensive projects, designers should exploit all the design checks that they can.

Risk-based design is a concept where the design is analyzed for its potential faults, and these faults are compared to risk criteria. These criteria might be public safety levels, repair costs, downtime limits, or other values. For example, the Burning Plasma Experiment design applied a risk-based radiation dose limit criteria of 10% of the current regulatory limits for the general public.[2-16]

Completed FMEAs and fault trees support safety and availability work. Completed safety work is necessary for US DOE construction approval, facility regulation, and can greatly support efficient facility operations.

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3. Normal-Conducting Magnet Operating Experiences

This section discusses water-cooled and cryogenic-cooled normal-conducting magnet operations in particle accelerators and fusion experiments. Some of these magnet experiences are germane to superconducting magnets, such as insulation breakdown, vibration difficulties, and conductor arcing.

Particle accelerator and other high energy physics publications have been reviewed to find descriptions of consequential faults. The U.S. Department of Energy's Occurrence Reporting and Processing System[3-1] and other U.S. government publications[3-2] were also searched for magnet fault events. Major faults of US magnets and their descriptions are listed in Table 3-1, along with major events from other countries. The table describes several types of accelerator and fusion magnet events: cooling water hose failures, numerous magnet fires from inadequate cooling or electrical short circuits, fires started from a radiation damaged power supply and aging-degraded magnet insulation, cooling water leak events, two accelerator-related sabotage events, weld or braze flaws, and maintenance-related fault events.

Lessons learned from the events in Table 3-1 include: 1. Designers should provide hardwired interlocks between magnet power supplies and magnet cooling, and between magnet power supplies and electrical power supply cooling systems; 2. Operators should maintain a watch on the magnets while under testing and operations; tighten maintenance procedures and adhere to occupational safety and health, fire safety, and other guidelines for industrial operations, and increase 'walkdown' visual inspections at operating facilities.

Montgomery[3-3] gives a good description of water-cooled magnet problems. Among these problems are toroidal field (TF) coil leaks, mechanical supports loosening as operating time increases, and rotation of ohmic heating (OH) coils. There have also been difficulties with magnet leads, buses, and ground plane insulation. Foreign material working into the coils from magnet vibration and allowing short circuits is a problem, and inadequate buswork bracing is a common problem.

TABLE 3-1. SUMMARY OF MAJOR WATER-COOLED MAGNET FAULT EVENTS

Event Date	Description of the Event and Reference Number
August 1, 1959	Disruption of water service to a stellarator was caused by overpressure in the well pump supply line. Damage was $12,000, report 59-23.[3-2]
May 6, 1965	A fire, attributable to the failure of one or more capacitors in a modulator, occurred at an electron accelerator. The amount of loss includes equipment damaged beyond repair and the cost of the cleanup operation, valued at $120,000, report 65-16.[3-2]
December 9, 1966	A rubber cooling water hose on an experimental magnet ruptured, causing water to spray on 2 main magnets. A short circuit occurred across the bus connections of one of the 2 main magnets. Polyethylene sheeting, used to protect the magnets from dust and water, was ignited. Most of the $8,300 damage was charring due to electrical arcing. Report 66-46.[3-2]
June 8, 1967	A spectrometer magnet was severely damaged ($17,200) by overheating of the coils when the unit was inadvertently connected to the wrong power supply. Report 67-22.[3-2]
August 24, 1970	A researcher was fatally injured when war protestors exploded a bomb at 3:42 am, in the university building. Low-energy physics equipment was damaged, but the loss was covered by insurance. Licensed radioactive materials were on hand in the building at the time of the explosion, but there was no release of radioactive material. Report 70-20.[3-2]

TABLE 3-1. SUMMARY OF MAJOR WATER-COOLED MAGNET FAULT EVENTS (Continued)

Event Date	Description of the Event and Reference Number
December 7, 1971	Two bombs, probably in protest of the Vietnam war, were detonated in the injector section of the facility, one in the main trigger generator and one in the master oscillator. There was no damage to the main tunnel and the scheduled date for turn-on should not be affected. Damage estimated at $45,000, report 71-20.[3-2]
December 26, 1973	A fire occurred in a beam line extension of the accelerator facility. Preliminary information indicated that the cause was a spark from welding operations being conducted inside the corrugated metal tube. Evidently the spark ignited the polyurethane foam insulation. The fire, which penetrated the side wall of the building, produced copious amounts of smoke and there was concern that this smoke may have damaged some of the expensive electrical equipment in the building. Damage estimated at $80,000, report 73-70.[3-2]
May 25, 1981	The motor for one of the three pumps servicing magnet cooling tower number 4 burned out. The electrical fault started a fire in the motor windings.[3-4]
May 26, 1981	Hot metal from cutting operations entered the outer shell of the magnet. These bits of metal ignited the mylar insulation around the magnet. The fire was extinguished and argon gas was set up to purge the magnet casing so that operations could continue.[3-5]

TABLE 3-1. SUMMARY OF MAJOR WATER-COOLED MAGNET FAULT EVENTS (Continued)

Event Date	Description of the Event and Reference Number
January 31, 1982	The power supply for an accelerator kicker magnet was located in a radiation area. Radiation damage to the oil-filled capacitors in the power supply caused them to rupture. The power supply then caught fire and was destroyed.[3-6]
January 20, 1983	A hose in the water cooling system burst. Water pumps tripped off automatically. All circuit breakers tripped open except for one of the magnet power supply breakers. Two magnets overheated. Smoke from the magnets triggered the fire detection system. The magnet operator responded and received smoke inhalation while securing the facility. The magnets were damaged and needed to be rewound. The facility was shut down for one week.[3-7]
March 18, 1986	During a magnet power test, a short circuit occurred because a wire connection on a meter panel came loose and contacted another wire. Excess thermal heating caused the polyethylene insulation on the wire to soften and melt. Insulation breakdown allowed arcing to the metal cable tray, resulting in small electrical fires along the cable tray.[3-8]

TABLE 3-1. SUMMARY OF MAJOR WATER-COOLED MAGNET FAULT EVENTS (Continued)

Event Date	Description of the Event and Reference Number
March 28, 1986	A fire started in a spectrometer magnet. The magnet had been energized without adequate cooling water. The fire was controlled by researchers and technicians in the area. Damage was estimated at $13,000. Several causes contributed to the event: the machinist had not completed his work on the cooling system, electricians should have repositioned power switches, the computer system inadvertently turned on the power supply, the water flow interlock was not yet installed, all magnet interlocks were deactivated (buggered out) during the work, and the run sign-off sheet was not being followed.[3-9]
May 30, 1986	Personnel noted smoke issuing from a synchrotron magnet. They summoned fire fighters, secured power to the magnet, and fought the fire with a hand extinguisher. Aging-degraded magnet insulation failure is believed to be the cause of this fire.[3-10]
September 9, 1986	While testing a synchrotron magnet, the electrical power bus overheated and ignited its Lexan protective cover. Temperature and water flow switches had been by-passed during some part of the testing program. The protective cover had no ventilation slots to release heat, and it was too close to the bus work in several regions. Magnet water hoses and bus cooling hoses were damaged. The magnet was removed and replaced with a spare.[3-11]
March 1987	A fire in the Y-band facility started in a low voltage power supply under the machine and spread over several of the magnets. Magnets were damaged and had to be replaced. Damage estimate was $1,000,000.[3-12]

TABLE 3-1. SUMMARY OF MAJOR WATER-COOLED MAGNET FAULT EVENTS (Continued)

Event Date	Description of the Event and Reference Number
1987 thru 1989	The Joint European Torus (JET) noted progressive degradation of the octant 3, number 1 toroidal field coil. The decision to replace the coil was made prior to the 1989 shutdown. A water leak at a brazed joint caused the coil degradation. The leak was either caused by a poorly made joint or by corrosion at the edge of the joint. Another coil in an adjacent octant also showed signs of degradation, so a switch from water coolant to trichloro-trifluoroethane fluid was made, since this new fluid is an insulating coolant. The changeout took a considerable amount of work, roughly 19 weeks of labor during a scheduled shutdown.[3-13,3-14]
March 1988	JT-60 experienced a cooling water leak from a toroidal field coil. Two months were spent finding the leak location and repairing it. The leak was between two pancakes.[3-3,3-15]
1988 and 1989	The Tokamak Fusion Test Reactor (TFTR), while trying to maintain high quality of its copper brazes for the magnet cooling circuits,[3-16] has experienced several leak events, one of which caused a ground fault. Efforts to repair these leaks have included injecting a sealant into the cooling lines.[3-3] TFTR personnel have also considered the possibilities of using an insulating coolant, similar to the fluid that was chosen at JET.

TABLE 3-1. SUMMARY OF MAJOR WATER-COOLED MAGNET FAULT EVENTS (Continued)

Event Date	Description of the Event and Reference Number
December 22, 1990	Smoke was discovered during a cold weather damage check of a building. The smoke was coming from an overheated water-cooled magnet. The water line had been isolated due to ruptured pipes, and the coolant was not interlocked to the magnet power.[3-17]
February 7, 1991	During magnetohydrodynamic (MHD) magnet operation, an operator noted water leaking from a corner of the magnet. Cause information is not available at this time. All steps to salvage the magnet in a safe, cost-effective manner will be taken.[3-18]
June 23, 1991	The pulser box for a kicker magnet caught fire. A short circuit in the pulse forming cable caused a resistor to overheat. The fire was quickly brought under control.[3-19]

In summary, the tallies of events are:

Electrical fires	8 events
Loss of cooling water inside the building	7 events
Failure to provide cooling water	2 events
Industrial fires	2 events
Sabotage	2 events
Magnet overheated due to improper lineup	1 event

Smaller tokamak experiments have had experiences similar to those cited in Table 3-1. For smaller tokamaks, Montgomery[3-3] described events where a wrench in the magnetic field caused a short circuit in the buswork, a magnet coolant loss of flow event (a valve was incorrectly left closed), and an event where the magnet coolant inlet and outlet lines were inadvertently reversed after a maintenance session (causing magnet overheating). All of these events are definitely similar to the experiences discussed in Table 3-1, with the exception of electrical and other fires. Accelerator magnet fires might be due to the faster repetition rates for accelerators, pulsing on the order of once a minute as opposed to a fusion magnet that might pulse once every sixty minutes. Faster pulsing can lead to higher magnet body temperatures and places more demands on the electrical equipment. Magnets in general are viewed as having a definite demand lifetime, because of insulation wear and conductor fatigue. Therefore, accelerator magnets are likely wear out much faster than fusion magnets, because of their more robust operating schedule. I also note that fires in fusion facility magnets and power systems appear to be a rare phenomenon.

