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CRYOGENIC SYSTEM OPERATING EXPERIENCE REVIEW FOR FUSION APPLICATIONS

L. C. Cadwallader

EG&G Idaho

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FOREWORD

This report was funded by the International Thermonuclear Experimental Reactor research and development task. The report is part of a series of reports on operating experience compilations from fusion experiments and similar technologies, such as particle accelerators, the chemical industry, and space exploration programs. The first report, EGG-FSP-9977, was on magnets. This report is a companion to the magnet report, since cryogenics are mainly used in fusion research as superconducting magnet coolant. The next planned report will be on vacuum systems. There are also two other reports on data analysis of actual tritium component operating experiences, EGG-FSP-8973 (a tritium waste treatment system) and EGG-FSP-9450 (tritium air monitors). The next planned report for tritium components will be on gloveboxes.

ABSTRACT

This report presents a review of cryogenic system operating experiences, from particle accelerator, fusion experiment, space research, and other applications. Safety relevant operating experiences and accident information are discussed. Quantitative order-of-magnitude estimates of cryogenic component failure rates and accident initiating event frequencies are presented for use in risk assessment, reliability, and availability studies. Safety concerns with cryogenic systems are discussed, including ozone formation, effects of spills, and modeling spill behavior. This information should be useful to fusion system designers and safety analysts, such as the team working on the International Thermonuclear Experimental Reactor design.

EXECUTIVE SUMMARY

This report outlines cryogenic system operating experiences and accident events for use by fusion system designers and safety analysts. Cryogenic liquids are used for tokamak vacuum systems, neutral beam vacuum systems, pellet injectors, and magnet coolant. Magnet coolant systems are the largest, with system capacities 10's of cubic meters of liquid helium, perhaps up to 80 cubic meters. The cryogenic system, or cryoplant, must be available for magnets to be operable. Therefore, events causing downtime in the cryogenic system will affect the entire facility. This report discusses existing system operations, operational difficulties, major cryogenic accidents that have occurred, the use of field experience information from other industries to quantify component behavior, and presents what information can be learned from safety work from other industries that use cryogens. Learning from other industry experiences enhances design processes and safety, and insures a higher level of practical completeness in facility risk assessment.

The largest problems with system operations are related both to design and to operations/maintenance personnel. The largest design problem is properly calculating heat inleakage to the system. This is very difficult when one considers that the system may not be constructed exactly as shown on the drawings. System operations personnel from several operating facilities suggest oversizing the cryoplant, by 20% to 50%, even up to 100% excess capacity, to account for variations in heat inleakage. While additional capacity is expensive, the consequences of not being able to operate the machine surely outweigh the cryogenic system construction and operating costs.

The largest operations problem is inleakage of gases into the systems, causing freeze plugging and heat inleakage through the vacuum insulation. Building and maintaining a leak-tight system is not a trivial matter. 'Cold leaks' have occurred in most systems; that is, systems that are leak-free at room temperature develop small leaks when cooled to cryogenic temperatures. Even if future cryogenic systems are housed in helium or nitrogen atmospheres (less neutron activation than with an air atmosphere), inleakage gases will still present heat inleakage and freeze plugging concerns.

Cryogenic accidents have occurred in space programs, the chemical industry, and accelerator research. I found one citation of 3 suffocation fatalities from a nitrogen gas cloud, and one air separation plant event where five workers nearly suffocated from nitrogen exposure. Significant releases of cryogens have occurred in the US, greater than 2,000 m^3 of liquid oxygen from a space program storage tank, and releases up to 120 metric tons of ammonia from chemical plants. There have been many small public evacuations from the vicinity of US chemical plants, with some of these due to cryogenic gas (liquefied natural gas, liquefied petroleum gas, ammonia, etc.) releases. Such large releases cannot be overlooked for future fusion facilities, where several cubic meters of reserve liquid helium and liquid nitrogen will be stored for system startup cooldowns and possible magnet quench recoveries.

Large releases of cryogenic fluids pose several concerns. First, the confinement building may be at risk because of the effects of cold gas intrusion. The building pressure will drop by several 10's of kPa in a few minutes, then increase to several 10's of kPa overpressure as the cryogenic gas warms over the next hour. Therefore, confinement building seals and penetrations that normally experience only slight underpressures will be exposed to large pressure variations in relatively short time frames. The next concern is that cryogenic gas releases form a 'pancake cloud' shape that is characteristic of denser-than-air releases, and plant workers are at risk. Also, any radioactive isotopes entrained in the cloud (tritium, activated air, activated dusts, etc.) will produce higher doses at the site boundary, at least until the cloud warms and disperses - perhaps in a matter of minutes, unless the release is sustained over a long time period. Of course, activated aerosols may not be entrained in the cold gas cloud because of plateout on cold surfaces in the building, but since the fission industry has not been able to adopt a workable guideline for fission product plateout, it is unlikely that fusion safety work will be able to do so in the near future. Another effect of a large release is that the fusion magnets may be damaged, either structurally or by electric arcing when the cryogenic system is breached, allowing cryogen phase change. The final problem with large releases is one of public relations, which may threaten premature shutdown rather than speedy repairs.

I have taken cryogenic system component failure rates and initiating event frequency values from the literature on cryogenic systems and reviewed them for applicability to fusion systems. The results are given in the last two chapters of this report, and the failure rates are given in Table S-1 as well as in the text. The most notable difference from past practices is in the use of failure rates for cryogenic piping. Past work has typically used fission reactor derived failure piping rates for application to cryogenic piping. This is because the fission industry has compiled the best data sets. However, cryogenic piping is designed to be thin walled to reduce conduction heat transfer down the length of the pipe from the heat source (in our case, the magnets) to the rest of the system. Cryogenic piping can be 2 to 4 times thinner walled than fission reactor piping, and cryogenic piping is never clad with another material. Using a liquefied natural gas data base, I found that cryogenic piping failure rates were over a factor of 1000 higher than those for fission reactor piping. Fortunately, cryogenic piping runs are usually short, so there should not be too much effect in the risk profile from this suggested new failure rate. Cryogenic piping is also at risk from earthquakes, since it is thin walled and may not be able to carry seismic-induced stresses as well as the thicker walled fission reactor piping.

TABLE S-1. SUMMARY OF ORDER-OF-MAGNITUDE FAILURE RATES FOR CRYOGENIC SYSTEM COMPONENTS APPLICABLE TO FUSION FACILITIES

Component Description	Failure Rate	Error Factor*
Small reciprocating compressor		
all failure modes	3E-03/hour	10
Large reciprocating compressor		
all failure modes	5E-05/hour	100
Large turbo-compressor		
all failure modes	1E-04/hour	10
Small, dry reciprocating gas expander		
all failure modes	3E-04/hour	3
Small, wet reciprocating expander		
all failure modes	2E-04/hour	3
Axial flow turbo-compressor	5E-05/hour	10
all failure modes		
Plate and fin heat exchanger		
major failures (breach)	6E-06/hour	100
minor failures (leakage)	1E-05/hour	100
Motor-operated valve (all sizes)		
fails to operate on demand	1E-03/demand	3
plugging	1E-04/demand	3
external rupture	6E-07/hour	5
leak past the seat	3E-03/hour	5
freezing up in position	6E-07/hour	100
Air-operated valve (all sizes)		
fails to operate on demand	3E-04/demand	3
plugging	1E-04/demand	3
external rupture	6E-07/hour	5
leak past the seat	3E-03/hour	5

* note: The error factor is defined here as the upper bound/average value

TABLE S-1. SUMMARY OF ORDER-OF-MAGNITUDE FAILURE RATES FOR CRYOGENIC SYSTEM COMPONENTS APPLICABLE TO FUSION FACILITIES (Continued)

Component Description	Failure Rate	Error Factor
Pressure relief valve (all sizes)		
fail to open on demand	1E-02/demand	5
external rupture	6E-07/hour	5
premature opening	1E-05/hour	3
Motor-driven centrifugal pump (all sizes)		
fail to continue to run	3E-04/hour	100
fail to start on demand	3E-03/demand	5
fail to run at rated speed	2E-05/hour	100
external breach failure	1E-09/hour	30
Large cryogenic storage tank breach	1E-06/year	10
Liquid level sensor		
incorrect output	2E-03/hour	2
no output	6E-04/hour	2
erratic indication	4E-05/hour	2
Pressure transducer		
low output	8E-03/hour	2
high output	7E-03/hour	2
erratic output	6E-03/hour	2
external leakage	7E-04/hour	2
Venturi flow meter, all modes	1E-05/hour	10
Silicon diode temperature detector		
all failure modes	1E-05/hour	10
Cold cathode vacuum gauge		
all failure modes	1E-07/hour	10
Steel gas cylinder breach	1E-02/year	8

TABLE S-1. SUMMARY OF ORDER-OF-MAGNITUDE FAILURE RATES FOR CRYOGENIC SYSTEM COMPONENTS APPLICABLE TO FUSION FACILITIES (Continued)

Component Description	Failure Rate	Error Factor
Insulated dewar boils dry	3E-02/year	10
Metal cryostat inner or outer shell breach	1E-03/year	4
Concrete cryostat breach	1E-06/year	10
Cryogenic pipe (all diameters)		
breaches	5E-09/hour-m	100
leakage	6E-10/hour-m	100
Metal bellows breach failure (based on 7000 operating cycles)	3E-05/demand	10
Weld, small leakage failure		
Longitudinal weld	6E-08/hour-m	5
Butt weld	6E-09/hour-m	5
Circumferential weld	6E-10/hour-weld	5
Pipe fitting weld	1E-08/hour-fitting	5

Note: gas handling plant component failure rates are given in Table 5-1 Weld multipliers: large leak failure rate is 0.1 x given values, field weld failure rates should be 3.16 x given values, and maintenance welds should be 10 x given values. Weld ruptures should be 1E-02 x the given values. I estimate that small leaks can range from drops per minute to 5% of pipe flow, or 190 l/min, whichever is larger. Large leaks likely range from 5% up to 50% of pipe flow, and ruptures are taken to be 100% of pipe flow.

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I want to thank the reviewers, particularly Bob Fleming and Mike Marchlik at Princeton for their technical review. Of course, the conclusions are my own. Steve Piet and Doug Holland in Idaho gave significant time to review the total report. I would also like to thank the library staff for their time and effort to help collect all of the reference materials necessary for this document. The data collection task was both broad and seemingly endless. International Thermonuclear Experimental Reactor Safety and Environment task funding made this work possible.