Other water-cooled magnet experience has been found from particle accelerator conference proceedings. This information is summarized in the following paragraphs. Large accelerators have used many of these small magnets, on the order of thousands. This provides the opportunity to generate some meaningful statistics on such magnets, even if the radiation environment is very benign, for guidance on fusion magnet reliability.

Fermilab published several documents regarding water-cooled magnet reliability. An early article[3-20] stated that the Fermilab main ring magnets had a typical failure rate of 0.035/magnet-year. Since there were over 1200 magnets, this meant that more than 35 magnets were failing each year. The staff kept track of the failures and the types of failure mechanisms. Magnet short circuits were the leading cause of failures. The designers practiced with different techniques for injecting the epoxy insulation into the magnet windings to reduce the number of short circuits. A significant problem was that the epoxy did not allow for coil package movement with temperature variations. Vacuum assisted epoxy impregnation was the best method to provide reliable performance.

The magnets at Fermilab also had difficulty continuing to operate well when the cooling water temperature fluctuated. A water temperature control system and a mechanical interlock to disengage the water pumps when temperature fluctuations were sensed were both installed. Electrical transients also could be severe enough to cause magnet shorting. Changes were made in the electrical power system to eliminate spurious openings and closings of the vacuum circuit breakers in the electrical power system. The staff also noted that magnets whose resistance to ground becomes less than 10 megaohms are in an incipient short circuit failure state (likely due to internal water leaks), and these units are 'blacklisted' and scheduled to be removed from service. The staff was also confident that removing the external causes of failure from the magnets, such as the accelerator tunnel roof leaking through construction openings during a bad rainstorm - the inleakage water caused nine magnets to short to ground - would reduce the magnet failure rate to 0.016/magnet-year.[3-20] This is roughly a factor of two reduction in failure rate, but still not an enviable failure rate for a large fusion magnet. Using this magnet failure rate for a 24-TF coil fusion experiment, a magnet would fail every three years.

The Alternating Gradient Synchrotron (AGS) device published a document describing several magnet faults.[3-21] These faults were caused by water leakage from burst hoses or failed fittings, corrosion products blocking coolant flow, and poor quality soldered joints. Several design modifications were made: route the cool inlet water to enter on the larger, cooler side of the magnet to minimize magnet thermal stresses, provide chemistry control of the coolant water, locate water manifolds under magnets to prevent leaks from flowing down into the magnet body, and use more stringent joint soldering specifications.

The Tandem Mirror Experiment-Upgrade (TMX-U) published some of its operating experiences.[3-22] While these magnets were themselves housed in a vacuum chamber, some of the events that occurred to them are of interest to the more conventional tokamak magnet designers and operators. The first event was that the TMX-U staff discovered that three of the 24 flowmeters would read normal flow rates when there was no flow in the cooling system. The instruments were replaced and an inspection program was set up to verify correct functioning of the flowmeters. Another event was the buildup of rust-colored sediment in the magnet conductor and cooling water piping. A clear piece of tubing in one of the lines showed the operations staff that the material was accumulating. The cooling circuits were then periodically flushed with an acid solution to eliminate the foreign material buildup. There were also two ground fault problems. The first fault was in a power supply transformer. The circuit was bridged until a scheduled repair session. Reinsulating the transformer took a few weeks to finish. The other ground fault was in an Ioffe coil. The coil, upon installation, read a low resistance to ground. As the coil performance deteriorated, efforts to find the location of the fault (actually multiple faults) were unsuccessful. The circuit was grounded near the several short circuits to allow continued operation. After 2 years, a power supply shorted, allowing power to flow through both grounds. This resulted in an arc that punctured the conductor. The puncture location was roughly detected by listening with a stethoscope while pressurizing the conductor with compressed air. Upon investigation, the staff found that the coil insulation was charred and darkened, indicating heating for some time. The insulation had been damaged prior to impregnation when nearby welding had overheated it.[3-22]

A recent event for water-cooled magnets was the failure of inter-turn insulation for a field shaping coil on the RFX machine.[3-23] During acceptance tests, the coil experienced flash-over around the Kapton and epoxy resin insulation. The total flash-over path was about 70-80 mm long, and there were no discernible defects in the epoxy impregnation to initiate such a breakdown path. The breakdown went from the lowermost conductor, around the inter-turn Kapton insulation, then reached the second lowest conductor of the inner layer. A large carbonized area was created, and the whole area is delaminated due to the gas pressure generated by the event. Repairs were performed, but no specific repair information was discussed.

Another recent event occurred at the Texas Tokamak (TEXT) experiment.[3-24] In this event, a poloidal field (PF) coil that was discharged for a particular operating run had electromagnetic forces generated in it by the plasma itself. This energy deposition caused coil electrical damage. Magnet designers have generally noted that this sort of event is possible.[3-25] However, design analyses for the Next European Torus (NET) PF coils noted that an induced current event is not dangerous to the coils.[3-26] The NET team concluded that induced fields are much lower energy than the normal driving currents in the coils, for both TF and PF magnets, and the NET PF coils have low inductance coefficients, which should protect them from damage.

Accelerator design changes and the movement to the higher field superconducting magnets began in the early 1980's. Superconducting magnets were discussed in the last chapter. Suggested magnet component failure rates for both magnet types are presented in the next chapter.

Vibration, and perhaps thermal cycling, that causes bolts to loosen has been noted on the large tokamaks.[3-3] The Advanced Toroidal Facility[3-27] helical field coils had small load transducers installed on the clamping studs to monitor their tension. This option may be desirable if the radiation field of the device is not too strong to damage the transducers. Many transducers have ratings for high radiation, and their failure rates do not show any significant increase to account for high radiation fields.

An event that has been discussed in detail in several reports[3-3,3-28,3-29,3-30,3-31] is the structural failure of a large, normal-conducting magnetohydrodynamic (MHD) magnet in 1982. This magnet had a design of either operating as a water cooled magnet, or as a nitrogen precooled, cryogenic magnet. The magnet design allowed stresses above the ultimate tensile strength of the aluminum collar fingers, or keys (as in key ways), that held the magnet parts together. The magnet failed catastrophically at anout half its design load of 6 Tesla. The event served to greatly alter magnet design practices. Since this type of design is no longer used, such an event is not considered relevant to magnet design or safety work.

There is little published material on operating experiences for cryogenic normal-conducting magnets. Most fusion experiments currently use water-cooled magnets. MHD experiments are tending toward superconducting magnets, as have particle accelerators and medical technology applications.

The types of problems we have seen in fusion and other water-cooled magnet experiences are water cooling problems, insulation problems, and structural problems. Table 3-2 gives a brief summary of the problems discussed in this chapter. Water cooling problems include accidently shutting off valves, loss of coolant from burst hoses, foreign material buildup inside the cooling channels, leaking fittings and welds, cooling water temperature variations that affect magnet life, and cooling water hoses hooked to the wrong port after maintenance. Insulation problems include insulation that does not allow the magnet to thermally relax, insulation - either damaged or inadequate - that allows electrical breakdown between conductors, between coils, and between coil and ground, weld heating that degraded insulation, and water intrusion that degraded insulation.

Structural problems include magnet vibration that loosens bolts and allows foreign material to work into the coil turns, and the friction generated by small amounts of magnet shifting. Another event seen from accelerator and other non-fusion magnets is overheating or electrical faults that lead to fires.

Magnet designers should examine these events to appreciate the environment in which their magnets will be required to function. Provisions should be taken for non-ideal situations like high conductivity cooling water, high vibration, nearby welding whose heat degrades electrical insulation, and other features of the operating environment.