NOMENCLATURE

BPA	Bonneville Power Administration
BPX	Burning Plasma Experiment
C	Celsius temperature scale
CERN	Center for European Nuclear Research
DOE	Department of Energy
K	Kelvin temperature scale
kJ	kiloJoules
kW	kiloWatts
IE	Initiating event
ISR	Intersecting Storage Ring experiment at CERN
l	liter
LCT	Large Coil Task
LHe	Liquid helium
LN2	Liquid nitrogen
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LOx	Liquid oxygen
m	meter
mm	millimeter
MHD	Magnetohydrodynamics
MJ	MegaJoule
MRI	Magnetic resonance imaging
MSU	Michigan State University
NASA	National Aeronautics and Space Administration
NERVA	Nuclear Engine for Rocket Vehicular Applications
ORNL	Oak Ridge National Laboratory
ORPS	Occurrence Reporting and Processing System
ppm	parts per million, by volume
SMES	Superconducting Magnetic Energy Storage
TFTR	Tokamak Fusion Test Reactor
TNT	Trinitrotoluene explosive
US	United States

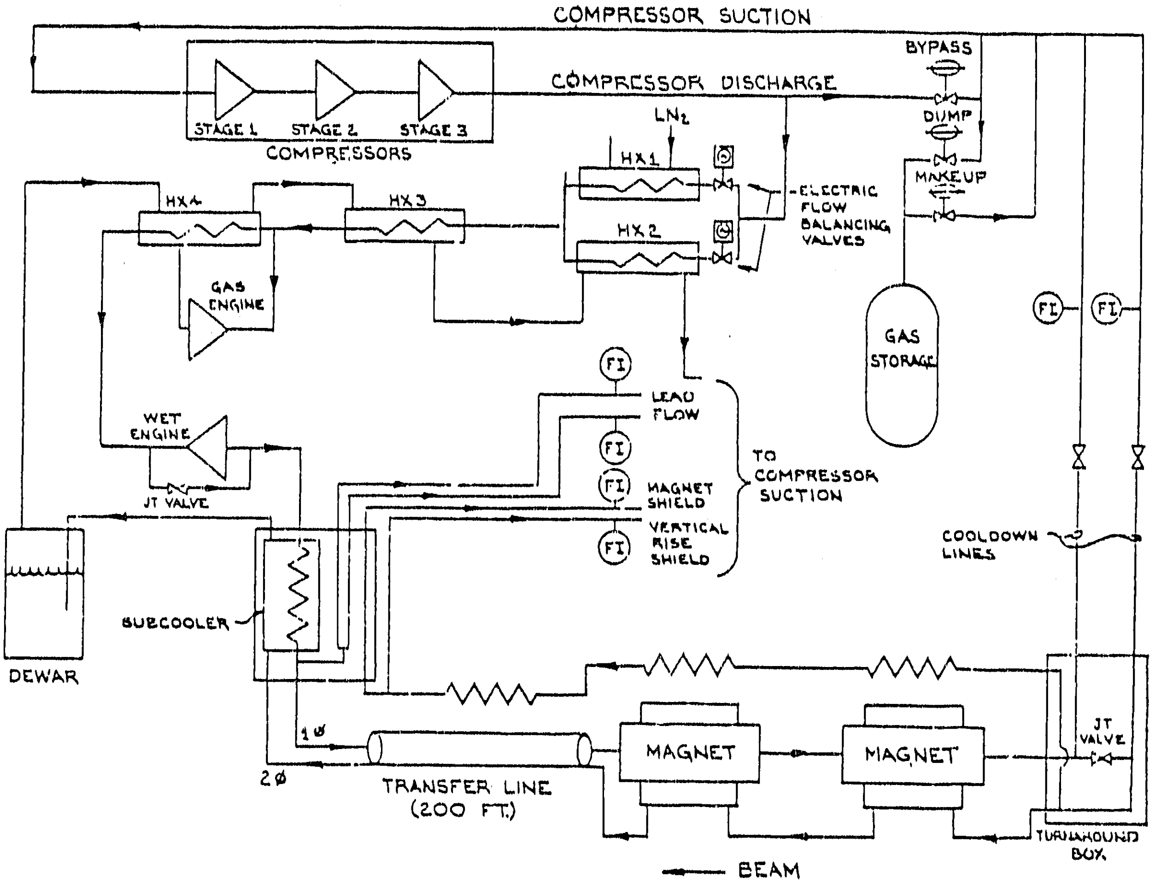
CRYOGENIC SYSTEM OPERATING EXPERIENCE REVIEW FOR FUSION APPLICATIONS

1. Introduction

This report outlines cryogenic system operating experiences for use by fusion system designers and safety analysts. Cryogenic liquids are used for tokamak vacuum systems, neutral beam vacuum systems, pellet injectors, and magnet coolant. Magnet coolant systems are the largest, using system capacities of 10's of cubic meters of liquid helium. Vacuum systems will use much less than that, pellet injectors will use on the order of hundreds of liters, and there are likely to be a few radiation detectors that will use tens of liters. A simplified cryogenic system schematic diagram for a particle accelerator facility magnet coolant system is given for reference in Figure 1-1.[1-1] The cryogenic system, or cryoplant, must be available for magnets to be operable. Therefore, events causing downtime in the cryogenic system will affect the entire facility. This report discusses existing system operations, operational difficulties, major cryogenic accidents that have occurred, the use of field experience information to quantify system behavior, and presents what information can be learned from safety work for other industries that use cryogens. Learning from experiences from other industries enhances design and safety, and insures a higher level of practical completeness in facility risk assessment.

This report is structured in order of: operations problems, including downtimes for some operational difficulties; large scale accidents involving large releases, fatalities, or major system component replacement; cryogenic safety concerns that must be treated for future fusion facilities; field experience and estimated failure rates for cryogenic components; and initiating event frequencies from fusion and other industries that are applicable to future fusion safety work.

Even though vacuum is employed as an insulation barrier for heat transfer in cryogenic systems, I have not addressed vacuum pump safety concerns or reliability in this report. In the future, I will write another report similar to this one, for vacuum systems. That report will include mechanical pump, turbomolecular pump, and cryopump operating experiences, and vacuum safety concerns.



Note: FI stands for flow indicator
HX stands for heat exchanger
JT stands for Joule-Thompson expansion valve
LN2 stands for liquid nitrogen

(figure taken from reference 1-1)

Figure 1-1. Liquid helium system schematic diagram.

Chapter 1. References

1-1. R. A. Andrews et al., "Helium Refrigeration System and Cryogenic System for Superconducting Switchyard Magnets at Fermilab," IEEE Transactions on Nuclear Science, NS-26, June 1979, pages 4093-4095.

2. Cryogenic System Operating Experiences

This chapter contains discussions of cryogenic system operating experiences from fusion experiments and superconducting magnet systems, such as: superconducting magnet energy storage (SMES) systems, medical technology, and cryogenic magnetohydrodynamic (MHD) devices.

2.1 Chapter Summary

In general, most cryogenic systems have experienced small cryogen leaks to the atmosphere or the building, and air leakage into the system. Condensation from water vapor in the air and even the freezing of nitrogen and oxygen from air onto cold piping has been an operations concern. Cryogenic components, such as pumps and valves, have failed and week-long shutdowns for entry into cold boxes have been necessary for several of the systems discussed here. Impurity gases and pump/compressor lubricating oils in the system have hampered proper operations. The Tokamak Fusion Test Reactor (TFTR), Tore Supra tokamak, and TEVATRON accelerator experiences are among the most insightful discussed here. The operating experience literature recommends extra system cooling capacity, from 20% to 50% and up to values as high as 100%, to negate problems with heat inleakage in as-built systems. Heat inleakage is difficult to calculate, especially after the inevitable variations introduced in the construction phase. In this chapter, I discuss some cryogenic system experiences from fusion, particle accelerators, medical technology superconducting magnets, and a superconducting magnetic energy storage (SMES) unit. Large accidents involving cryogens are discussed in the next chapter.

2.2 Fusion Cryogenic System Operations

Fusion operating experiences are widely varied. Some systems have worked well and others have been a continual source of operational problems. This section contains discussions of several fusion experiment experiences with cryogenic systems, including the Large Coil Task (LCT), Tore Supra, and the Tokamak Fusion Test Reactor (TFTR).

2.2.1 Large Coil Task Experiences. Typical problems with cryogenic systems have been found at the Large Coil Task (LCT) experiment at Oak Ridge National Laboratory (ORNL), which was used to test helium superconducting toroidal field magnet coil concepts for fusion applications. Designers stated that the helium refrigerator system was initially undersized, mainly due to economic reasons. The refrigerator could not supply enough liquid helium to meet the demand during some phases of operation, such as the high-current multi-coil tests, where the forced helium boiloff exceeded the cryoplant's rate of production. An accumulator storage tank and two small satellite systems were added to help reduce the impacts of these high demand operations. The system was accepted with this marginal cooling capability, but it presented problems throughout the life of the project.[2-1] The undersized unit also led to operational delays, such as long times for cooling the magnets, usually on the order of one to two days, such as when electrical power was lost to the helium cooling system. Other difficulties caused even longer recovery times.

The LCT also uncovered several other issues related to cryogenic cooling systems. Several of the magnet coils had difficulty with helium leaks into the insulating vacuum jackets and air leaks into the system heat exchangers. To solve the helium leak problem into the liquid helium (LHe) dewar storage vacuum jackets, vacuum pumps were set up to continuously pump down the vacuum region. On one occasion, a mechanical pump stopped, and valving failed to prevent air flow into the vacuum jacket. The enhanced heat transfer from gas in the jacket boiled the dewar dry. Five days of repairs to the dewar consisted of repairing the pump, warming the dewar, and evacuating the vacuum jacket. In the time span of these repairs, the magnets warmed up to about 50 K and had to be recooled to continue operations.[2-2] Future fusion experiments will probably be housed with nitrogen or helium atmospheres, rather than air, to limit neutron activation of the atmospheric gas and also to reduce chemical reaction concerns (such as graphite fires). These inert atmospheres also mitigate effects of electrical fires. Nonetheless, any warm (295 K) atmospheric gas inleakage would still present a problem of increased cryogenic system heat transfer.

An LCT cold box heat exchanger plugged up shortly after operation began, due to air freezing in the cold heat exchanger. The air leakage into the heat exchanger was found to be through a faulty burst disk.[2-2] The heat exchanger had to be replaced because of mechanical damage from the volume expansion of the frozen gases.[2-3]

Air leakage, or contamination, into the LCT system allowed nitrogen and oxygen to freeze in the helium channels, accumulating up to tens of kilograms, especially for the pool boiling magnets.[2-1] Air does not even have to leak into the machine to cause difficulties. Superconducting Tokamak T-7 experiences showed that ice buildup from atmospheric humidity onto the liquid nitrogen temperature vacuum vessel flanges caused extra stresses that led to small amounts of flange separation and consequently, air leakage into the piping. Thermal insulation was recommended to serve as a barrier against ice infiltration.[2-4] Water vapor condensation building up to form ice has been an operations problem for many cryogenic systems. A liquid nitrogen feedthrough tube, passing through a larger pipe in the insulation of a chamber, suffered a rupture due to ice buildup. Water vapor condensed on the outside of the liquid nitrogen tube, between the tube and the larger insulation pipe passageway. The ice built up to the point where the tube was compressed by the pressure of the annulus of ice around it. The liquid nitrogen flowing through the tube built up pressure at this constriction and caused the tube to rupture.[2-5] Ideas to prevent this sort of event are to invert the insulation pipe, so moisture does not collect there, flush the annular area with dry gas to purge the moisture, or plug the opening with a sealant such as silicone. These fixes should be performed prior to high neutron flux operation.

2.2.2 T-15 Experiences. Heat leakage into a cryogenic system is difficult to calculate, so extra cooling capability must be designed for in fusion cryogenic systems. Accelerator experience tells us that refrigeration plant output is reasonably specific, but heat loads and the execution of design details about heat loads during construction have a greater chance for error.[2-6] Another superconducting experiment, Tokamak T-15, experience shows this fact, since the heat flows from the pipelines into the magnet cases, also coupled with the problem that the liquefiers were not able to deliver rated capacity, prevented the machine from reaching lower than 12 to 8 K.[2-7] The design value for magnet temperature was 4.5 K. Even at 30 metric tons/hour flow rate through the tokamak, with one helium liquefier unit in the liquefying mode and one in the refrigerating mode, lower temperatures could not initially be reached.

2.2.3. Tore Supra Experiences. The superconducting tokamak Tore Supra has also had some difficulties with the magnet cryogenic cooling system.[2-8] Some of Tore Supra's detrimental early experiences were excessive liquid helium consumption at rated temperature, reduced thermal shield effectiveness from expected design values, air inleakage through the safety relief valves, and water inleakage from compressor heat exchangers.

The Tore Supra cryogenic system has had later difficulties as well.[2-9] Over a time period of six months in the third year of operation, there were 18 machine outages due to faults in the magnet liquid helium cooling system, for a total downtime of 41 hours. This is an improvement over initial operations, because for the first two years of operation, the cryogenic system averaged one operational day (11 hours) of downtime per month, or 66 hours per half year. Past problems with the system included contaminants in the cold box, a ball bearing failure on one of the screw compressor motors, and clogged liquid helium filters. For a six month period that was closely surveyed, the general problems were in these areas:

Components (valves, gauges, etc.)	9 failures for 25 outage hours
Computer control faults	3 failures for 8 outage hours
Analyzers (oxygen monitors, etc.)	3 failures for 3 outage hours
Power outages	2 failures for 4 outage hours
Cloggings (filters, etc.)	1 failure for 1 outage hour
Engines (compressors, pumps, etc.)	0 failures for 0 outage hours
Utilities (cooling water, etc.)	0 failures for 0 outage hours

The paper also noted that summer thunderstorms, which have a tendency to cause losses of offsite power, added to the cryogenic system utilities' power outage downtime. The latter 6 months of the operating year at

Tore Supra showed no cryogenic system problems that precluded normal facility operations. The staff attributed this increase in cryogenic system availability to more efficient preventive maintenance practices that were implemented after closer system scrutiny.[2-9]

2.2.4 TFTR Experiences. The Tokamak Fusion Test Reactor (TFTR) uses a 1-kW refrigeration capacity liquid helium system for their neutral beam injector cryopanels. Two years (11,000 hours) of operations experience with this system has shown that there have been several types of problems. The system is built with redundancy in mind, such as a third helium compressor, several storage tanks for liquid helium, and a variety of redundant sensors. Startup problems included electrical control problems, compressor oil and cooling water contamination, and process helium gas contamination The compressors shut down due to improper set points on the circuit breakers, and on low oil until the oil supply system was replaced with a less complicated system.[2-10]

There have been other problems from the TFTR system as it matured. While the compressors and their motors have operated well, there has been vibration and mechanical fatigue in tubing that allowed two large compressor oil leaks, which are both a fire hazard and a significant unavailability issue. Small leaks are also present - they are unsightly, but were not considered to pose a safety or availability concern. The compressor cooling water was initially found to be contaminated with a variety of debris, including: weld slag, paper, cleaning rags, etc. A strainer was placed in the cooling water line, but in summer months the strainer became fouled with algae. The recurring algae plugging has caused shutdowns to clean the strainer. During the first wintertime shutdown, freezing temperatures occurred and frozen compressor cooling water caused a flow control valve to burst. The compressor room is heated now for wintertime conditions.[2-10]

The TFTR cold box for temporary liquid helium storage has had several mishaps. A vacuum shell is used for cold box insulation. A single diffusion pump was initially used to maintain the vacuum, but there were multiple vacuum demands on the pump, so a spare mechanical pump was added to assure that the vacuum in the shell would be properly maintained.

Later, the diffusion pump failed due to oil loss in a high throughput operation period. It was replaced with a turbomolecular vacuum pump. This turbomolecular pump was found to be defective. The system was shut down to replace it. Also, a brazed aluminum to stainless steel joint leaked, causing a shutdown for repair. Some of the primary units in the pairs of temperature sensor diodes have had failures, so the redundant units are used for temperature readings. One diode well leaked helium gas, so the cold box had to be opened for repairs. This operation caused significant downtime for purging, warmup, and then cooldown after repairs were completed. During replacement, a vacuum isolation valve drive mechanism failed to close its valve properly and air was admitted into the vacuum shell.[2-10]

A faulty diode in the TFTR turboexpander power supply caused a shutdown, and a faulty optical link in the turbine speed circuit caused another shutdown. Over 30 system trips due to gas high impurities have occurred in two years of operation. These impurity trips average more than one per month over the operating period discussed. Even though these events seem frequent, the system is said to have performed well overall. Martin et al.[2-9] thought complex cryogenic system startup was full of unexpected, unpleasant, costly, and downtime-intensive surprises. They did recommend that a 'safety factor' of 50% be included when sizing a moderate duty liquid helium refrigeration system.[2-10]

2.2.5 ORMAK Experiences. The ORMAK fusion experiment at ORNL has also published some of their liquid nitrogen (LN2) magnet coolant system operating experiences.[2-11] The magnet cooling system was thoroughly pressure tested, and weaknesses in the electrical ceramic insulators placed in the LN2 lines were discovered at 7.5 MPa. The insulator design was changed to withstand the 10 MPa pressure test (the normal system operating pressure was 1.4 MPa). Helium leak testing also revealed that less than 1% of all controlled field brazes leaked. These brazes were reworked.[2-11] Initial ORMAK shakedown operations revealed that several ball valves were delivered by the manufacturer with incorrect seals and seats. The original ultrasonic level sensors were faulty and were replaced with more reliable thermistor level sensors. The LN2 centrifugal pump seals were rated for 500 hours of operation, and several seal failures at the 500 hour time caused the ORMAK staff to replace the pump with a hermetically enclosed unit.[2-12]

2.3 Particle Accelerator Cryogenic System Operations

This section discusses Fermilab and TEVATRON operating experiences, and a brief discussion of the Intersecting Storage Ring and a university cyclotron.

2.3.1. Fermilab Experiences. Particle accelerators, and Fermilab in particular, began switching over from water-cooled magnets to liquid helium-cooled units in 1979. Some of the early problems with the liquid helium units at Fermilab were that oils from the compressors and expanders leaked into the helium stream, but could be removed from the helium down to 10 parts per billion. Liquid helium satellite unit (producing 95 liters/hour in the liquefying mode) reciprocating compressors converted from ammonia and freon service worked between 800 and 1,500 hours before failure (the Mean Time Between Failure, or MTBF), and reciprocating expansion engines could run for 800 hours for gas and 1,100 hours for liquids between failures.[2-13] One interesting note was that the Fermilab staff discovered that magnet cooldown was very difficult due to system instabilities (flow reversals, or geysering) unless there was at least 20% excess refrigeration capacity present. Typical repair or replacement downtimes for these equipment items were: cold box, 146 hours; transfer line, 1 hour; compressor, 60 hours; wet expander, 1 hour; dry expander, 8 hours; and plugging leaky expander heat exchanger u-tubes took 0.1 hour per tube.[2-14]

Later work published on accelerator cryogenic cooling systems[2-6] declared that a major problem of cryogenic systems was their reliability. The present helium refrigerators were cited as suffering from low reliability, premature component failures due to poor design, and operations related problems, such as contamination. Brown stated that only attention to reliability in all stages of cryogenic system design, fabrication, installation, operations, and maintenance - with a little good luck - would provide the satisfactory performance sought for Fermilab.[2-6] Indeed, discussions of accelerator major problem areas at that time showed that cryogenics is an area that requires redundant components and double the amount of calculated cooling ability.[2-15]

Fermilab reported on their satellite liquid helium system, the forty-eight 25 liter/hour units, again in the early 1980's. This operations paper rather fatalistically suggested that "redundant components significantly improved the likelihood of continued operation in the event of equipment failure".[2-16] The initial subsystem interactions tests in June 1982 proved unsuccessful when the helium transfer lines and the magnets would not stabilize at operating temperatures, similar to the T-15 experiences. After two weeks, the testing was suspended. A 'brute force' approach of using all available LHe finally overcame the problem and allowed proper magnet cooling. The satellite expanders suffered several major mechanical problems, such as broken drive shafts and bad piston seals. An interesting problem with the magnet relief valves was that during magnet quenches, debris would be blown from the magnet interior into the relief valves, eventually clogging them. This and other problems, such as defective seals and weak welds, gave relief valve failure rates of 1 failure per 100 valve openings on magnet quench.[2-16]

More recent work published on the Fermilab TEVATRON accelerator main cryogenics system was more optimistic. The Fermilab central helium liquefier is rated at 5,000 liters/hour, using three large 1.5 MW reciprocating helium compressors to give 4.5 K helium refrigeration. During the six year system preoperational testing and system debugging session, there were several major problems. In order of severity, these problems were: Expander low efficiency due to valve leaks, seal leaks, broken drive shafts, bad piston shaft seals, and large pressure drops when operating above 66% of rated speed; Contamination problems from water, nitrogen, and particulates; Control faults such as microprocessor rebooting, and communications link failures when building air temperatures rose above 32 C or fell below 13 C; and Expander load regulation problems, such as blown fuses and expander runaways that forced emergency braking. The eighteen month system commissioning session also exhibited operational problems. These were: Contamination by nitrogen leaks through closed valves, and mixtures of aluminum oxides with water and nitrogen causing plugs in lines and in the turbine inlet filters; Control instability caused by heat loads that led to flow oscillations; Inadequate power lead cooling; Magnet quench relief valve leakage due to broken valve bellows and magnet clamp parts becoming lodged in the valve poppets; Magnet vacuum leaks; and Sixteen small pump motor failures.[2-17]

Overall, TEVATRON operations experiences showed that contaminants such as water (impurities as low as 0.7 parts per million, or ppm, by volume) and nitrogen (impurities as low as 1 ppm) can be a problem, even for 5,000 liter/hour systems. Pipe plugging by frozen carbon dioxide, and neon or hydrogen, occurred at least 8 times in the 5 K and 10 K helium piping, at one hour of downtime per event. Control system problems caused 10 to 15 hours of downtime per month, and human operations errors caused 2 to 3 hours of downtime each month. The liquid expanders, with the use of high performance Nitrile piston O-rings and felt seals, have managed up to 3,000 hours of operations with no failures or major maintenance downtimes. Efficiencies up to 77% have been obtained for the expanders. This is the best performance obtained for these units over roughly nine years of testing and operations.[2-17]

2.3.2 Intersecting Storage Rings Experiences. Surprisingly, the Center for European Nuclear Research (CERN) reported that their cryogenics and refrigeration system for the Intersecting Storage Rings (ISRs) experiment performed flawlessly for the first 10,000 hours of operation. This operation included 15 cooldown/warmup cycles. The paper did refer to several component failures during commissioning, but gave no details about the failures.[2-18] A paper on helium leak detection referred to an initial, persistent helium leak in the horizontal vessel of the cryostat that housed a CERN ISR magnet. The leak was large enough to hamper proper operation of the cryostat. A method was devised to locate the leak, so that complete cryostat disassembly and replacement would be avoided - saving weeks of ISR downtime.[2-19]

2.3.3 MSU Cyclotron Experiences. The superconducting cyclotron at Michigan State University (MSU) suffered a leak of helium from the coil cryostat to the vacuum jacket. The leak was very small at room temperature, but rose significantly when the cryostat was cooled to cryogenic temperatures. When the diffusion pump on the vacuum jacket was turned off, the pressure in the jacket would rise by a factor of greater than 2 within 3 hours.[2-20] These leaks are referred to as 'cold leaks', that is, a system appears to be vacuum tight at room temperature but leaks profusely when cooled to LHe or LN2 temperatures.[2-21] The MSU cyclotron leak was a tolerated operational problem for over three years of cryostat operations. Finally, a new method to detect the leak, which turned out to be several leaks, was developed and tested by MSU researchers.[2-20,2-22] Flowing cold gas over the exit ports of the cryostat provided the means to determine the leak locations in the upper part of the cryostat. Leaks in the lower part of the cryostat were roughly determined by tracking the cryostat's liquid helium level and the helium content in the vacuum jacket. The leaks have been sealed well enough now that the diffusion vacuum pump does not need to run continuously to maintain the vacuum pressure in the insulating vacuum jacket. Although helium cold leaks are said to be a common problem, MSU appears to have solved it for their cyclotron.[2-23]

2.4 Superconducting Magnet Energy Storage Cryogenic System Operations

There is only limited literature on Superconducting Magnet Energy Storage (SMES) system performance. The experience from one 30 MJ SMES unit was interesting for this report. A trailer mounted helium refrigerator, using liquid nitrogen for heat exchange and refrigeration shield, supplied a SMES unit for the Bonneville Power Administration (BPA) electrical grid.[2-24] This refrigerator was a continual source of hardware and operational problems over the 1,200 hours of operation reported. The refrigerator responded very slowly to manual adjustments, with up to 12 hours of time lag. This was partly a funding limitation, which forced the BPA to purchase a unit that was not fully automated. Power outages to the refrigerator caused tedious and complex system recoveries. There were several unspecified mechanical component failures, usually repaired within hours by company personnel. Two design defects were discovered that forced the utility to de-rate the capability of the refrigerator by 30%, and to revise the heat inleakage to a higher value. These two major design problems meant that the sustainable SMES unit power was decreased from 7 MW to 4 MW.[2-24]

2.5 Medical Technology Magnet Cooling System Operations

I have had a search of medical magnet experiences from the US Food and Drug Administration's event data base, called the Device Experience Network,[2-25] performed under the US Freedom of Information Act. The time period I searched was 1980 to 1991. The results for cryogenic helium concerns with magnetic resonance imaging (MRI) units are given in Table 2-1. These cryogenic events and violations of regulations involve magnet quenches and violations of safety protocols. During magnet quenches, magnet heat boils some of the liquid helium coolant, so that gaseous helium has to be vented from the magnet case. The MRI magnet vent stacks to the atmosphere were breached or otherwise disconnected and allowed the helium gas to escape into the MRI patient scan room. The most extreme event of that type caused the MRI technician to break a window to enter the scan room so that he could rescue the patient, since the helium overpressure kept the technician from opening the door to the room. Some other events cited inspection results of oxygen monitors being either improperly mounted or not powered from battery-backed power sources, both of which are violations of safety protocol and the MRI unit manufacturer's suggested operating practices.