TABLE 3-2. SUMMARY OF NORMAL-CONDUCTING MAGNET OPERATING EXPERIENCES RELEVANT TO FUSION DESIGN AND SAFETY

Electrical fires

Loss of cooling water into the building

Failure to provide adequate cooling water

Industrial fires

Sabotage

Magnet overheating by connection to incorrect power supply

Loose wrench in the magnetic field causing a short circuit in buswork

Loss of cooling water flow

Magnet overheating due to inadvertent switch of cooling water lines

Short circuits due to improper epoxy insulation

Cooling water temperature fluctuations

Electrical power transients causing magnet short circuits

Support system instrumentation faults in flowmeters

Foreign material intrusion in cooling water

Electric arc because of ground fault

Inter-turn insulation failure

Plasma electromagnetic forces generated damaging current in an unused PF coil

Bolts loosening because of vibration and thermal cycling

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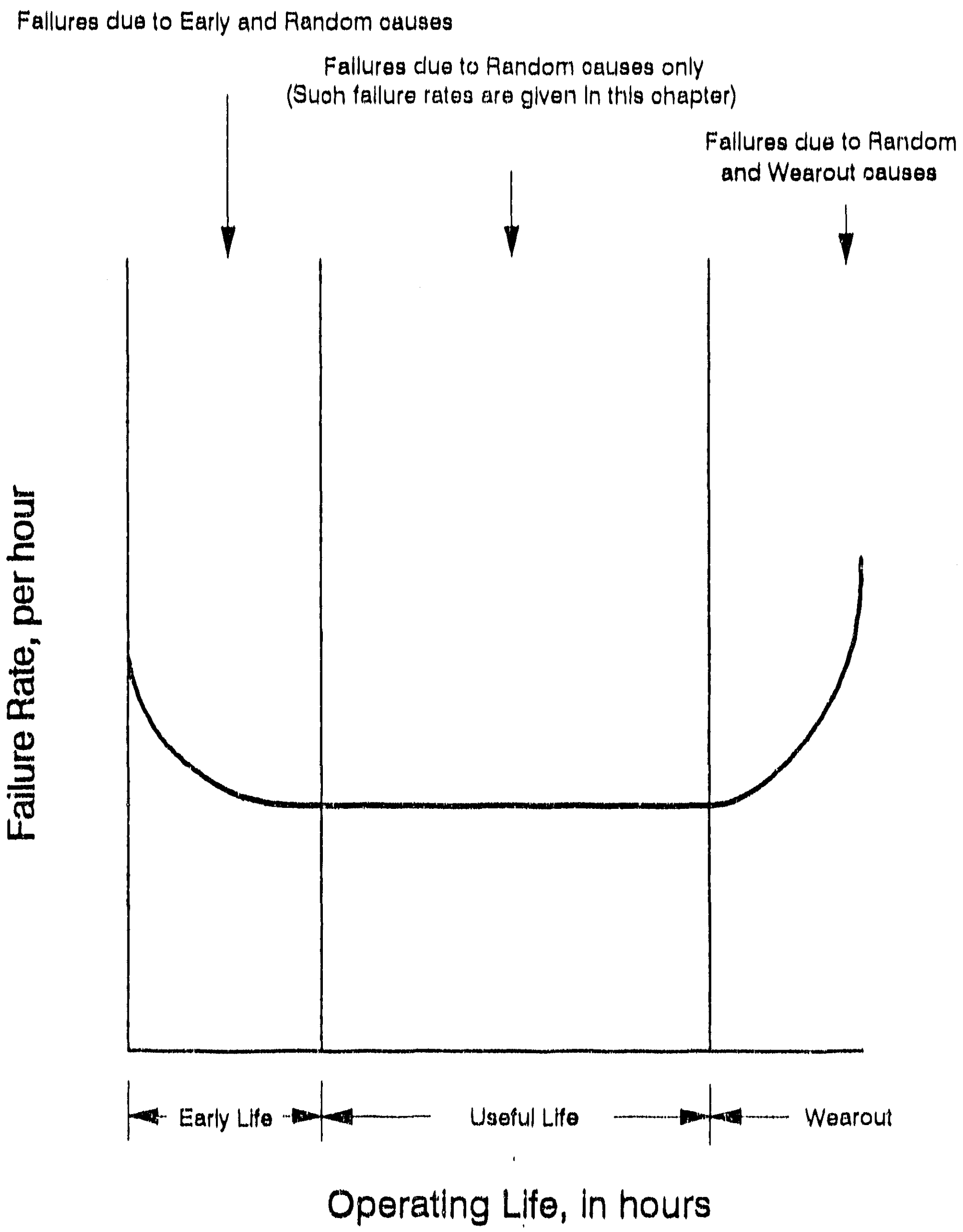
4. Suggested Failure Rates for Magnet Components

This chapter describes selection of suggested failure rates for resistive and superconducting magnet subcomponents. These failure rates can be applied to specific magnet designs to develop system reliabilities, unavailabilities, or can be used for probabilistic risk assessment calculations. Fault tree analysis, quantified with component failure rates, is the primary tool for modeling systems to obtain their unavailabilities.

The failure rates described here are mainly taken from failure studies of similar equipment. Reported failure rates are generally given for mature equipment that exhibits reasonably consistent behavior; therefore, the reported failure rates are constant values. This means that all early failures, such as 'burn-in' or 'break-in' faults, manufacturing defects, assembly errors, installation errors, chemical/physical contamination of materials, use of substandard materials, poor workmanship, etc., have not been included in the analysis to generate the failure rates. The classical "bathtub curve", as shown in Figure 4-1, applies to components in this chapter. The figure shows a plot of failure rate versus operating hours, where the early failure rate is initially very high and decreases with time, then levels out to a practically constant value for the chance failure rate over the majority of component operating life, and finally the wearout failure rate increases with time in the end of life region.[4-1,4-2] Chance failures might be caused by insufficient safety factors, stress or strain conditions that exceed the design envelope, potential human errors in operations, and component misapplications. Wearout failure causes might be material wear, fatigue, creep, corrosion, general deterioration, a life of poor maintenance, or a short design life.[4-1] The failure rates presented in this chapter are chance, or random, values over the useful component operating life. Error factors or conservative upper bounds on the failure rates are given whenever possible.

If analysts choose to use these failure rates for risk or availability assessment, then they are implicitly assuming that there have been rigid quality assurance and pre-operational testing programs to eliminate the



Note: Early life should have testing and QA
Useful life should have D-T operations, before wearout

Figure 4-1. The reliability bathtub curve.

(Taken from reference 4-1.)

early or 'burn-in' failures. They are also assuming that there is an adequate design margin in the equipment to provide a long life span, such that wearout failures are not encountered during facility operation, just like the design life of the equipment chosen to draw analogies to these fusion magnet components. I have not addressed common cause or dependent failures in this chapter. Some of these failures are highly influenced by the reactor design, and must be treated when adequate design information is available. Generally, these types of failures can be approached using the standard Beta factor methods and by explicit modeling, such as for internal floods and other consequential events.[4-3] Some human error probabilities for initiating event modeling are discussed in the next section.

To give the reader some insight as to the approximate regions of the early, useful, and wearout life spans, I have some examples from the literature. Electronic components have been scrutinized for their early life or 'burn-in' characteristics. For an electronic assembly, such as a circuit card, the early life might be on the order of 50 to 150 operating hours, and the early failure rate might reduce by factors of 2 up to 10 to the useful life value.[4-4] On a much more complex scale, a study of 22 newly started US commercial nuclear power plants showed that for the first testing period after initial criticality (startup), the inadvertent shutdown (scram) rate was a factor of 5 higher than for the 76 mature US nuclear plants. The number of inadvertent shutdowns can be considered to be an indicator of plant safety, with the fewer shutdowns being better. Some of these new plants averaged better than one inadvertent shutdown each month. A US commercial nuclear power plant might be in pre-operational testing after initial criticality for periods on average of 8 months, while a few plants have taken two or more years. The new plants study[4-5] showed that equipment forced outages caused an average 3 hours of downtime per 1,000 operating hours in the first quarter year after initial plant criticality. The equipment induced outages reduced to 0.5 hours of downtime per 1,000 operating hours by the beginning of the second year after initial commercial operation. The new plant study considered a mature plant to be over 4 years of the standard 40 year power plant life.[4-5] Therefore, I consider the early life for the power plant equipment to be on the order of 3-4 years (including the 8 months of testing), with inadvertent outages reduced by a factor of six. Magnet systems would probably be somewhere between these estimates, perhaps closer to 1 or 2 years of early life, and on the order of 10 or more years of useful life.

Montgomery[4-6] has correlated his data base on magnet failures with the time of failure, and he found that 72% of the failures were in initial or early operations (likely within the first year), 20% of the failures were in the useful life region (perhaps on the order of 10 years), and 8% of the entries were wearout type failures. Several insights can be drawn from these results. First, many of the magnets exhibit their faults early on, perhaps within the first year of operation. More rigorous pre-tokamak operations testing of the actual magnets to be installed may lead to improved identification of any inherent magnet flaws before the magnets are installed around the torus. Second, for a two phase experiment like ITER, the first year or two of the Physics Phase might serve as an important break-in period, since hands-on maintenance is allowed during that phase. However, we must also note that extensive downtime early in the project life may threaten its funding for later stages of operation. Third, so many early faults leads us to question the adequacy of existing magnet quality assurance practices.

Magnets themselves are made up of only a few components. Both normal-conducting and superconducting magnets are composed of a conductor, spacers, electrical insulation, an exterior case, and current leads to route electrical power to the conductor. The magnets are usually supported or buttressed by large structures, such as structural braces and concrete pedestals. This section will address failure rate information for the components mentioned here, which form the bounds for the magnet system. Other subsystems, such as magnet cryogenic coolant and electrical power, will be topics for future work in the fusion component reliability area. Since there are already fission-related data bases for water cooling[4-7] and electrical component failure information,[4-8] those subsystems will not be given attention here.

Field experience is the best means available for good estimation of magnet component failure rates. Unfortunately, the fusion operating experience published to date does not typically contain enough information to calculate failure rates. When possible, inferences are drawn here from the collected information. Laboratory testing or accelerated life testing is another typical means to obtain failure rate data; however, few of these test results are available for use in this report. Fusion safety analysts typically use an 'analogy method' to obtain failure rates; that is, apply failure rate values from analogous or similar equipment used in other industries or fields of scientific research, such as the fission power industry.[4-7,4-9,4-10] Since the same industrial base will fabricate fusion components, equipment already produced and used by that industrial base gives good insights to future fusion component performance.[4-10] Normal-conducting magnet subcomponents, both water-cooled and cryogenic liquid cooled, will be considered first, then superconducting magnet subcomponents will be addressed.

4.1 Normal-conducting magnet components

This section presents failure rates for components in water-cooled and cryogenic cooled normal conducting magnets. The conductor, conductor electrical connections, cooling lines, electrical insulation, spacers, and magnet mountings are considered.

4.1.1 Normal-Conducting Magnet Conductors. The conductor for water cooled magnets is basically a copper, or other material, tube. Established nuclear fission industry failure rates for N-stamp (American Society of Mechanical Engineers [ASME] nuclear grade approved) steel pipes and welds can be generally applied to water-cooled magnets. However, since all of the large experiments, JT-60, JET, and TFTR, have had significant downtime and suffered problems with water leakage from their magnets, the suggested fission plant piping failure rates may be liberal values, and may not accurately account for future occurrences. Unfortunately, accurate failure rate calculations based on the three large tokamak failure events would require more information; namely, the length of coolant tubing, the number of brazes/welds, and the total magnet pulse demands or time of operation for each of the three tokamaks. Considering the overall magnet leakage operating experience of these three fusion experiments, we can find a rough, approximate failure rate. JET has 32 TF coils, for about 256 magnet-years; TFTR has 20 TF coils for 180 magnet-years; and JT-60 has 18 TF coils for roughly 108 magnet-years. These values give a point estimate failure rate for water-cooled TF magnet leakage of 3 faults/(256+180+108 magnet-years) = 6E-03/magnet-year. An upper bound failure rate would be a 95% Chi-square value using (2x3)+1=7 degrees of freedom, or 14.067/2(256+180+108) = 1.3E-02/magnet per year. Please note that all Chi-square values are taken from standard statistical tables, such as Amstadter.[4-11]

The conductor tubes are separated by some form of insulator, usually some kind of fiber reinforced epoxy resin or perhaps mylar sheeting. Short circuits between conductors have been a problem for accelerator magnets (mentioned in Chapter 3), and a concern for fusion magnet designers. A major reason for this concern is that repairs to a wound conductor are difficult at best, usually requiring machine disassembly and significant downtime, and impossible at worst. Fusion safety analysts are also concerned that possible arcs or fires could volatilize the neutron activated magnet structure. Magnet replacement is a typical response in the case of a magnet arc, as seen in the accelerator data for their resistive magnets. The magnet reliability data published by Fermilab for their main ring accelerators suggests that insulation faults that allow short circuits from turn-to-turn and to ground have been severe.[4-12] Between 1972 and 1979, many of the 1258 water-cooled magnets had short circuits, a high failure rate being 0.09/year. Over 1978 and 1979, this value decreased to 0.035/year. Fermilab personnel believed that due to new techniques of applying epoxy resins, the post-1979 failure rate would be reduced to 0.016/year. This average value seems high, especially for a system with over 1,200 magnets. Overall, since fusion resistive magnets appear to have been more reliable than these older accelerator magnets, I have investigated other 'similar equipment' to approximately quantify electrical insulation failure rates.