In closing, Table 2-2 summarizes information given in this chapter by citing brief phrase descriptions of the problem areas that have been discussed in this chapter. Some problems only hamper good operations, such as system pressure changes that reduce thermal efficiency. Other problems can be safety or availability concerns, or even lead to cryogenic system initiating events (IEs), such as line plugging, valve leakage, leakage into the vacuum insulation space, etc., if they are severe enough. Component failure rates and cryogenic initiating event frequencies will be treated in following chapters.

TABLE 2-1. MAGNETIC RESONANCE IMAGING CRYOGENIC EVENTS

Event Date	Description of the Event
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.
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.
April 27, 1990	A defective Balzer cold head (LN2 thimble to cool the insulation space) was making enough training noises to hamper communications with the scan patient.
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 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.

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

Event Date	Description of the Event
May 24, 1991	The scan room's 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 2-2. SUMMARY OF OPERATIONS PROBLEMS ENCOUNTERED IN LIQUID HELIUM AND LIQUID NITROGEN SYSTEMS

<u>Design-related Problems</u>
Improper size of system to deal with all scheduled modes of operation
Inability of system to deliver rated temperature or flow rate
Inability to cool down magnets to desired temperature
Control system faults that led to system run on and premature shutdown
Room oxygen monitors not functioning properly due to improper mount design
System flow reversals, causing pressure oscillations and instability
Slow system response to changed input parameters
<u>Operations-related Problems</u>
Leakage of nitrogen, helium, or air into vacuum insulation jacket, or into the process piping
Leakage of water into system from the compressor or its heat exchangers
Atmospheric humidity condensing onto exterior of cold piping
Pipe and filter clogging due to foreign materials or frozen gases
Spurious gas compressor shutdowns
System contamination from compressor oil, or construction debris
Instrument failures, such as temperature and liquid level sensors
Centrifugal pump seal failures, expansion engine piston seal failures
Relief valves clogging from debris, or leaking past the seat
Human operations errors
Helium leakage out of small 'cold leaks'

Chapter 2. References

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3. Summary of Accidents in Cryogenic System Operations

This chapter gives details of published accident information on cryogenic liquid and gas accidents. Cryogens other than nitrogen (LN2) or helium (LHe) are included here, since events with these other cryogens, such as liquid oxygen (LOx), hydrogen, ammonia, propane, liquefied natural gas (LNG), and liquefied petroleum gas (LPG), can be applicable to LN2 or LHe. Since LHe and LN2 are not explosive, any concerns of that nature for the other cryogens have not been treated. This chapter is by no means a complete review of all cryogenic accidents, but it is representative of the types of accidents that have occurred and could possibly occur again without proper design and operations precautions. Insights gained here also support completeness in qualitative safety assessments. The chapter is structured to first discuss accident and incidents with US government funded scientific research projects, such as the space program. Then chemical industry events are discussed, followed by ozone explosions. Fires near cryogenic systems, and large releases from cryogenic storage tanks are discussed. Lastly, I close with discussions of human errors in fusion cryogenic systems and events that have occurred with small cryogenic dewar containers.

3.1 Chapter Summary

This chapter cites incidents of large cryogenic gas releases to buildings or the atmosphere because of equipment material failures, operator errors, weld failures, and contaminants in the cryogen that caused phase changes. Judging from the chemical industry events, the public can be endangered, and there is a very negative public opinion associated with these releases. I extrapolate that large "white cloud" releases would create a media sensation at a future fusion facility. Workers are also at risk when dealing with cryogenic systems. A large nitrogen gas release in the Netherlands in 1972 caused several fatalities. Also, in 1953, a nitrogen gas release event in a Japanese air separation plant nearly suffocated 5 workers.

There have been several ozone explosion events in irradiated LN2 systems, as early as the 1950's and as recently as the 1970's, with two probable events in the 1980's. Damage from ozone-related events has ranged from minor effects to equipment so badly damaged that replacement was the only means of repair.

3.2 Cryogenic Accidents in US Government Operations

National Aeronautics and Space Administration (NASA) hydrogen release events were collected and reviewed for safety insights in possibly using liquid hydrogen for automobile fuel. There have been 96 hydrogen mishaps, most being liquid hydrogen releases, reported in the records kept by NASA for the time period between NASA inception in 1958 and 1973.[3-1] These events are too numerous to reproduce here, and since the original report is quite cryptic in accident descriptions a reproduction of the events would not be meaningful. Most of the events were large enough releases to pose a safety threat. The summary information about these events is valuable and is given below. The following is an approximate breakdown of the causes of the 96 hydrogen mishaps reported:

Valve malfunctions or valve leaks	20%
Leaking connections or fittings	16%
Safety rupture disk failures	11%
Materials failures (hydrogen embrittlement, etc.)	11%
High venting rates (system design inadequacies)	11%
Cryopumping (discovery of 'cold leaks')	10%
Air trapped in systems (flammable mixtures formed)	5%
Highway tanker truck accidents	5%
System overpressure, bellows ruptures	4%
Hydrogen evolution from batteries	4%
Tank and line ruptures, insulating vacuum losses	3%

In 69% of the incidents, hydrogen was released to the atmosphere. This percentage includes the 5 tanker truck accident events. Most of the rest of the report dwells on ignition of the hydrogen gas, which is a primary safety concern for that lighter than air, flammable gas.

NASA oxygen release events were also reviewed.[3-2] There were 55 events involving liquid oxygen (LOx) between 1958 and 1970 in NASA operations. These 55 LOx events are summarized by major cause:

Materials failures/incompatibilities	29%
System contamination	20%
Other (personnel errors, etc.)	18%
Ignition source near vent outlet	11%
Tank, line ruptures	9%
Valve malfunctions and errors	7%
LOx delivery accidents and releases	6%

When oxygen was released, it went directly to the atmosphere because of the general nature of engine test stands. About 56% of these 55 LOx events resulted in explosions or fires. Intrusion of foreign materials, such as hydrocarbons, aluminum metal shavings, steel fines from surface abrasion (pump impeller shaft and valve seat wear), materials left in the system (most notably cleaning fluid jugs and pads), cleaning fluid corrosion products on the pipe walls, etc., caused the system incompatibilities and contamination events. Poor welds and metal chamber wall failures caused the rest of the materials failures.

U.S. Department of Energy (DOE) operational occurrence reports were searched for cryogenic events, as well as pertinent journals. Table 3-1 gives past events from published reports[3-3] and listings from the Occurrence Reporting and Processing System (ORPS).[3-4] The breakdown of events from Table 3-1 is: Gas compressor explosions and fires, 4 events; Cryogenic overpressure explosions, 2 events; Loss of insulating vacuum, 2 events; Accelerator window failures, 1 event; Hydrogen explosion, 1 event; Bellows liner failure, 1 event; and Helium refrigerator shaft failure, 1 event. In another DOE event, the Alcator C fusion facility had an air leak into a magnet cryogenic enclosure. Ice built up overnight, blocking flow. The coil was damaged beyond repair when it was operated the next operating day.[3-5]

TABLE 3-1. CRYOGENIC EVENTS FROM U. S. DEPARTMENT OF ENERGY OPERATIONS

Event Date	Description of Event and Reference Number
June 28, 1960	The stainless steel lining of a new liquid nitrogen storage tank being installed collapsed when its contents were partly evacuated during an acceptance test. The event cost was $7,000 to repair the tank. Report 60-21.[3-3]
July 21, 1964	An explosion took place in a hydrogen purifier for a bubble chamber expansion system when a valve was inadvertently left in a closed position during purging operations. The precooler and the adsorber coils were torn open and the containing dewar bulged. The event cost $11,000 for repairs. Report 64-41B.[3-3]
November 16, 1964	An explosion occurred in the first stage of a nitrogen compressor, resulting in shrapnel being thrown through the compressor building roof and also damaging the building walls. Repairs cost $16,000. Report 64-59B.[3-3]
July 5, 1965	An explosion and fire occurred in the experimental hall of an accelerator complex. The incident was caused by a sequential failure of the inner and outer beryllium windows of a liquid hydrogen bubble chamber. One person died and seven others were injured. The repair cost was $1.5 million. Report 65-24.[3-3]
March 18, 1966	When the main hydrogen flow through a purifier was begun, an explosion occurred at the inlet to the adsorber coil. Immediately, the liquid hydrogen contents of the chamber were dumped to the atmosphere through a safety vent system. Repairs cost $11,000. Report 66-8.[3-3]

TABLE 3-1. CRYOGENIC EVENTS FROM U. S. DEPARTMENT OF ENERGY OPERATIONS (Continued)

Event Date	Description of Event and Reference Number
June 27, 1966	An explosion (the cause was undetermined) occurred in a nitrogen compressor, followed by a lower intensity explosion in an oil demister downstream from the compressor. Two men, located 2 and 4 meters from the point of major failure of the compressor, were not injured. Repairs cost $40,000. Report 66-26.[3-3]
December 24, 1967	A fire, probably originating in electrical wiring, occurred in the compressor trailer of a bubble chamber facility. The compressors and associated piping, and wiring were damaged. Repairs cost $15,000. Report 67-50.[3-3]
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.[3-6].
1986	The Fermilab nitrogen reliquefier suffered a major delay when a 254 mm diameter pipe bellows liner failed. The reciprocating compressor was damaged, and rework and recommissioning added to the delay. The liner was excited by an upstream compressor bypass into a resonant failure. The bypass line was moved to another position in the system.[3-7]

TABLE 3-1. CRYOGENIC EVENTS FROM U. S. DEPARTMENT OF ENERGY OPERATIONS (Continued)

Event Date	Description of Event and Reference Number
June, 1987	The Tritium Systems Test Assembly suffered a helium refrigerator failure in their hydrogen isotope separation system. The shaft that coupled the expansion engines to the inlet and outlet valves broke during operation. The major test run in progress had to be postponed while repairs were made. The test run was subsequently performed in July 1987.[3-8]
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.[3-9]
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

TABLE 3-1. CRYOGENIC EVENTS FROM U. S. DEPARTMENT OF ENERGY OPERATIONS (Continued)

Event Date	Description of Event and Reference Number
July 19, 1991 (con't.)	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 should begin on October 1, 1991.[3-10,3-11].

3.3 Cryogenic Accidents in the Chemical Industry

The liquefied natural gas (LNG) and liquefied petroleum gas (LPG) industries have had many serious accident events. LNG and LPG events are discussed first, then other liquefied gas accidents are treated. These events serve to illustrate several points of good design. Proper materials must be used, systems must be inspected regularly for leaks, and proper procedures for system operations must be followed. A good summary of chemical industry accidents is given by Lees.[3-12] Several accidents of potential concern to fusion are a 1961 compressor explosion in an oxygen plant in Ecorse, Michigan, a 1964 oxygen plant explosion in Charleston, West Virginia, and a 1972 nitrogen release event in Rozenburg, the Netherlands that asphyxiated three people. These explosions resulted from large breach events mainly due to material failures. Other events are the Cleveland, Ohio LNG storage tank leak and explosion in 1944 (the tank materials were not suitable for LNG temperatures, became brittle and failed) that killed 144 people. In November 1970, operators at Gulf Oil's Blair, Nebraska plant accidently overfilled a refrigerated ammonia storage tank. The tank released about 145 metric tons of ammonia, but no one was injured. An LPG rail car derailment in Crescent City, Illinois, in June 1970, caused a large LPG explosion. Heat from the ensuing fires caused other, intact tank cars to overpressurize, and open their pressure relief valves, feeding the fire with more petroleum gas. A major leak of ammonia from a pipeline in McPherson, Kansas in December 1973 occurred due to a block valve failing to open in the pipeline. The pipeline overpressurized and ruptured. No one was injured. A summary of the 295 public evacuation events from the vicinity of chemical plants in the US between 1980 and 1984 shows the frequency of chemical plant events and the increasing public hostility toward that industry.[3-13] Several of those evacuation events dealt with releases of LNG, LPG, ammonia, and chlorine. Carson[3-14] also gives tables of many chemical industry events, including ammonia, propane, LNG, and LPG accidents.

Since many of these release events happened because of material failures, proper materials are very important to cryogenic systems. Materials considerations are also important in fission reactor systems, to avoid embrittlement. Materials considerations will be taken into account when I set the order-of-magnitude failure rates for cryogenic components, such as piping, valves, cryostats, cryogenic storage tanks, etc., in Chapter 5.

Air separation plants have had their share of unfortunate events as well. While most are explosions of liquid oxygen, there was one event at a Japanese facility in 1953. Two workers went into a heat exchanger pit to plug a leaking heat exchanger tube. While working in the heat exchanger, nitrogen gas overcame them. Three more workers saw these two men in danger, and they rushed in to the pit to rescue them. All five were overcome and nearly suffocated before the nitrogen flow was stopped and rescuers with portable breathing apparatus rescued the five.[3-15]

Some recent accidents in Europe also show some of the risks in working with cryogens. In 1983, a pipe fitter at an ammonia plant was changing the valve operator from a manual handwheel to a motor operator. The fitter inadvertently began working on the wrong valve, and removed all four bolts that held the valve cap in place (rather than one at a time, as the procedure directed). The fitter was choked by anhydrous ammonia when line pressure blew the valve cap off.[3-16] In another event, a compressor house in an ammonia plant had a fire in 1983. A lubricating oil line for the ammonia compressors suffered a breach failure from vibration. The oil caught fire in the warm plant environment. A plant operator walking through the plant noticed the flames and sounded the fire alarm. Several plant operators battled the fire, using more than ten portable fire extinguishers. The fire kept reigniting, since oil was still being supplied and the portable extinguishers were not large enough to cool the environment adequately. One operator suffered a fatal heart attack from the stress and physical exertion of fighting the fire. When the compressor and the lube oil pump were shut down, a standby electrical lube oil pump started (designed to protect the compressor in case of low oil levels) and also had to be shut down, since it added more oil to the fire. Firemen arrived and finally extinguished the fire by cooling down the surrounding area. Damage to the plant was over $0.6M, and the plant was down for about two weeks for repairs.[3-17] This compressor fire event is particularly important to us, since small compressor and turbo-expander oil leaks have been noted as operational problems in Chapter 2.

Accidents with liquefied propane gas have also occurred. A propane truck, overfilled and with the safety relief valves inoperative, exploded outside the driver's home. The driver had gone to lunch, leaving the truck motor idling. The heat from the exhaust pipe warmed the stationary vehicle's propane tank. These three conditions combined (overfill, heating, and failure of pressure relief) caused a propane warmup, pressurization, and explosion. The truck was destroyed.[3-18] In Japan, some year-old liquid propane cylinders split open and discharged their contents. There were no reported effects from the propane release. Metal fault inclusions in the drawing processes for the cylinder end caps were found to be the cause of the cylinder fractures.[3-19] Lees[3-12] also mentions delivery truck accidents leading to releases and explosions, notably the 1978 disaster in Spain where a propane tank truck exploded, the 1976 accident with an ammonia tank truck in Houston, Texas, and the 1970 LOx tank truck explosion in Brooklyn, New York. Release events from delivery trucks could also happen with LN2 or LHe.

The use of perlite insulation for LNG and LPG has also led to several failure events.[3-20] When the perlite in the vacuum insulation space settles and packs down, the local heat transfer rate increases, which has led to overpressure accidents. Equipment under vibration, such as truck or rail transport, has the highest risk of this type of event. However, perlite can also be beneficial. For large storage tanks, perlite has been shown to have a significant damping effect if the inner tank wall fails, restricting the size of the inner wall break and retarding the cryogen outflow.[3-21] Fortunately, liquid helium fusion uses requiring absolute minimization of heat transfer would likely require the more advanced aluminized mylar sheet insulation rather than perlite.

3.4 Ozone Explosion Events

Another major safety concern for cryogenic systems is creation of ozone in systems that entrain oxygen and are under irradiation. There have been several events of ozone explosions in the 1950's and 1960's, and there are two additional possible ozone events in the U.S. DOE ORPS data base in the 1980's. These ozone events are cited in Table 3-2. Oxygen impurities in commercial liquid nitrogen or in nitrogen systems inadvertently exposed to air can begin to form ozone in the presence of radiation, such as gamma rays or electron beams, or by neutron bombardment. Brereton[3-22] calculated that for 10 m^3 of LN2, with an initial oxygen impurity concentration of 20 ppm (to account for air inleakage) and a gamma/neutron exposure for a 500 MW Burning Plasma Experiment (BPX) pulse, the ozone creation is on the order of 75 grams. For that amount of ozone, the decomposition energy is roughly 226 kJ, or about the same as detonating a quarter of a stick of trinitrotoluene (TNT, about 50 g per stick). If the ozone was allowed to build up for all of the 3,000 BPX full power pulses, the decomposition energy could have been as high as 678 MJ (or about 680 sticks of TNT, since TNT is roughly 1 MJ per stick).

For systems that are meant to remain cold after initial startup, such as refrigerating shields and cryotraps, the buildup of ozone could be a problem. The ozone freezes out on the LN2 pipe walls, so it can accumulate in the radiation field's location. Milligram quantities of ozone can be created from oxygen impurities in just minutes of medium to high irradiation. Since commercial liquid nitrogen is generally now much purer than that in the 1960's, the ozone formation concern is reduced, but air inleakage must be kept to a minimum to keep the oxygen concentration near the commercially obtainable 5 ppm.[3-22]

Ozone creation in LHe systems is also a safety concern for fusion. The oxygen impurity will freeze out in LHe, but small air leaks into the system near the tokamak neutron and gamma radiation field will still allow ozone creation.[3-22] Another source of air admission is a vessel leak-up-to-air event, where the oxygen in air freezes out in liquid helium or liquid nitrogen cryopumps. Such an event was postulated during the TFTR safety work.[3-23] A variety of ozone ignition sources could be present: vibrations from machine operations, static electricity buildup, impact from other foreign materials circulating in the cryogenic system, and cryogenic system pressure fluctuations or localized heating that could dislodge ozone chunks so that they would impact at a downstream bend in the piping. There are probably other ignition sources as well.

TABLE 3-2. OZONE EXPLOSION EVENTS FROM LIQUID NITROGEN IRRADIATION

Event Date	Description of Event and Reference Number
1955-1957	Two explosions at the Oak Ridge Graphite Reactor. In the first explosion, an open mouthed aluminum dewar was filled with LN2. The 6.5 m dewar, positioned inside the reactor, operated for 3 days before the explosion occurred. Afterward, there was an intense odor of nitrous oxide associated with ozone.[3-24] The second explosion occurred during a cryostat run. A vacuum line to the LHe cryostat ruptured, allowing air to enter and freeze in the sample chamber. After the test run, when the cryostat was warming up, it exploded.[3-24]
1958	Another explosion at the Oak Ridge Graphite Reactor. An open dewar of LN2 was irradiated and it exploded.[3-25]
1960	Harwell Laboratory researchers noted several explosions while conducting electron irradiation experiments with LN2 present. They attributed these to ozone production and explosion.[3-26]
1960	Hanford laboratory researchers noted several ozone explosions when they tested materials in electron beams generated by their Van de Graff accelerator. LN2 was used to cool the samples during the electron bombardment.[3-26]
1964	During tests of the Nuclear Engine for Rocket Vehicular Applications (NERVA), liquid hydrogen lines caused air to freeze and pool near the surface of the cold gaseous helium shroud. Radiation from the NERVA test caused ozone formation and subsequent detonation.[3-27]

TABLE 3-2. OZONE EXPLOSION EVENTS FROM LIQUID NITROGEN IRRADIATION (Continued)

Event Date	Description of Event and Reference Number
May, 1969	A Los Alamos employee was testing superconducting coils for radiation resistance. An LN2 dewar ran almost dry, and the employee removed it from the gamma radiation field to refill it. He carried it to the refilling station and set the dewar down on the floor. The mild jarring when he set the dewar down caused an explosion. The top of the dewar was blown off. The man was not hurt, other than a bloody nose and damage to his safety glasses.[3-28]
1969	The cryostat at the Ames Laboratory Research Reactor operated successfully with high purity, oxygen free LN2 for many weeks. Then, when the cryostat was opened for a short time (about 45 minutes) to exchange irradiation samples, oxygen was admitted. After 2.5 hours, the cryostat began losing vacuum. The inner chamber had ruptured from an ozone or hydrocarbon explosion.[3-29]
June 5, 1987	Continuous Air Monitors began sounding and an operator heard a sound like a large door slamming. Operators tried, but could not stabilize the cryogenic section of their radioactive rare gas treatment unit. An ozone or hydrocarbon explosion is believed to have occurred from oxygen inleakage to the liquid nitrogen cryogenic system. The cryogenic unit's vessel was ruptured by the explosion. A 3 month delay resulted when the vessel had to be replaced. Corrective actions included changing the flow sheet and operations procedures to preclude future events.[3-30]

TABLE 3-2. OZONE EXPLOSION EVENTS FROM LIQUID NITROGEN IRRADIATION (Continued)

Event Date	Description of Event and Reference Number
May 2, 1989	A cryopump was being warmed to release frozen gases trapped in the pump. An explosion occurred, which blew off the lower 203 mm diameter pump flange and crushed the lab jack below the flange. The pump walls were distorted and the inner cryoshields were mangled. The entire vacuum chamber was lifted from its supports and misaligned. Potential causes for the event were: an ozone explosion created from the operation of the sputter ion gun, or gases forming an explosive mixture (ignited by a thermocouple gauge). Changes to preclude event recurrence included more frequent regeneration of the pumps to avoid ozone buildup, evacuating the cryopump with a roughing pump to reduce foreign materials buildup, and installation of an additional relief valve.[3-31]

3.5 Fires in Facilities that Use Cryogenic Fluids

Fires near cryogenic equipment are a safety concern for the LNG community,[3-32,3-33] and should be for all cryogenic gases. This is because of the extra heat load that fires can create near cryogenic storage tanks or piping. We have already read four nitrogen and hydrogen compressor explosion/fire occurrence summaries (given in Table 3-1). For fusion facilities, there are other chances for fires due to the high voltages, high frequencies, and high electrical power levels required for plasma heating, magnet power, diagnostics, instruments and controls, and secondary system operations, such as water systems and cryogenic cooling units. Even though the fires discussed here are not near the cryogenic systems, there is a chance that a fire could spread into other areas unless it is adequately blocked by fire barriers. Since fusion facilities need so many services routed to and from the torus, the torus is a locus for possible fault events.

Reports of fires at fusion facilities are rare, but there are several events to mention here. One electrical fire event occurred at the Princeton Plasma Physics Laboratory.[3-34] In September, 1970, two ground resistors on a 138 kV to 4160 V transformer began smoking and then burst into flames. Timely operator intervention with portable fire extinguishers limited the spread of the fire so that only three 4-kV circuit breakers were badly damaged and two others moderately damaged. The fire was extinguished before the local fire department arrived at the scene. The other event occurred at the DIII-D reactor near San Diego, California, in the 1980's. A foreign object in the toroidal field coil electrical buswork on the floor below the torus caused a short circuit, then a minor explosion and fire.[3-35] There has also been an electrical explosion event at the Joint European Torus in November 1983. A poloidal field coil power system circuit breaker protection switch, operating at 2 kV of its rated 24 kV, exploded for unknown reasons during the final run before a scheduled shutdown. The electrical protection system acted correctly to shut down the coil. A spare switch was installed during the ensuing maintenance shutdown, but the cause of the explosion was not identified.[3-36]

Another fire event of interest occurred during the construction of a liquid ammonia storage tank in Canada in 1966. During the construction process, a valve on the bottom of the tank had frozen shut, due to cold weather and condensation drainage in the tank. A mechanic tried to heat the valve with a propane torch to thaw it out. Unfortunately, the urethane insulation on the tank was seal coated with Flintcote (asphalt and gilsonite, blended with 100-flash petroleum solvent, asbestos fibers and mica filler). The seal coat caught fire from the torch's heat. The fire quickly spread to engulf the entire tank. The mechanic barely managed to escape. Equipment items near the tank, such as welders, air compressors, kerosine heaters, etc., were destroyed. The fire burned fiercely for a few minutes and then died out. Later, the contractor discovered that the petroleum solvent would be exuded from the seal coat for up to 30 days, until the coat had cured properly.[3-37] Fires, of industrial and electrical origin, should be carefully analyzed for fusion facilities.