To account for advances in insulation materials and fabrication technology since 1979, I searched for large capacitor failure rates. Unfortunately, available information on large, high voltage capacitors is not readily applicable to normal magnet operation, since capacitors generally have a high voltage between plates, while magnets usually have a low voltage between plates. I obtained a point estimate failure rate of 1E-06/operating hour for all capacitor failure modes, reported by Green and Bourne.[4-13] Since this value would have to be scaled up to account for size differences between fusion magnet pancake plates and capacitor plates, the resultant failure rate value would likely be larger than the accelerator experience value given above. I recommend using the accelerator values for initial safety and risk analyses, until designers and manufacturers can provide more definite failure rates for specific equipment.

Studies of electrical insulation accelerated life tests under a variety of conditions (cryogenic temperatures, mechanical stresses, and irradiation) may provide some future guidance in failure rate estimation. Since irradiation can reduce dielectric breakdown voltage, even the relatively mild irradiation that fusion magnets receive is a very important factor in coil life.

The conductors can also plug up, perhaps stopping the flow of coolant. For water-cooled resistive magnets, using fission reactor pipe plugging values is applicable. Water coolant for magnets can carry impurities that plate out in elbows, eddies, or the lowermost parts of the coil, and there can be corrosion products carried from the coolant pipe walls that can also plate out, as discussed in the TMX-U experiment experience from Chapter 3. These same conditions of impurities, fouling, plateout, etc., can easily exist in a fission plant. Failure rates for N-stamp (that is, ASME nuclear quality) small diameter water coolant piping from fission reactors can be applied to gain order of magnitude failure rate information. My suggested value for the pipe plugging failure rate is 1E-10/hour per meter of pipe, with an error factor of 30.[4-14] The error factor is the 95% upper bound divided by the median failure rate. For our purpose, the error factor is approximately the 95% upper bound divided by the mean failure rate.

Conductor connections are very similar to standard electrical connectors or joints. Typically, a combination of brazing to copper and mechanical bolted connections secure power leads to the magnet conductor. An estimate of the failure rate of these copper joints would be 5E-06/hour per joint for open circuit and the same value can be used for short circuits, based on electrical connectors. Both of these values have an error factor of 10.[4-14]

Another area of interest is water cooling line connections to the conductor. Fittings or other hose clamps are typically used to secure the lines together. Chapter 3 discussed occasions where the hoses either breached or became detached from the magnet. Since there are many, virtually uncounted cooling water hoses at each fusion facility, I cannot provide an accurate estimate for a hose failure rate. Applying the breach/leakage failure rate for flexible hydraulic hoses (assuming a hose section is roughly 4 meters long and has fittings on both ends) gives a failure rate of about 2E-06/hour, with a 3E-06/hour[4-15] upper bound.

4.1.2 Normal-Conducting Magnet Spacers. The stainless steel spacers that hold coil windings to appropriate tolerances are similar to the zirconium fuel element grid spacers found in fission reactors. Grid spacers function to hold fuel pins to exact tolerances, providing clearance for liquid coolant flow. The grid spacers must function in conditions of high heat fluxes, neutron and gamma irradiation, mechanical stresses, and fuel pin flow-induced vibration. While these fission components are widely used, there is little reliability data published on them. They are the heart of a successful fuel element design, and are guarded as a trade secret.[4-16] Published work on boiling water reactor fuel element performance have discussed the fuel element overall performance and do not quote grid spacer faults as a contributing fault mode for fuel elements (the faults considered are corrosion, vibration wear, etc.). With boiling water reactor fuel performance reliability better than 99.998%,[4-17] the set of grid spacers must have an upper bound failure rate of much lower than 2E-05/element per year. This random failure rate for a set of fuel element grid spacers is a good approximation of a magnet spacer failure rate, since the environment is comparable and since the size of a set of fission grid spacers is about the same size as a magnet spacer for a large toroidal field coil. Spacer performance in earthquakes, i.e., rupture causing coolant channel blockage[4-18], must be examined separately.

4.1.3 Normal-Conducting Magnet Mountings. Mountings for magnets are similar to any sort of heavy industrial equipment mounting. Magnets can weigh from a few up to several hundred tons. Considering similar weight items, such as large turbines and generators, that exert forces besides gravitational force on the mount, and the successful operating experiences these items have had, we intuitively know that the failure rate of their mountings is small. A reliability study for world power plant turbine-generators[4-19] and review of recent editions of the US Engineering News Record journal show that while vibration problems and blade cracking can occur, no turbines have broken their metal mountings or concrete floor pedestals. Considering that there are about 3420 fission reactor-years of experience in the world[4-20], with no turbine-generator mounts failing, and a 50% Chi-square distribution on zero faults[4-21], this gives 0.455/(2x3420 reactor-years) = 7E-05/reactor-year for an overall mounting failure rate. Considering three such mountings in a nuclear power plant (for the low pressure and high pressure turbines, and the main generator), this gives an individual mounting random failure rate of about 2E-05/operating year. This is a reasonable value to apply to each of the equipment mounts at a tokamak facility, given the weights involved and the forces exerted. Considering the environment that the concrete is in, irradiation of concrete does not seem to greatly weaken it, and since concrete is used as tank walls for cryogens such as liquefied natural gas,[4-22] possible exposure to colder temperatures should not be a degrading influence, either. The 95% upper bound Chi-square mounting failure rate would be 3.841/(2x3420 reactor-years x 3 mounts/reactor) = 2E-04/operating year. Mounting performance during seismic events must be considered separately, such as the analysis performed for the "Power Generating Fusion Reactor" design.[4-23]

4.2 Cryogenic Cooled Normal-Conducting Magnet Components

Much of the information to be presented in the superconductor subsection will apply to this magnet design. For a Bitter plate magnet design, failure rates for copper alloy fracture, Bitter plate joint fracture, and electrical insulation faults are needed. Failure rates for arcs between electrical leads are also needed.

There has been some testing of copper alloys for the fusion applications. One of these materials tests was an accelerated life test for brazed copper alloy joints and copper alloy plates. Samples of brazed joints were tested under a 276 MPa loading for 80,000 cycles, and did not experience a failure. The plates were tested under a 310 MPa load for 80,000 cycles and also did not experience a failure.[4-24] For the no failures case, using a 50% Chi square distribution[4-21] on the number of cycles gives 0.455/(2x80,000) = 3E-06/cycle. The 95% Chi-square upper bound is 3.841/(2x80,000) = 2.4E-05/cycle. The cycle stresses approximate loads during an experiment pulse, so these failure rates can be used per experiment pulse. This average failure rate should be appropriate for copper alloy Bitter plates and the brazes that join them together.

Irradiation of normal-conducting magnets poses some small design adjustments, such as increases in electrical resistivity, that must be accounted for in the power supply design.[4-25] Electrical insulation degrades under irradiation, and can be a life-limiting factor in magnet operating life. Electrical insulation, such as Spaulrad-S, has been tested under high irradiation conditions and shown decreases in electrical resistance and in mechanical strength.[4-26,4-27] Insulation shrinkage under irradiation can also cause stresses to be generated inside the magnet. These irradiation tests show degraded resistivity for large irradiations, but do not attempt to quantify probabilities of failure. Assuming large design margins (which may be optimistic for magnet design), an electrical insulation failure rate would likely be on the order of that for electrical cable circuits, 1E-07/hour with an error factor of 10.[4-14] A circuit is perhaps 200 feet long, or enough insulation material to be equivalent to about a third of that needed between one set of Bitter plates for a small tokamak experiment. Therefore, the magnet insulation failure rate should be about 3E-07/hour, between one pair of Bitter plates, with an error factor of 10.

The failure rate for cooling flow blockage must account for likely events, such as freeze plugging by contaminants in the cryogen, such as hydrogen and oxygen, and blockage from foreign materials. Foreign materials might include metals, such as bolts, washers, welding slag, broken probe pieces, tools, etc., from the rest of the cryogenic piping. Flow blockage failure rates from nuclear fission plants should be appropriate, but I suggest raising the value by a factor of 10 to account for special cryogenic (frozen air plugging, impurity plugging, etc.) conditions. A pipe plugging failure rate value of 1E-09/hour per meter of pipe, with an error factor of 30, should be used.[4-14]

Magnet mounts, electrical leads, and other equipment failure rates needed for cryogenic cooled normal-conducting magnets are very similar to superconducting magnets. Due to the design similarities and coolant similarities, the superconducting component failure rates can be used for these magnets. The superconducting magnet component failure rates are discussed in the next subsection.

4.3 Superconducting magnet components

This section dwells on forced flow superconducting magnets rather than pool boiling magnets, since this sort of magnet design is needed for higher field fusion applications.[4-28] This section gives recommended failure rates for superconductors, their conduits, electrical insulation, spacers, mountings, electrical leads, and magnet cases.