3.6 Large Storage Tank Accidents

Cryogenic storage systems, generally large (hundreds of cubic meters capacity) insulated tanks, have been subject to accidents. Design precautions of dikes to prevent liquid flow away from the tank and cylindrical bund walls to confine liquid in a boiling pool around the tank appear to be generally effective for the LNG industry. Using crushed gravel as a flooring material near the tanks also helps the released liquid to diffuse and warm up.[3-38] Of course, these added expenses are assumed because of the large scale effects and loss of life that LNG explosions have been known to cause. The largest NASA storage tank incident occurred in August 1966.[3-39] A large LOx tank was going to be partially emptied as part of normal operations. When the outlet valve was opened, LOx entered the outlet line, as normal. Then, the warm line caused heating and phase change in the flowing LOx. Pressure pulsations occurred as the warm gas built up pressure in the outlet line. The resulting pressure pulsations, often referred to as 'water hammer', caused a 457-mm diameter metal flexible hose to twist and tear open. About 2,755 m^3 of LOx was released. The cold fluid caused the transfer pump carbon steel base plate to crack, and caused minor cracks in the storage vessel support columns. The inner sphere of the storage tank buckled inward due to the decreased pressure in the ullage space as the LOx rapidly drained. The inner sphere was made of 304 stainless steel, and it was later filled with water and pressurized to force the sphere back into shape. At 41.4 kPa above atmospheric pressure, the damaged area "popped out". The storage tank was ready to receive LOx one month after the event occurred. Conference participants hearing this paper presentation suggested that pre-chilling the outlet line would prevent recurrence of the event.[3-39] These pressure pulsations have been described as geysering.[3-40] Geysering is a phenomenon of gaseous and liquid cryogen coexisting in a vertical line. The downward flowing liquid forces the vapor up, violently expelling the vapor into the chamber or container. The vapor causes a pressure increase which causes a pressure wave, or water hammer, that travels back down the vertical line, sometimes with disastrous consequences. The geysering inhibitor[3-40] is an annular line, cooled to cryogenic temperatures, to prechill the transfer line and prevent large amounts of vapor formation.

Another tank failure occurred for a liquid ammonia tank in November 1978.[3-41] This tank had two simultaneous problems. Cold weather and a power outage combined to fail the tank. When a plant-wide power outage occurred, the pressure transmitter for the tank froze up due to moisture in the instrument air system and also the cold weather (-12 C ambient temperatures). When power was restored, the transmitter read a false low signal. The refrigerating compressors serving the tank actuated and began to run continuously, cooling the ammonia more than normal. Two days later, the incoming plant shift personnel noted the refrigerating compressors were still running, and they realized that something was seriously wrong. Before they could act, the tank had collapsed inward. Operators shut down the compressors immediately, but the tank collapsed a second time, creating a small rupture in the tank. The tank had adequate overpressure relief valves, but not vacuum relief valves. 2,267 metric tons of ammonia were lost due to the rupture and the repair operations. Tank insulation was removed, the damaged panels were cut out and replaced. Repair operations took almost 3.5 months.[3-41]

Storage tanks are susceptible to human errors and to the elements, such as the cold weather related failure discussed above, and to other external events, such as earthquakes or aircraft crashes. In Chapter 2, I noted several events of tank overfilling due to operator error, and there are more events like that in the literature.[3-42,43] I also note that oil storage tanks suffered damage in an earthquake event in October 1979.[3-44] Tank anchoring is recommended to prevent liftoff in the event of strong ground motion. Earthquake analysis for fusion facilities must be performed, especially for the case of large LN2 releases. Japanese experience with underground LNG storage tanks has been favorable. Designed as tall cylinders to reduce sloshing fluid impacts to the tank ceiling in case of earthquakes, these tanks have performed well for many years, and are not visible to passersby.[3-45]

3.7 Selected Human Error Events Involving Fusion Cryogenic Systems

I have been told of two events at fusion facility cryogenic systems that involved human errors. The first event happened in the 1970's. It was a flange breach, due to a quality assurance error that allowed workers to inadvertently use carbon steel bolts in a cryogenic flange.[3-46] The carbon steel bolts embrittled at cryogenic temperatures and fractured. The second event, in the 1980's, was the inadvertent installation of a ball valve not intended for cryogenic service in the outlet line of a liquid nitrogen storage tank. When the ball valve was closed for the first time, a small amount of liquid was trapped in the ball's flow channel. Such a valve meant for cryogenic service has a small port drilled in the ball, so that any fluid trapped there can exhaust downstream as it vaporizes. This inappropriate valve trapped LN2 in the flow channel. The valve suffered an overpressure within the ball channel that forcefully tore open the valve body and allowed the tank contents to be vented to the atmosphere.[3-47] No one was injured in either of these cases.

3.8 Incidents with Small Cryogenic Containers

Other events in the literature are dewar overpressure explosions. These referenced cases describe dewar failures from corrosion, air humidity icing inside the vacuum space that collapsed the dewar neck, and an ice plug from atmospheric humidity that formed in the neck of a dewar. Readers will recall that dewars are simply insulated containers that do not suppress cryogen boiling, but merely reduce heat inleakage to retard boiling. Normal heat inleakage boiloff was prevented by the ice plug, and the dewar pressure rose until the material failed in an explosive pressure release.[3-48,3-49]

3.9 Conclusions

A great deal of practical information on accidents has been obtained from cryogenic system operating experiences, most notably from the reported events in NASA, DOE, and chemical industry operations. The review of LNG and other cool gas information has shown that attention to details, such as use of proper materials, adhering to system cleanliness requirements, and following good operating procedures helps insure safe operations. We have seen that cryogenic equipment (compressors and expanders) have maintenance and service life eccentricities, and can have dismal service records. Creation of ozone in LN2 can be suppressed by starting with very high purity cryogens, and with cautious operating practices the ozone threat can be managed by eliminating cryogen exposure to air. Table 3.3 gives a summary of the types of events discussed here.

TABLE 3.3 SUMMARY OF TYPES OF CRYOGENIC ACCIDENTS, INCIDENTS, AND EVENTS

Design related events

High venting rates (system design inadequacies)
Discovery of 'cold leaks'
Air trapped in liquid hydrogen systems, flammable mixtures formed
Helium refrigerator shaft failure from improper design
Ozone explosions in LN2 systems under irradiation

Operations related events

Cryogen rail tank car derailment and tank truck accidents
Storage tank overfill spills
Human errors on cryogenic systems, supplying incorrect equipment
Fires potentially near cryogenic systems
1953 near-suffocation event

Equipment related events

Valve malfunctions and valve leaks
Leaking connections or fittings
Safety rupture disk spurious failures
Materials failures (from hydrogen embrittlement, etc.)
Tank and line ruptures

Loss of insulating vacuum
Accelerator window failures
Bellows liner failure
1972 nitrogen asphyxiation event
Pipeline ruptures

Liquid propane truck explosion, storage cylinder fracture
Titan missile fuel leakage due to materials problems, human errors
Large cryogenic storage tank failures
Dewar failures

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4. Potential Safety Concerns with Cryogenic Fluids

There are several features of cryogens used in fusion that present potential safety concerns for facility operations. These features or qualities are discussed in this chapter. Briefly, these potential safety concerns are: extreme cold effects on the surrounding environment, phase change pressurization effects and the possibility of personnel asphyxiation, safety of the warm gas handling plant, concerns from contaminants, large cryogenic liquid or gas releases to the environment, and dielectric breakdown of helium and nitrogen. I will address each of these areas here. In addition, there are five sources of information on cryogenic safety that are very good references. These are cited as references 4-1 to 4-5. There are also several excellent papers that outline the basic safety concerns with these fluids, cited as references 4-6 to 4-9.

4.1 Introduction to Potential Safety Concerns with Cryogenic Fluids

There are several possible safety challenges and concerns that can arise when using cryogenic fluids that have not occurred as operational problems or large accidents. There are other concerns that have been realized through their occurrence. All of these concerns must be addressed in some form of safety assessment or analysis for a future cryogenic system. Personnel safety issues have not been directly addressed among these safety concerns.

Safety concerns that have not occurred but should be analyzed are dielectric breakdown in the superconducting magnets, confinement building pressure responses to large release events, and local effects of cryogen leaks near the tokamak. These are addressed in the given order in the following subsections.

System safety concerns that have occurred are contamination, large spills to the environment, warm gas handling plant accident events, and safety concerns over cryoplant noise levels. I discuss safety issues for these topics in the following sections.

4.2 Dielectric Breakdown Through Cryogenic Gases

When cryogenic helium or nitrogen is used to cool superconducting magnets, there is a concern that a failure event might allow the liquid coolant to warm up, change to gaseous phase, and allow an electric arc to form between magnet leads or the coils in a magnet. There are several sources of information on breakdown voltages needed for sustaining arcs in helium and nitrogen.[4-10 to 4-15]

Breakdown voltage is a function of gas pressure. The breakdown strength for helium, from Levitov et al.,[4-12] for cold helium gas at densities above 30 kg/m^3 and pressures between 0.4 and 1.0 MPa, is over 200 kV/cm. Gerhold[4-14] gives the Paschen curves for helium and nitrogen, showing the relationship between gas density x breakdown gap distance to the minimum required breakdown voltage. Nitrogen gas has its lowest breakdown voltage of about 4 kV at about 2E+22 molecules/m^2. These values are for clean surfaces. Fusion magnet surfaces should be clean and free of any greases or other foreign materials. Foreign materials will likely decrease the given breakdown voltages.

Intuitive design suggests more solid insulator use, such as mylar or kapton, in regions of high voltage difference or in close proximity to chamber walls for fusion magnets. The mylar sheets, fiber epoxy resin, kapton, or other electrical insulation can be used to reduce the possibility of electric arc occurrence if the system has an off-normal event - perhaps a magnet quench - that causes cryogenic helium or nitrogen to change phases to gas and also drives voltages up to high values. When there is no clearance for extra insulation or if radiation effects have decreased the insulation value, smooth surfaces (no point discharge locations) and provision to keep cryogen temperatures low will help reduce the chance of arc initiation.

Another concern about arc formation is impurities or foreign materials in the cryogenic fluid. Jaksts and Mazurek[4-16] have studied the ability of breakdown between two plates in a flowing LN2 stream when tungsten particles are introduced in the fluid. The voltage difference they applied between the plates is much larger than the voltage between pancake coils for large, toroidal fusion magnets (100 kV in the experiment versus a few hundred volts in magnet ramp-up; superconducting magnets should have only a few volts difference between pancakes while in steady state operation), however, this concern should be addressed in the magnet or cryogenic system design. An unidentified foreign material did cause a short circuit in one of the Tore Supra toroidal field coils.[4-17] Some foreign materials may not contribute to electrical breakdown between magnet pancakes, but they can restrict coolant flow. Filters should be used to capture impurities in the magnet coolant. Even though such filters can plug up, they should be employed to prevent possible breakdown in off-normal magnet situations (when pancake coil to pancake coil voltages can become quite large) and debris accumulation in inaccessible locations within the magnets or cryopanel piping. Filters can be placed away from the machine, so that they have the advantage of being accessible for hands-on maintenance or replacement.