4.3.1 Superconductors. For superconductors, the conductor conduit is probably 60% filled with the niobium-tin superconducting wires themselves. Gas impurities entrained in the liquid helium can freeze in the conduit, and hydrogen or other elements, created from radiation bombardment in the insulating material, can freeze in the conduit and block flow. Warmed helium gas vapor can block or vapor lock the conduit. For the reason of decreased flow area, I increased the fission-related flow blockage value by a factor of 10 for conservatism to account for these additional failure modes. This factor of 10 practice has been applied for conservatism in other fusion risk assessment work.[4-7,4-29,4-30] The value I suggest for use in estimating superconductor conduit plugging is 1E-08/hour per meter, with an error factor of 30.[4-14]

Conduit breach is an important failure mode because of the severe consequences to magnet availability and due to helium release and possible overpressurization inside the magnet case. While the stainless steel conduit may be square cross section rather than circular, nuclear industry small diameter N-stamp (i.e., ASME nuclear quality) piping leakage failure rates can be applied. This value is 3E-08/hour per meter, with an error factor of 30.[4-14]

Niobium-tin and niobium-titanium superconductors themselves have shown reliable behavior in the LCT[4-31] and other superconducting applications. It is generally reasonable to expect that when a component has no failures for a long period of time it is unlikely that is has a high failure rate.[4-32] I have chosen copper electric transmission line cable failure rates to describe the order of magnitude of superconductor failure rates. Perhaps this is not the best analogy, but it is the only one readily available. Several sources of failure information on electric cables contributed to the following failure rate estimate.[4-8,4-33,4-34]

For transmission line cables of 15 kV or lower, the failure rate is on the order of 7.5E-06/hour per 305 m (1000 feet), with an upper bound value of 2E-04/hour per 305 m.[4-8] Large electric power transmission cables experience on the order of 0.4 to 0.7 failures/year per 160 kilometers.[4-31] An entire fusion reactor toroidal field magnet set might have on the order of 80 km (50 miles) of conductor, so these transmission cable failure rates seem somewhat high to apply to superconductors, given LCT and TESPE experience. Even though superconductors are under the influence of radiation and thermal stresses that these cables are not, the superconductor failure rates intuitively seem to be lower than that of transmission cables. Buende[4-35] used fission plant control circuit wiring as an order-of-magnitude failure rate for superconductor wiring. These values were 3E-06/hour per magnet turn for open circuits (error factor of 3), 3E-07/hour per magnet turn for short circuits to ground (error factor of 10), and 1E-08/hour per magnet turn for short circuits to power (turn-to-turn, error factor of 10). I assume that a magnet turn is on the order of about 30 meters (100 feet) in length.

I chose a value of 1E-07/hour per meter as a reasonable point estimate open circuit failure rate for superconductors, with about 3E-06/hour per meter as the upper bound. Other values by Buende,[4-35] given above, can also be used as needed. Future testing of ITER superconducting cables will provide more accurate information on which to base true superconductor and conduit failure rates.

4.3.2 Superconducting Magnet Cases. Magnet cases for superconducting magnets are robustly designed and solidly built structures. They withstand large pressures originating from magnetic fields, perhaps up to several hundred MPa. These vessels are similar to fission reactor pressure vessels, since they are thick walled, are under irradiation, experience temperature extremes, and undergo mechanical stresses. Powell et al.[4-36] also made this analogy for superconducting magnet cases. A nuclear pressure vessel 99% upper bound breach failure rate for an ASME Section I designed steam drum was reported by Bush[4-37] to be less than 1E-05/year. This random failure rate value is applicable to breach events for each well designed magnet case at a given fusion experiment. Magnet case responses to seismic events must be considered separately by analysts skilled in that type of analysis.

4.3.3 Superconducting Magnet Mountings. The discussion for the resistive magnet mountings also applies here, since the superconducting magnet weight is more closely approximated by fission plant turbine and generator weights (on the order of hundreds of tons per unit). The mounting failure rate calculated earlier is 2E-05/year, with an upper bound of 2E-04/year.

4.3.4 Superconducting Leads. These electrical power leads are a crucial interface between the magnet cryogenic area and the ambient environment. They need cooling and must simultaneously insulate the magnet windings against heat inleakage. Lead open circuits are similar to pipe rupture events, since the leads are usually hollow to provide gas cooling flow. Leads are also subject to the same sort of environment of the conductor conduit, which was treated as a pipe. My suggested pipe rupture value to apply to this hollow electrical lead open circuit failure rate is 1.5E-09/hour-meter. I noted that Powell et al.[4-36] cited an assumed lead open circuit failure rate of 1E-05/hour, a backup lead failure rate of 1E-03/demand, and a magnet sensor (or detector) failure rate of 1E-03/hour. I suggest using 1E-05/hour as the upper bound for lead open circuit failures.

Conductor lead arcing as a random failure rate is similar to circuit breaker arcing. This may not be the best analogy, since breakers can be inductively loaded, which can drive arcs more energetically than resistive magnet loads. However, this is the best information available, even if it might be overly conservative. If outside influences affect lead arcing, such as entry of foreign gases with different electrical breakdown characteristics, then this random failure rate is not appropriate. I assumed voltages up to 1000 Volts during superconducting magnet discharging when I chose the circuit breaker type. Circuit breakers can arc over between contacts when opening or closing. This is referred to as 'internal breakdown across open poles' in the literature, and has an average failure rate of 5E-07/hour, with an upper bound of 6.3E-07/hour, accounting for a high radiation environment.[4-8] This failure rate is applicable to an arc between two fusion magnet leads. Insulation failures may need to be taken into account, depending on the lead design. Buende[4-35] cited 1E-08/hour as the failure rate for a short circuit between a connection and the magnet case, such as an insulation breakdown failure.

4.3.5 Superconductor Electrical Insulation. Much work has been devoted to studying the mechanical behavior and irradiation behavior of electrical insulation for superconducting magnets. Unfortunately, accelerated life tests have been few. The Frascati Tokamak Upgrade (FTU) device tested some glass fabric epoxy insulation and showed that the samples would withstand over 20,000 laboratory test pulse cycles, in normal and cryogenic temperatures, for an upper bound failure rate of 5E-05/cycle (assumed to be equivalent to full power pulses).[4-38] Above 150 MPa axial stress the samples would degrade, but below that stress, there was no appreciable electrical degradation. However, this test was not performed on irradiated material. There is some concern that irradiation will weaken the insulation so that it mechanically cracks under normal operational stresses.[4-39] ITER magnet life is constrained by insulation useful life. Buende[4-35] cited an insulation breakdown failure rate of 1E-08/hour for a short circuit to a magnet case. Investigating further, I noted that epoxy insulation is used widely in electrical motors and other rotating machinery. My brief review of nuclear reactor primary coolant pump motor insulation failure rates showed results on the order of 1E-02 to 1E-03/year per motor.[4-40,4-41] This range is roughly one to two orders of magnitude larger than Buende's value; however, reactor coolant pump electric motor epoxy insulation is in potentially harsh high temperature and high vibration conditions rather than low temperature, higher irradiation, and moderate vibration conditions. Until more accelerated life testing is performed specifically for fusion magnet insulation, the 1E-08/hour random failure rate for insulation failures (assuming an error factor of 10) should be used. This is not a conservative failure rate if there have been machining chips, screws, nuts or bolts, tools, or other foreign materials, left in the machine.

Considering that major foreign material intrusion events have occurred twice (see Chapter 2) in the roughly fifty years of fusion and accelerator research, a point estimate failure rate is 2/50 years = 4E-02/year, with a 95% Chi square upper bound of 11.07/(2 x 50 years) = 1.1E-01/year. This is not a very satisfying statistic, since we do not have the information to give a per magnet failure rate. However, if we consider total operation in a year, 8760 hours/year, and a 1E-08/hour insulation random failure rate, this gives about 1E-04/year, or roughly a three orders of magnitude reduction in failure rate if quality assurance is very strict in keeping foreign materials out of the magnet.

Tables 4-1, 4-2, and 4-3 list the failure rates suggested here for water-cooled normal-conducting, cryogenic normal-conducting and superconducting fusion magnet risk and availability calculations. There has also been some failure experience reporting on electrical components for magnet electrical power systems,[4-42,4-43] and references 4-8 and 4-34 can also be used with conservatism.

The data reported in these two tables can be used for fault tree analysis to determine magnet-related initiating event frequencies and magnet availability. Risk and safety analysts appreciate that typically the order-of-magnitude for failure rates are the primary concern for quantifying fault tree analysis. In fact, extreme precision may not even be believed.[4-44] These gross estimates of magnet component failure rates should suffice for most analyses. .

The magnet availability task has already been performed for ITER, using similar failure rate primarily from nuclear fission data

TABLE 4-1. SUGGESTED FAILURE RATES FOR NORMAL-CONDUCTING FUSION MAGNET COMPONENTS

Subcomponent name	Failure mode	Suggested Failure Rate	Upper Bound Failure Rate
Conductor	breach	6E-03/mag-yr	1.3E-02/mag-yr
Conductor	plugging	5E-10/hour-m	1.5E-08/hour-m
Conductor connection	open circuit	5E-06/hr-joint	5E-05/hr-joint
Conductor connection	short circuit	5E-06/hr-joint	5E-05/hr-joint
Conductor cooling line	breach or leakage per 4 m section	2E-06/hour	3E-06/hour
Epoxy insulation	short circuit	1.6E-02/mag-yr	3.5E-02/mag-yr
Winding spacers	fracture	(a)	2E-05/mag-yr
Mounting	collapse,shift	2E-05/mag-yr	2E-04/mag-yr

Note: mag-yr stands for per magnet per operating year
hour-m stands for per operating hour per meter of length
hr-joint stands for per operating hour per joint

(a) Use of the 95% confidence upper bound is acceptable for most studies.

TABLE 4-2. SUGGESTED FAILURE RATES FOR CRYOGENIC COOLED NORMAL-CONDUCTING FUSION MAGNET COMPONENTS

Subcomponent name	Failure mode	Suggested Failure Rate	Upper Bound Failure Rate
Copper Bitter coil	fracture	3E-06/pulse	2.4E-05/pulse
Copper coil braze	fracture	3E-06/pulse	2.4E-05/pulse
Cooling channel	plugging	5E-09/hour-m	2E-07/hour-m
Magnet insulation	short circuit	3E-07/mag-hour	1E-06/mag-hour
Winding spacers	fracture	(a)	2E-05/mag-yr
Mounting	collapse or shift	2E-05/mag-yr	2E-04/mag-yr
Electrical leads	arcing per pair	5E-07/hour	6.3E-07/hour
Electrical leads	open circuit	2E-09/hour-m	1E-05/hour-unit
Magnet case	breach	(a)	1E-05/mag-yr

Notes: The times cited here are operating times, not calendar times.
Mag-yr stands for per magnet per operating year,
hour-m stands for per hour per meter of length
hour-unit stands for per hour per unit (pair of leads)
Cooling for these magnets will be treated in a future cryogenics system operating experience report.

(a) Use of the 95% confidence upper bound is acceptable for most studies.