4.3 Confinement Building Pressure Responses to Large Cryogen Spills

If significant quantities of liquid helium or liquid nitrogen escaped, the surrounding air would be cooled, and the building internal pressure would initially decrease. Provisions for building pressure fluctuations must be made to assure that confinement building integrity is maintained. While most thick-walled (2 m and larger) confinement buildings can withstand modest internal overpressure, perhaps on the order of 35 kPa above atmospheric pressure,[4-18] special design considerations need to be made for internal underpressure much below 101 kPa. Confinement building penetration seals and door seals should be examined for response to underpressures. This must be a consideration for the building design. An unpublished calculation for a total magnet cooling system liquid helium release from the Fusion Engineering Device showed that the 1E+05 m^3 building air pressure decreased from near atmospheric pressure to 84 kPa in 2.5 minutes, then the pressure rose up to a maximum of 45 kPa overpressure in one hour.[4-19] Some means of passive overpressure protection was required to prevent confinement building breach in such an event. Piet and Brereton discuss several means of passive confinement building overpressure protection.[4-20]

Releasing cryogens will cause heat transfer from whatever they contact. The liquids will boil very quickly and then begin to pressurize. At atmospheric pressure, and room temperature (about 295 K), nitrogen has a gas to liquid volume ratio of about 700:1, and helium has a ratio of about 600:1.[4-21] Fortunately, future fusion facilities will be large - they must incorporate a large 'lay down' area to work on parts and the building will also be tall to provide heavy crane lifting clearance for replacing torus sections or toroidal field magnets. While detrimental to costs, this extra air space and the thick walls for radiation shielding allow for large cryogenic fluid/gas releases without overpressurizing the confinement building. Sizing cryogenic systems so that entire inventory releases would not lift the confinement building pressure relief valves would be a conservative safety design approach. A special concern to be treated for cryogenic gas releases is that the humidity in air does not freeze on pressure relief valves or other pressure relief devices, holding them open after the pressure is relieved.

There are several safety concerns with these large cryogen releases. First, a cryogenic overpressure could mobilize any radioactive isotopes in the building, such as neutron activated air, tritium gas, volatilized neutron activation products, or tokamak dusts. For example, if liquid helium was released due to a magnet movement that sheared lines open and breached the vacuum vessel, then tritium and tokamak dust might be lofted and expelled from the torus hall to the crane hall, and then to the atmosphere, if the building overpressure relief valves opened.[4-14] The cold gas would also help to keep the radioactive isotopes initially near the ground. As the gas warmed in air, perhaps on the order of minutes, the isotopes would be lofted. Mixed cryogen and radioactive releases will likely have higher site boundary doses than room temperature radioactive releases. This cold effect must be analyzed to verify if standard dose calculation methods can be conservatively used for cryogenic spill-driven releases.

Another safety concern is personnel protection. With a cold gas cloud contained in the building, there is a hazard that unprotected personnel might enter the oxygen-diluted atmosphere. There is a fairly narrow band of acceptable oxygen concentration for humans, and while helium will rise in air, enough helium trapped in a chamber will still present a real threat.[4-22] The breathable air guidelines in the US are a minimum of 18% oxygen by volume[4-23] and no prolonged exposures above 50% oxygen.[4-24] Also, oxygen should not exceed 23% by volume due to concerns for much easier ignition of fires,[4-25] especially near electrical equipment.

4.4 Effects of Cold Temperatures on Surrounding Structures

Normally, liquid helium (LHe) piping or storage for fusion applications has a liquid nitrogen (LN2) refrigerating shield within the insulating vacuum space to further reduce heat transfer into the LHe. Therefore, we have leakage concerns for helium and nitrogen. If liquid helium were to leak out into the vacuum space, heat transfer from the ambient air would greatly increase, and there could also be condensation and even air liquefaction on the outer wall of the piping or storage vessel. This liquefied air would drip off the piping or vessel. A danger is that the nitrogen in this liquid air would evaporate first, leaving oxygen rich liquid behind. This is a fire hazard, as well as a heat transfer (inleakage) problem for the original liquid helium system.[4-1,4-26] Gutters or catch pans should be used to route away any dripping liquefied air to safe locations for vaporization.

If liquid nitrogen or liquid helium were to escape from the cryogenic piping, any mild (carbon) steel cooled down by impingement or immersion would become brittle due to its body-centered cubic structure nil-ductility transition.[4-27] Therefore, no equipment near - above or below - the cryogenic lines should be built with carbon steel or any other material that embrittles at low temperatures. This includes the vessel supports, pipe hangers, cable trays, and any cooling water lines.

Heat removal from surrounding structures poses a safety concern. Even stainless steel has contraction under LHe cold, on the order of 2.7 mm per meter. This contraction is significant. Thermal contraction has forced designers to use metal bellows, flexible lines, and a variety of pipe bend configurations so that temperature-induced flexure does not overstress the pipelines. Contraction could also occur to copper electrical lines exposed to extreme cold, and electrical insulation could become brittle. Therefore, plasma diagnostics and control system wiring could be at risk when placed near cryogenic lines. Electrical insulation might become brittle after cryogen exposure, causing a decrease in its life and possibly increasing the probability of short circuits and fires.

Another concern over extreme cold temperatures is that prolonged exposure of water piping to cryogenic fluid or to very cold gas could cause ice formation in the piping. Ice could plug the lines, or the thermal shock to the 393 K (120 C) and higher piping being exposed to 77 K or 4 K cold gas, could lead to fracture. With the combination of sudden contraction stresses and possible pipe plugging, the pipes may not fail, but this would lead to the suspicion of decreased service life and then early piping changeout. If a cooling line ruptured, it would compound the already occurring magnet cryogen leakage accident. I have noted that the Canadian fission reactors use a LN2 cooling jacket to freeze plug stagnant deuterium oxide coolant lines for maintenance work.[4-28] If a cryogen, such as LN2, leaks during machine scheduled downtime (perhaps the nightly shutdown), any nearby water coolant lines would probably be freeze plugged the next morning. If the ITER cooling water piping is insulated, then the heat transfer from the cryogenic gas is reduced and more time is then available to allow the cryogenic gas to warm up in the ambient environment.[4-26] Piping insulation for critical areas around the tokamak is a conservative safety idea, although it would hamper remote video camera visual inspections and perhaps remote maintenance, and might increase the amount of low level waste to be disposed of. This safety trade-off must be examined during the ITER Engineering Design Activity.

4.5 Cryogen Contamination concerns

Contamination of the liquid cryogens is a concern for several reasons. First, the contaminants, either gases or solids, can plug up a magnet conductor conduit, causing magnet localized overheating. Plugs can also form in the cryogenic lines themselves, causing loss of flow events. Next, the contaminants can become activated, and if they circulate around the cryogenic system, maintenance could become difficult. Another reason is the concern over chemical reactions.

If oxygen liquefies in LN2 or LHe, there is a small possibility that it will be an oxidant. Systems for liquid oxygen (LOx), primarily in the aerospace industry, have experienced such events. Tests of centrifugal pump responses to pressure decreases (small breach events) in LOx systems showed pump impellers partially consumed in LOx fires.[4-29,4-30] Other industries have also noted the possibility of bad pump bearings overheating the aluminum impeller and causing aluminum-refrigerant reactions. These reactions can be forceful enough to fracture the impeller and breach the pump casing.[4-31] Oxidant reactions are a small concern compared to another problem with oxygen intrusion into a fusion system.

When the amount of oxygen dissolved into LN2 is high, 20 ppm or more, gamma or neutron radiation fields are likely to cause ozone creation. Several events of this type, with ozone or nitrate explosions occurring, happened in the 1960's, as discussed in Chapter 3. In fact, Chapter 3 also discusses two more probable ozone explosion events in the US in the 1980's. While oxygen would freeze at LHe temperatures, (freezing point is 55 K at 1 atmosphere pressure), it still flows at LN2 temperatures. However, if air leakage into LHe, or even small air leakage into the insulating vacuum, is near the source of radiation, ozone can still be created in frozen oxygen. Ozone freezes at 80 K at atmospheric pressure, so LHe or LN2 will freeze it out near where it is created, allowing it to accumulate on magnet or neutral beam refrigerating shields, or in cryotraps. The best known means of suppressing ozone formation is to use very high purity cryogens. LN2 with oxygen concentrations of less than 10 ppm has been used without incident in low level gamma irradiation fields,[4-32] although 5 ppm or lower is recommended for safety in higher irradiation field fusion experiments.[4-33] Other ideas to reduce the ozone threat are to warm and purge the system, thus sweeping out ozone, or use filters to trap any circulating ozone. Unfortunately, system purging to sweep out ozone may not be practical for some systems, and additional filters increases the risk of line plugging.

4.6 Modelling Large Cryogen Spills to the Environment

Most cryogenic systems maintain a reserve supply of cryogenic fluid, on the order of tens of thousands of liters, for peak demands. In the case of fusion, perhaps a magnet quench would require a reserve of LHe for recooling the magnet, purging a system with cool gas for pre-cooling, or other operational demands. Storage tanks for cryogens present a safety concern. In Chapter 3, we saw that several cryogenic storage tanks have leaked their contents to the environment, and that the chemical industry has had many public evacuations for cold or toxic gas releases. The ammonia treatment industry for agricultural fertilizers, liquefied natural gas energy utilities, and aerospace industrial concerns have all analyzed the problem of releasing a cryogenic liquid or gas cloud over land and on water.[4-34 to 4-42] These approaches use the typical gaussian plume modeling, treating heavier than air gases. Since these clouds are generally heavier than air, even refrigerated ammonia, the models are applicable to LN2. LHe has the advantage of being lighter than air and is not considered a threat if released outdoors. Small LHe clouds have been seen to initially settle because of their cold temperature, then very quickly rise again as they warm in air.[4-26]

A release of LN2 from a storage tank, because of a fire, impact event, overpressurization, earthquake, or for any other reason, would likely form a "pancake cloud" shape until it warms. This slumped gas cloud shape is characteristic of a heavier-than-air gas or cryogenic temperature gas release.[4-41] Site specific analysis would have to be performed to understand the safety implications of a release of a simple asphyxiant gas such as nitrogen. If radioactive isotopes are entrained in the cryogenic cloud, the gas warmup time to allow lofting would greatly affect the radiological dose at the site boundary. Many of the sophisticated models for heavy gas plumes, such as the DEnse GAs DISpersion (DEGADIS) computer code,[4-41] assess the potential for gas cloud explosions rather than simple asphyxiation. Wind speed, air temperature, location of site building ventilation air intakes relative to the release point, and distance to public habitations must be considered in such an analysis. Proposed 1 km site boundaries for future fusion facilities would likely provide enough distance for turbulent mixing in air to protect the public from any detrimental effects of a large LN2 release, but this should be verified. Support buildings on the fusion facility site must be protected from nitrogen gas entry into their ventilation systems. Another important safety tip is to have more than one access road into and out of any facility, so that if a plume of any kind is released (tritium gas, LN2, smoke from a fire, etc.), evacuating personnel or incoming rescue personnel have two options available to try to avoid the plume rather than be forced to drive through it. Multiple roads are generally considered to be a security problem, but it is very important to personnel safety to have at least two evacuation roads in different directions.

4.7 Gas Handling Plant Safety

In most cryogenic systems, there are warm (room temperature) gas handling requirements. For example, nitrogen plants generally begin by compressing air and then separating the components. Some systems must deal with boiloff gases. Fusion facilities have to have provisions for gas boiloff in case of a magnet quench event. There are several safety concerns for the gas handling plant. These plants, such as for liquefying nitrogen, can handle high pressure, high temperature gas. The same safety concerns for personnel exposure exist, with the additional concern for explosions. Pressurized systems can be quite hazardous. A study of simple 0.3-m diameter, 1.4-m tall, 14-MPa gas storage cylinders showed that breaking the valve off of a given cylinder allowed it to become a missile, crash through two standard construction brick walls, and remain airborne for some distance before stopping.[4-43] There are concerns that the plant might experience energetic explosions in the compressor or storage tanks, due to air inleakage or hydrocarbon contamination. Older information indicates that compressors have had explosions and fires due to lubricating oils,[4-44] and Chapter 3 gave some compressor fire events. Forceful explosions could easily damage nearby equipment, such as electrical power lines, cryogenic liquid storage tanks, or other facility support systems (instrument air building, cooling water pump house, etc.). Pipe whip from broken high pressure lines could also be a problem. Fortunately, fusion facilities use only helium and nitrogen as cryogenic gases, not explosive gases such as hydrogen, oxygen, ammonia, propane, or natural gas. The component failure rate section gives values for some equipment in the warmed gas plant as well as cryogenic components.

4.8 Noise Protection for Cryogenic Systems

Noise in the gas handling plant is also a personnel health and safety concern. Modern ammonia gas handling plants can generate around 100 decibels near large compressors,[4-45] and I assume that nitrogen and helium compressors produce comparable levels. To put this in perspective, a turbofan jet engine, with acoustic treatment, generates only a few decibels higher noise level on takeoff.[4-46] Noise and vibration must be considered in cryogenic system design and in the system's location within a fusion facility.