TABLE 4-3. SUGGESTED FAILURE RATES FOR SUPERCONDUCTING FUSION MAGNET COMPONENTS

Subcomponent name	Failure mode	Suggested Failure Rate	Upper Bound Failure Rate
Conductor	open circuit	1E-07/hour-m	3E-06/hour-m
Conductor conduit	breach	3E-08/hour-m	1E-06/hour-m
Conductor conduit	plugging	5E-9/hour-m	2E-07/hour-m
Magnet insulation	short circuit	1E-08/mag-hour	1E-07/mag-hour
Winding spacers	fracture	(a)	2E-05/mag-yr
Mounting	collapse or shift	2E-05/mag-yr	2E-04/mag-yr
Electrical leads	arcing per pair	5E-07/hour	6.3E-07/hour
Electrical leads	open circuit	2E-09/hour-m	1E-05/hour-m
Magnet case	breach	(a)	1E-05/mag-yr

Note: The times cited here are operating times, not calendar times.
mag-yr stands for per magnet per operating year,
hour-m stands for per hour per meter
Cooling for these magnets will be treated in a separate report.

(a) Use of the 95% confidence upper bound is acceptable for most studies.

bases.[4-45] The overall magnet system random failure rates for the ITER design were calculated to be 3E-04/hour (error factor of 2) for the set of toroidal field magnets, and 1.5E-04/hour (error factor of 2) for the set of poloidal field magnets. Liberal estimates for downtime for the toroidal magnets is 1400 hours, and 4200 hours for the poloidal magnets.[4-45] More recent downtime estimates are on the order of several years rather than fractions of a year. These failure rates and repair downtimes should be comparable to similarly designed and sized magnets, and can be used as a validity check on results for future work.

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5. Magnet Initiating Events

This chapter discusses initiating events for superconducting magnets. Initiating events (IEs) are those failure events that can result in significant damage, so that passive or active protection systems are needed to protect either the magnet, the general public, plant workers, or all three. IEs are thought of as internal - faults within the facility or system, like weld failures, etc., and external - faults outside the system (earthquakes, aircraft impacts, etc.). Since future fusion experiments call for superconducting magnets, the effort for IEs will be directed toward those types of magnets. I first briefly summarize what the operating experiences are telling us, then I briefly review the work published to date on magnet initiators. Finally, I present a set of IE frequencies from these published evaluations for NET and ITER.

Table 5-1 gives the summary of the types of operating experiences listed at the end of Chapters 2 and 3. The major types of operational problems that would become IEs in a risk assessment would be those that are a large threat to orderly shutdown of the magnet (thus propagating an accident and leading to long downtimes for repairs), threats to adjacent systems (particularly the vacuum vessel, any coolant lines, or tritium lines), or threats to the confinement building. An explanation is given next to the summary description in Table 5-1 if I believe that it has the potential to threaten the magnets or other systems in a fusion facility. Accelerator experience shows us that fires from both electrical systems, such as faulty power supplies or electric arcs, and industrial operations, such as welding, are an area that need more risk analysis attention in fusion facility risk assessments. I discuss this more in section 5.2. Other possible IEs appear to be treated under major headings of Loss of Coolant, Loss of Flow, Loss of Insulating Vacuum, Short Circuit, etc.

The Toroidal Energy Storage Experiment (TESPE) in Germany and the Large Coil Task (LCT) at the Oak Ridge National Laboratory have contributed greatly to magnet safety knowledge regarding the ways that magnets can fail, the consequences of failures, and failure severity. Probabilities of failure are more difficult to find, but there is some published work in this area. Most of the data for basic magnet failure

TABLE 5-1. SUMMARY OF MAGNET OPERATING EXPERIENCES FOR INITIATING EVENTS

Superconducting Magnets

Loose ferrous objects in the magnetic field	An IE, could puncture a vacuum shield or torus port
Electric arcs Damaged electrical insulation Magnet turn-to-turn short circuit Electric arc between magnet leads Pancake-to-pancake short circuits due to foreign material intrusion Diagnostic lead short circuit	References 5-4 to 5-8 recognize arc events
Electrical fires Power supply short circuiting Helium compressor motor short circuit	This IE should be treated
Magnet quenches Plasma disruption induced magnet quenches	This event is treated as IE
Helium vent piping failures	This event could help propagate an accident
Insulating vacuum jacket rupture or breach Liquid helium boil and overpressure release from gas recovery system Cracked welds on magnet cases, leading to helium admission to vacuum insulation space Vacuum thermal shield leaks	This IE is treated in reference 5-6 as Loss of Insulating Vacuum
Cryogenic helium leaks	potential IE, Loss of Coolant
Bolt loosening from vibration and thermal cycling	possible IE if breaches system or becomes a missile
Human left in the experiment vault just prior to fusion pulse operations	Personnel hazard only
Unsoldered magnet inter-turn splices Niobium-Titanium superconductor strand breakage	IE, Rupture of a winding
Poor cryogenic system performance to keep magnets cool	--
Magnet training	--

TABLE 5-1. SUMMARY OF MAGNET OPERATING EXPERIENCES FOR INITIATING EVENTS (Continued)

Normal-conducting Magnets

Electrical fires Industrial fires	This IE must be treated
Loss of cooling water into the building Failure to provide adequate cooling water Magnet overheating by connection to incorrect power supply Magnet overheating due to inadvertent switch of cooling water lines	This IE is treated under Loss of Coolant Accident
Loss of cooling water flow Foreign material intrusion in cooling water	This IE is called Loss of Flow Accident
Loose wrench in the magnetic field causing a short circuit in buswork	This IE should be treated
Short circuits due to improper epoxy insulation Electrical power transients causing magnet short circuits Inter-turn insulation failure Electric arc because of ground fault	Short circuits and arcs are IEs treated by safety work
Plasma electromagnetic forces generated damaging current in an unused PF coil	This IE needs further treatment
Bolt loosening from vibration and thermal cycling	possible IE if breaches system or becomes a missile
Sabotage (two events during the US-Vietnam Conflict)	--
Cooling water temperature fluctuations	--
Support system instrumentation faults - flowmeters	--

rate quantification appear to have come from nuclear fission plant data sources.

Magnet failures and their effects on other systems are regarded as important to overall fusion facility safety, as discussed for the IGNITOR and ITER projects.[5-1,5-2,5-3] Magnets contain stored electrical energy that can volatilize irradiated metals, either the magnet itself or adjacent structures, and such faults could easily release cryogenic liquids whose overpressure could defeat confinement building integrity. Magnet motion, even on the order of a few centimeters, could break tritium lines or diagnostic penetrations into the vacuum vessel and lead to radioactive releases. Even for less severe transients, magnets are very hard to repair, and significant downtime, months to years - or even several years - could be realized when trying to replace a coil. Therefore, magnet transients are an important issue for fusion facilities.

5.1 Internal Events

A set of superconducting magnet initiating events from the Next European Torus (NET) magnet safety study is given in Table 5-2.[5-4,5-5,5-6] The IE frequencies of occurrence are cited or estimated from the published work and are presented in this table. Other work by Buende[5-7] is also included in this table. Work by KfK also lists these same initiators.[5-8] Table 5-3 gives some International Thermonuclear Experimental Reactor (ITER) magnet IE frequencies.[5-9] These frequencies are specifically calculated for the NET and ITER machines, but can be applied as order-of-magnitude indicators to forced flow superconducting magnets of similar design, especially for screening out low probability accident scenarios. Specific IEs for a given design must be calculated using component failure rate data or human error probability data. Typically, fault trees are used to provide IE frequencies.

There are other internal events of concern not addressed in the tables.[5-10] As stated by Montgomery[5-11] and from 1979 Princeton Large Torus operating experience with a wrench breaking a vacuum window,[5-12] unsecured tools in the magnetic field have caused

TABLE 5-2. SUPERCONDUCTING MAGNET INITIATING EVENTS FROM NET STUDIES

Initiating Event Title	IE Frequency	
TF Coil Quench	1.5E-01/year	Reference 5-3, and 5-4
TF Coil loss of Wire Continuity	> 1E-03/year	
Arcing due to Coil Damage	> 1E-02/year	
Complete TF Coil Break	> 1E-04/year	
Large Cryogenic Loss of Coolant	1E-04/year	
PF Coil Quench	> 1E-04/year	
Complete PF Coil Break	> 1E-02/year	
Short Circuit in TF Current Leads	1E-08/hour	Reference 5-5
Rupture of a TF Current Lead	1E-09/hour	
Short Circuit in a TF Winding	1E-07/hour	
Rupture of a TF Winding	1E-09/hour	
Short Circuit in TF Pancake Connection	1E-08/hour	
Rupture in TF Pancake Connection	3E-09/hour	
Loss of Insulating Vacuum	3.4E-03/year	Reference 5-6

TABLE 5-3. SUPERCONDUCTING MAGNET INITIATING EVENTS FROM ITER STUDIES

Initiating Event Title	IE Frequency	
TF Coil quench (per coil set)	9.6E-05/hour	Reference 5-9
TF Coil external short circuit (per coil set)	1E-12/hour	
TF Coil internal short circuit (per coil set)	6.4E-06/hour	
PF Coil quench (per coil set)	3.5E-04/hour	
PF Coil external short circuit (per coil set)	3.6E-12/hour	
PF Coil internal short circuit (per coil set)	5.5E-05/hour	

Note: Assuming 25% availability for ITER gives about 2200 hours/year. These failure rates are generally order-of-magnitude comparable to those presented for NET, which demonstrates reasonable accuracy, given the design differences and the applicability of the data. The 3.6E-12/hour rate for PF coil faults is extremely low, virtually insignificant. I do not have an explanation for this value.

unwanted events at fusion facilities. As Chapter 2 of this report discussed, the medical industry has had a significant problem with this sort of event, including many personnel and MRI patient injuries. The probability of leaving a ferritic object, such as a tool or a lost bolt, etc., in the work area is on the order of 1E-02/maintenance session, based on human error rates.[5-13] Also, magnet charging and discharging transients can create an overcurrent condition that allows a sustained arc event if the magnet protective systems do not actuate to dissipate the electrical energy in the coils. Such transients could occur with a frequency as high as 1E-02/year.[5-14] If protective systems are considered comparable to fission reactor protective systems, then a failure rate for such a system is 3E-05/demand.[5-14] Spurious (unneeded) protective system actuations should be expected to occur as a 1/year event, just as unnecessary nuclear power plant shutdown events occur yearly due to their protective systems sending false signals.

There have not been any magnet structural failures or fatigue failures in fusion experiment magnets. A rough probability based on this experience is zero failures in roughly 45 years to give a 50% Chi square point estimate of 5E-03/year that any of the magnets would suffer a major structural failure. There is a considerable positive feeling among designers that this sort of worst case 'magnet missile' structural failure event has been totally designed out of fusion magnets, to give a less than 1E-06/year frequency (meaning not credible). Indeed, magnet safety work for a fusion experiment[5-15] and for a superconducting MHD[5-16] experiment gives the probability of major structural failure as "Low", meaning that it is not expected to occur over the life of the facility. This is certainly in the 1E-04 to 1E-06/year frequency range. For completeness, we must acknowledge that magnet structural failures encompass more than just the worst case missile event. Magnet shifting, even on the order of a few centimeters, was already explained to be a safety threat. A concerted effort on the part of ITER designers to design in high coefficients of friction for the TF magnets on ITER should mean that some outside perturbation or failure event must occur to cause magnet shifting. Either highly unbalanced magnetic forces, pedestal failure, or an earthquake are the likely causes of magnet shifting. We now have an individual magnet mount or pedestal failure rate on the order of

2E-05/year, from Chapter 4. However, that is an extremely low failure rate. Therefore, for conservatism, I assume that magnet shifting will occur with a frequency of 1E-04/year,[5-9] which is the generally assumed design value for the return period of a severe earthquake at a given site.

Loss of magnet coolant flow should be addressed, since inadvertent valve closures, human errors, or control errors could result in no helium flow. A human error rate of 1E-03/machine operating period will likely dominate the probability for that event,[5-13] although computer control faults should also be examined.

The events discussed here and their frequencies can serve as a guide for future magnet safety analysis and risk assessment work. External events, including fires, are discussed in the following subsection.

5.2 External Events

Magnet responses to external events should be considered for a complete treatment of magnet safety. Among the most frequently occurring of the so-called external events are fires inside buildings. Electrical fires could cause electrical events inside the magnet set, such as partial depowering. Fires could also cause liquid helium boiling, which leads to insufficient magnet cooling, vapor locking of flow, etc. Electrical and industrial fires might occur with a rough frequency of 3E-02/year, based on fission reactor experiences.[5-14] Recall that the Brown's Ferry power plant fire began as a small cable tray fire that became a major event as the staff struggled to get the plant back under control with the loss of so many electrical control signal cables.[5-17]

Magnet motion during seismic events is important, if the cases move or if cooling pipes sway and impact on the more rigid casings. Water floods inside the building could cause cryogenic system and electrical equipment problems. Cryogenic system breaches must be examined for their damage to the magnet system, their release of cold fluid into the room, and the effect of overpressure on the confinement building. Can cryogens freeze water piping into fracturing or plugging from ice buildup? Can cryogens cause electrical cable degradation due to thermal contraction? Flooding is often overlooked in fission power plants, but should be considered as a design basis event for fusion, so that adequate provision for water or cryogen draining - in case of a pipe leakage/rupture event or fire suppression system actuation event - has been made.[5-18] Significant seismic events and major in-building floods are probably on the order of 1E-03 to 1E-04 events per year. I note that for several fission reactor risk assessments, while no single IE is a major contributor to risk at all power plants, external events (earthquakes, fires, and floods) were a significant portion of the overall facility risk profile, on the order of 40% to 80% of plant risk.[5-19] These events cannot be ignored.

Electrical power outages from switchyard problems, lightning strikes, incoming power lines arcing over, etc., would not greatly affect the flywheel energy storage systems for PF magnet power, but would hamper control room instrumentation readings, electrical control power, and would challenge safe shutdown backup power sources. Loss of offsite power events would probably be on the order of 0.5 to 1/year during facility operation. Of course, these estimates are only informed judgements based on my risk assessment experience. Future fusion facilities would need site specific data gathering to calculate good internal and external IE frequency estimates.

Design-specific event external to the magnets themselves, such as loss of the cryoplant or the computer control system, can be difficult to quantify. There are also other events that are difficult to quantify without specific information. For example, water coolant lines for the fusion blanket, first wall, or divertor could breach and allow steam or hot water to impinge on the magnet casings. Flywheels, if used at a given facility, could fracture and present concerns similar to fractured turbine blades at conventional power plants.

Other external event frequencies would be highly site specific, such as those for aircraft impacts, forest fires, dam failures, heavy rains, mudslides, hail storms, etc. Analysts must judge what appropriate probabilities would be, based on site meteorological data and other information. Review of safety information for other industrial and scientific facilities in the regions near the proposed site should support these additional analyses. I have noted that the United Nations Educational, Scientific and Cultural Organization (UNESCO) publishes annual summaries of natural disaster information, which is a useful source of data for finding severity and return periods for external floods, forest fires, heavy snowfalls, extreme hailstorms, mudslides, etc., around the world.

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APPENDIX A

SUMMARY INFORMATION ON SELECTED MAGNET FAILURE EVENTS

APPENDIX A

This appendix contains a reproduction of magnet failure event citations from the less accessible past studies of magnet historical operating experiences. Work by Powell et al.[A-1] and Thome and Czirr[A-2] is treated. More recent events from the past six years are discussed in the main body of this report.

Table A-1 gives citations from the work by Powell et al.[A-1] More information on these failures, including photographs, can be found in Hsieh et al.[A-3] Table A-2 gives a reproduced table of the failure events collected by Czirr and Thome.[A-2] More information on those failures can be found in Thome et al.[A-4]

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TABLE A-1. MAGNET SYSTEM FAILURES

Magnet Classification	Failure Description	Cause of Failure	Notes
Alternator	Sections of lead wire conductor evaporated and magnet arced to ground causing some damage to the outer outer helium dewar wall.	Lead conductor does not have adequate copper to keep the temperature low during quench condition. Insufficient lead cooling.	Six turns of damaged conductors were stripped and the magnet is back in operation with an asymmetrical coil.
Accelerator Field Coil	Lead wire melted open and magnet arced to ground.	Insufficient cooling of the lead conductor due to the plug of cooling channel.	Magnet was repaired and is operational.
Bubble chamber magnet	Power lead overheated causing hydrogen leaks into helium dewar vacuum space.	Insufficient lead cooling flow arising from inadequate instrumentation.	Magnet intact and power lead was repaired. System is operational.
SUMMA magnet tests	Outer NbTi coil of 4th magnet: Insulation and end packing strips were blown out and magnet arced in many places.	Insufficient mechanical support and electrical insulation.	The magnet was repaired.
	The Nb_3Sn inner coil shorted among pancakes at the ends due to slipping of Nb_3Sn ribbon under pancake separator strips.	Insufficient mechanical support.	Coil was repaired.

TABLE A-1. MAGNET SYSTEM FAILURES (Continued)

Magnet Classification	Failure Description	Cause of Failure	Notes
SUMMA magnet operations	One of the 32 power leads connected to an outbore coil pair overheated and was damaged during operation.	Insufficient cooling and instrumentation.	Lead was replaced, the magnet is operational, but its performance was degraded from 400 amps to 260 amps.
Beam transport magnet	One of the power leads overheated and the conductor wire connected to this lead melted. The magnet arced to ground.	Faulty power lead, insufficient instrumentation, and improper lead wire installation.	New power leads were tested before installation, the damaged
Prototype Synchrotron magnet	Arcing between current feed under liquid helium.	One of the current feeds broke off at full current.	Magnet intact and a new current feed was installed.
High field Solenoid	Mechanical deformation of Nb_3Sn pancakes. The NbTi coil and the 1.27 cm thick stainless steel end plate. Minor damage due to arcing after the mechanical failure of the NbTi coil.	Diamagnetic force and insufficient mechanical support.	Both coils have been rewound and potted with epoxy resin. Magnet is operational.
Energy doubler accelerator magnet	Arcing produced between coil shells and windings were burned open.	Energy removal system was short circuited due to failure of the powering circuit, causing dissipation of stored energy. Also, dielectric breakdown between coil shells when the helium boiled and heated to 400 K.	All but one half shell windings were burned beyond repair and the remaining one was damaged.

TABLE A-1. MAGNET SYSTEM FAILURES (Continued)

Magnet Classification	Failure Description	Cause of Failure	Notes
Beam transport magnet	Burnout occurred between two corresponding coils at the same radius, one on each pole.	Believed to be a short between windings.	Failure occurred during testing with only part of the windings completed. Additional insulation was added to repair the magnet.
Levitated Ring magnet	Coil degradation due to conductor movement.	Insufficient mechanical support.	A spare ring was installed to continue operations.
Test Solenoid magnet	The lead wire melted. The magnet quenched, but the coil was not damaged.	Design error	
Hybrid magnet	Degradation, each time the magnet is operated it quenched at a lower current than previously.	Probably due to the quality of the conductor	Coil will be rewound with modern NbTi composite.
3-Section Solenoid magnet	Lead failure, one of the power leads connected to the center section burned.	Insufficient instrumentation and insufficient cooling flow. The lead may have been defective.	The magnet parameter of this solenoid will not be reported, since it is not being used.
	Coil damage to the center section. Total room temperature resistance is lower than before.	Unknown, perhaps arcing during the quench after the lead accident.	

TABLE A-2. MAGNET ACCIDENT DESCRIPTIONS REPRODUCED FROM CZIRR AND THOME

The following pages give A table from Chapter three of the report by Czirr and Thome,[A-2] where 31 magnet and magnet related events are briefly described. More information is available in reference A-4.

EVENT	MAGNET DESCRIPTION	NUMBER OF SC COILS	NUMBER OF COPPER COILS	COIL GEOMETRY AND SIZE	NUMBER OF CIRCUITS	MAXIMUM STORED ENERGY (MJ)	MAXIMUM POWER DISSIPATION (MW)	MAXIMUM OPERATING CURRENT (KA)	MAXIMUM APPLIED VOLTAGE (V)	MAXIMUM DISCHARGE VOLTAGE (V)	MAXIMUM VOLTAGE TO GROUND (V)	TOTAL HOURS OF OPERATION	NUMBER OF OPERATING CYCLES TO DATE	NUMBER OF THERMAL CYCLES TO DATE	NOTES
3.1 Lead Burnout	Short Sample test apparatus & dewar in bore of Solenoid	-	1	0.15 m ID Solenoid	1 for Solenoid.	~8	~8	~40	~200	~200	200	-	-	-	Magnet circuit OK
					1 for short sample apparatus	-	-	14	-	-	~10	-	-	-	Lead burnout in short sample circuit
3.2 Short Circuit in SC Coil	2 Copper Solenoids nested in SC Solenoid	1	2	0.035 m ID Copper, 22 T	1 for Copper	~8	7.7	40	~220	~220	220	300	>300 hrs	75–100	SC system operable at reduced voltage after development of short in winding
				0.356 m ID SC, 7.5 T	1 For SC	3.5	-	1.5	10	600	300	300	>300 hrs	75–100	
3.3 Lab. Dewar Overpressure	—	-	-	-	-	-	-	-	-				-	-	Rupture of unattended, small, laboratory helium dewer
3.4 Error in PLC Utilization	Axisymmetric tandom mirror with baseball anchors	-	70	47-0.8 m ID solenoids; 9-0.25 m ID solenoids; 4-1.6 m ID solenoids; 2-baseballs 4-cees 4-0.6 m ID solenoids;	12	~5	10	3.4	450	450	225	~200	~5000	~5000	Bellows between magnet sections stretched due to overcurrent condition

EVENT	MAGNET DESCRIPTION	NUMBER OF SC COILS	NUMBER OF COPPER COILS	COIL GEOMETRY AND SIZE	NUMBER OF CIRCUITS	MAXIMUM STORED ENERGY (MJ)	MAXIMUM POWER DISSIPATION (MW)	MAXIMUM OPERATING CURRENT (kA)	MAXIMUM APPLIED VOLTAGE (V)	MAXIMUM DISCHARGE VOLTAGE (V)	MAXIMUM VOLTAGE TO GROUND (V)	TOTAL HOURS OF OPERATION	NUMBER OF OPERATING CYCLES TO DATE	NUMBER OF THERMAL CYCLES TO DATE	NOTES
3.5 Dump Resistor Arcing	SC Racetrack pair with test coils in gap	2	0	6 T race track pair (gap: 0.1 m x 0.35 m x 1 m	1 for race track; 1 for test coils	11	-	4.1	~10	~1000	~500	< 20	~100	~5	Arcing in dump resistor with no failure propagation
3.6 Structural Failure	Dual mode water or LN Cooled Saddle magnet	-	2	Saddle Coils (bore 1m square x 7 m long)	1	160	~15	9.4	1600	1600	~800	1	~30	~10 (<300 K) ~20 (<160 K)	Failure in primary structure; electrical values given are at failure point
3.7 Sensor Leads Short to Winding	Large D-Coil	1	0	D-shape 3 x 5 m	-	100	-	10	-	800	-	0	0	0	Coil not tested yet
3.8 Lead Burnout	Short Sample test in SC 8 T split Solenoid	1	0	Solenoid 6" ID 1" split	-	-	-	-	-				-	-	Magnet system OK Leads of short sample circuit burned out
3.9 Bad Structural Weld	Large D-coil	1	0	D-shape 3 x 5 m	-	100	-	10	-	800	-	0	0	0	Coil not tested yet
3.10 Dipole Short	Accelerator steering magnet	1320	1300	Quadrapoles dipoles, spool magnets	24*	0.5 per dipole	-	4.4	12kv total	2500	2500	~0	few	2	*Power supplies for accelerator ring; turn-to-turn short circuit

EVENT	MAGNET DESCRIPTION	NUMBER OF SC COILS	NUMBER OF COPPER COILS	COIL GEOMETRY AND SIZE	NUMBER OF CIRCUITS	MAXIMUM STORED ENERGY (MJ)	MAXIMUM POWER DISSIPATION (MW)	MAXIMUM OPERATING CURRENT (kA)	MAXIMUM APPLIED VOLTAGE (V)	MAXIMUM DISCHARGE VOLTAGE (V)	MAXIMUM VOLTAGE TO GROUND (V)	TOTAL HOURS OF OPERATION	NUMBER OF OPERATING CYCLES TO DATE	NUMBER OF THERMAL CYCLES TO DATE	NOTES
3.11 Splice Failure Between Dipoles	Between accelerator dipoles	1320	1300	-	-	-	-	-	-	-	-	0	0	0	3 joints not soldered out of ~2000 when system assembled
3.12 Vacuum Leaks in Beam System	Accelerator beam system	1320	1300	-	-	-	-	-	-	-	-	0	0	1	3 vacuum leaks in joints between magnets
3.13 Lead Burnout	Accelerator spool magnet	-	-	-	-	-	-	-	-	-	-	2000			Software error in power supply control
3.14 Grounded Input Leads	Accelerator steering magnet	-	-	-	-	-	-	-	-			500 to 2000	1-4 mo of high field running	13-17	5 lead failures out of 200 magnets with similar defects in construction
3.15 Partial Quench & Helium Loss	Large bore SC magnet surrounding bubble chamber	2	0	500 cm OD x 188 cm double solenoid	1	396	-	5.0	10	180	-	2×10^4			Coil was allowed to operate at low helium level; quench on discharge led to overpressure & loss of helium
3.16 Insulation Failure	Time projection chamber magnet	1	0	2.2 m diam. 3.3m long	1	11	-	2.2	10	2300	2300	During acceptance test		-	Caused by iron chip

EVENT	MAGNET DESCRIPTION	NUMBER OF SC COILS	NUMBER OF COPPER COILS	COIL GEOMETRY AND SIZE	NUMBER OF CIRCUITS	MAXIMUM STORED ENERGY (MJ)	MAXIMUM POWER DISSIPATION (MW)	MAXIMUM OPERATING CURRENT (kA)	MAXIMUM APPLIED VOLTAGE (V)	MAXIMUM DISCHARGE VOLTAGE (V)	MAXIMUM VOLTAGE TO GROUND (V)	TOTAL HOURS OF OPERATION	NUMBER OF OPERATING CYCLES TO DATE	NUMBER OF THERMAL CYCLES TO DATE	NOTES
3.17 Lead Burnout	Accelerator dipole	6	0	Dipole 1.0m long	1	~0.8	-	1.2	60	700	700	During testing phase	1(for group of 6 magnets)	4	Power supply circuit miswired
3.18 Ground Short	Baseball magnet	2	0	Baseball 1.7m x 1.7m	1	17.3	-	2.4	-	-	-	Few			Inadequate ground insulation
3.19 Lead Vacuum Leak	Baseball magnet	2	0	Baseball 1.7m x 1.7m	1	17.3	-	2.4	-	-	-	Few			Thermal expansion/contraction of seals following quench led to vacuum loss.
3.20 Structural Failure	Cu baseball magnet	0	1	1m diam. baseball magnet	1	2.5		4.2					~200		Low-cycle high stress fracture in tie bolts
3.21 Short Between Layers	Simple Solenoid for magnet development tests	1	0	Solenoid ID 61.2 cm, OD 68.4 cm length 15.2 cm	1	0.55	-	0.15	5.0	6.6 KV	6.6 KV	~400	34	14	Short developed during quench; short removed and magnet repaired; test continued as planned.
3.22 Dump Resistor Failure	Cyclotron Magnet	4	0	180cm diam. x 50cm long	2	17	-	0.7	10-20	200	200	Few	100-1000 at full field	11	Burnout due to low water level
3.23 Broken Support Link	Cyclotron Magnet	4	0	180cm diam. x 50cm long	2	17	-	0.7	10-20	200	200	Few			Overload on link supporting coils within iron return frame

EVENT	MAGNET DESCRIPTION	NUMBER OF SC COILS	NUMBER OF COPPER COILS	COIL GEOMETRY AND SIZE	NUMBER OF CIRCUITS	MAXIMUM STORED ENERGY (MJ)	MAXIMUM POWER DISSIPATION (MW)	MAXIMUM OPERATING CURRENT (kA)	MAXIMUM APPLIED VOLTAGE (V)	MAXIMUM DISCHARGE VOLTAGE (V)	MAXIMUM VOLTAGE TO GROUND (V)	TOTAL HOURS OF OPERATION	NUMBER OF OPERATING CYCLES TO DATE	NUMBER OF THERMAL CYCLES TO DATE	NOTES
3.24 Turn to-Turn Short	Cyclotron Magnet	4	0	180cm diam. x 50cm long	2	17	-	0.7	10-20	200	200				Short in well-cooled design. Did not hamper operations
3.25 Heat-Shield Deformation	Cyclotron Magnet	4	0	180cm diam. x 50cm long	2	17	-	0.7	10-20	200	200				Eddy currents due to quench deformed thermal radiation shield
3.26 Helium Loss Due to Quench	Cyclotron Magnet	4	0	180cm diam. x 50cm long	2	17	-	0.7	10-20	200	200				Coil operated with low helium level
3.27 SCR Failure	Accelerator dipole	1	0	0.12m aperture ~4.5m long	1	0.75	-	4.0	-	-	-		-	-	Failure of SCR to stay off led to excesive energy input, quench and overpressure.
3.28 Flux-Jump Induced Quenches	6 accelerator dipole magnets	6	0	0.12m aperture ~4.5m long	1	4.5	-	4.0	-	-	-		-	-	Inadequate splice design for fast discharge initiated quench
3.29 Local Normal Region Burnout	300KJ, 10KA pool bath cooled	1	-	~0.7m Solenoid	1	0.54	-	13.4	200	68 kv	68 kv	3	30	5	Coil intentionally driven to sample limit and burnout

EVENT	MAGNET DESCRIPTION	NUMBER OF SC COILS	NUMBER OF COPPER COILS	COIL GEOMETRY AND SIZE	NUMBER OF CIRCUITS	MAXIMUM STORED ENERGY (MJ)	MAXIMUM POWER DISSIPATION (MW)	MAXIMUM OPERATING CURRENT (kA)	MAXIMUM APPLIED VOLTAGE (V)	MAXIMUM DISCHARGE VOLTAGE (V)	MAXIMUM VOLTAGE TO GROUND (V)	TOTAL HOURS OF OPERATION	NUMBER OF OPERATING CYCLES TO DATE	NUMBER OF THERMAL CYCLES TO DATE	NOTES
3.30 Inadequate Suppcrt Link	TPC detector magnet	1	0	2.2m diam. x 3.3m long	1	11	-	2.2	10	2300	2300	0	many (no iron)		Support link had insufficient spring constant relative to force changes vs displacement between coil and iron.
3.31 Magnet Lead Burnout	Detector sole	1	0	2 m diam x	1	9.4	-	1.6	5	~300	~300	100	10	3	Insufficient lead t a feedthrough

END

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