There are probably other cryogenic safety concerns not mentioned here. Designers and safety analysts must thoroughly assess the systems for fusion magnet cooling, cryopump cooling, and radiation detector cooling at future fusion facilities.

4.9 Special Cryogenic Safety Issues to Examine for Future Facilities

Future fusion experiments, such as ITER, will use large amounts of LN2 and LHe. Therefore, the safety issues discussed here must be examined during an ITER safety assessment. The straightforward issues of cryoplant availability and large cryogenic accidents, loss of coolant and loss of flow, must be analyzed. Of the potential safety concerns discussed here, the issue of radioactive isotopes entrained in a large cryogen release initially being held closer to the ground because of the cold gas cloud requires particular attention. The issue of a small overnight cryogen leak causing water coolant line freezing, electrical cable degradation, or structural support overstress should also be examined. The effects of a 1 km site boundary on large LN2 releases must also be verified.

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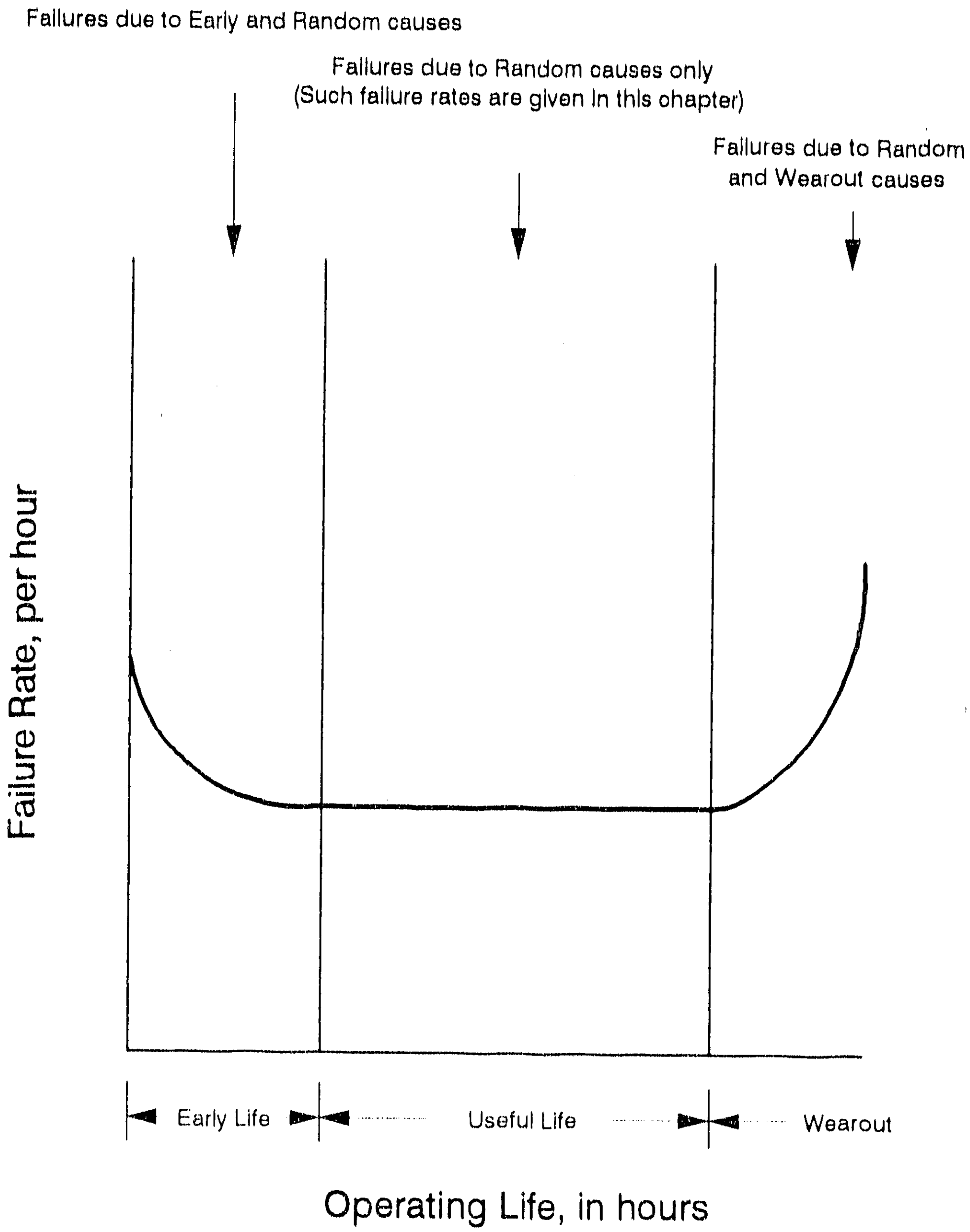
5. Suggested Failure Rates for Cryogenic Components

This chapter describes selection of suggested failure rates for cryogenic liquid and gaseous system components. These failure rates can be applied to specific systems 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. More accurate component failure rate values might be obtained from manufacturers when a fusion design progresses further.

The failure rates described here are generally taken from failure studies of similar equipment, mainly from LNG plants and particle accelerator LHe systems. Reported failure rates are usually 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 5-1, 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.[5-1,5-2]

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.[5-1] 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 the failure rate itself is an upper bound, then that fact is stated.



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

Figure 5-1. The reliability bathtub curve.

(Taken from reference 5-1.)

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 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 most of the equipment chosen to draw analogies to these fusion cryogenic components.

I have not addressed common cause or dependent failures in this chapter. Many of these failures are highly influenced by the fusion reactor design and spatial layout. Common causes, especially those from cold cryogen release, must be treated when adequate design information is available. Generally, many common causes can be approached using the standard Beta factor methods and some by explicit modeling, such as for internal floods and other consequential events.[5-3] 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 an example from the literature. 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 fewer inadvertent shutdowns generally meaning higher safety and better operations. Some of these new plants averaged less 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[5-4] also 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.[5-4] 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 dropping by a factor of perhaps 6 in that 3-4 year time interval. Cryogenic systems would probably behave similar to nuclear plants, perhaps closer to 1 or 2 years of early life. Accelerator experiences with cryogenic systems show these 1-2 year times, and sometimes longer, for early system life. The Large Coil Task (LCT) magnet testing experience for a year showed that the problems with the cryogenic system, such as cryogen leaks, air inleakage, etc., were not fully resolved.[5-5] Accelerator experiences also show that these systems require frequent maintenance, but not major component replacement. Life spans of 20 or more years are probably reasonable for cryogenic systems, with good maintenance and operational practices. Accelerator experiences show that factors of 2 to 3 or greater reductions in early life to useful life failure rates are possible for major components. Since future fusion experiments will have phased missions, by the time tritium operation is reached, the systems should be operating at their constant value failure rates.

Some of the failure rates given here are taken from accelerator helium system experiences, some from liquefied natural gas (LNG) experiences, and some are estimated values. Cryogenic systems for each of these gases, helium, nitrogen, or LNG, have their own types of liquefaction systems, based on the ease or difficulty of liquefaction. Helium gas is usually compressed in a large compressor, usually either a reciprocating or screw type unit, then expanded in one or more reciprocating expansion engines (large scale applications, in the hundreds of tons per day range, use turboexpanders). Heat exchangers, usually plate and fin units, are used to remove unwanted heat from the gas, then the gas is further depressurized by a Joule-Thompson (J-T) expansion valve into a reservoir. The effluent from the J-T valve is part liquid and part gas. A wet expander or expansion engine is used instead of, or in parallel with, a J-T valve for some magnet cooling systems, perhaps the 5,000 liter/hour size and larger. Any cool gas exhausted with the product helium resides in the upper region of the storage tank until it is circulated back into the process stream. Pre-cooling the system with LN2 can decrease the number of components or, more likely, the time required to produce a given volume of LHe.[5-6] For turboexpanders of less than 37 kW (50 horsepower), a dynanometer can be used to dissipate the shaft energy obtained from the gas expansion. For larger powers, electric generators, pumps, blowers, or integral compressor loads are usually used.[5-7]

Some of the failure rate information I am applying to fusion originated from LNG facilities. LNG systems are more complex due to the variety of gases included in natural gas. In the US, LNG is mainly methane (85 to 95%), but contains other gases, such as propane, that liquefy at temperatures different from the freezing point of methane. A mixed refrigerant cascade system is most often used to liquefy natural gas. Compressors and J-T expansion valves are used to liquefy the component gases, expanding them down to cryogenic temperatures (about 110 K at atmospheric pressure).[5-6]

Large quantities of nitrogen are typically liquefied by a cascade system, similar to that first used to liquefy air in the 1930's. Several compressor steps with intermediate cooling by cold ammonia, methane, or freon refrigerant are used. A final J-T expansion valve lets a mixture of liquid and gaseous nitrogen down to a storage tank. The gaseous nitrogen is circulated back into the process stream.[5-6] This LN2 cascade technique is efficient but expensive. Nitrogen is sometimes liquefied and sold as a byproduct of natural gas distribution plants, where LNG is warmed to back into gas for pipeline routing and distribution.[5-8]

I will examine major components individually. The main types of components treated here will be those just discussed, namely, reciprocating and turbo compressors, piping, reciprocating expansion engines and turboexpanders, heat exchangers, electric and pneumatic valves, pumps, storage tanks, and dewar-type vessels. Instruments for temperature, pressure, and flow rate measurement will be treated using data from other industries. Warm gas handling subsystem components, such as piping, storage tanks, compressors, gas cylinders, and instruments to deal with re-liquefying boiloff gases, or to make LN2 on-site, will also be examined.

5.1 Cryogenic Compressors

These compressors are slightly different than those units that service needs such as power plant instrument air or breathing air. Compressors for cryogenic systems of our interest can be large (perhaps 1.5 MW or larger), and compress gas up to moderate pressures (on the order of 20 atmospheres). These compressors may have several stages of compression with intercooling, followed by aftercooling, then oil removal and filtration.

Small reciprocating helium compressor (95 liters/hour, 20 atmospheres pressure) experiences at Fermilab show that the compressor first stage has a mean time between major failures of 1,500 hours for the 48 units. The failure rate is the inverse of the 1,500 hours value, if we assume small repair times (compared to the 1,500 hours). The second and third stages each have a mean time between failures (MTBF) of 800 hours. Since this is a series unit, we add the failure rates for each stage to get an overall compressor failure rate of about 3E-03/operating hour. I note here that the authors of the accelerator papers are implicitly using the constant failure rate assumption when they give MTBF values. An interesting operations statistic is that using an LN2 heat exchanger to pre-chill the helium in the system can allow production of LHe within 10 hours of start up from room temperature.[5-9]

The Energy Doubler accelerator helium system compressor availability has also been discussed. For failures, the staff estimated that it would typically take 60 hours of downtime to repair the compressor (so a Mean Time to Repair, or MTTR, is 60 hours). When the redundant, standby unit was installed, they believed that an instantaneous switchover to the standby unit could be performed with no system transient effects after primary unit failure.[5-10]

Literature for multi-stage reciprocating air compressors showed that failure rates are in the range of 4E-06/hour to 2E-04/hour.[5-11] The larger units appear to be more reliable, according to the literature. This may be because larger units can more easily be run at partial speeds to meet non-peak demands, reducing piston and piston seal wear. Major LNG compressor (both reciprocating and turbo units) system failures have a MTBF of 19,000 hours,[5-12] or a failure rate of about 5E-05/hour, if repair time is reasonably assumed to be much smaller than 19,000 hours. For the case of major gas explosions in the compressor, its downtime was reported to be between 3 and 6 days. Therefore, downtimes for less catastrophic events, perhaps more on the order of the 60 hours cited in the Fermilab paper, are probably appropriate for a fusion compressor MTTR.

Given that reported reciprocating compressor failure rates vary between 2E-04/hour to 3E-03/hour, and literature values for turbomachine compressors vary between 4E-05/hour to 6E-05/hour,[5-11] I suggest a conservative failure rate of 3E-03/hour should be used for small reciprocating units and 1E-04/hour be used for for small turbo units. These values could easily vary by as much as a factor of 10, so I assume an error factor of 10. The error factor for a lognormal distribution value is the 95% upper bound failure rate divided by the median failure rate. For this rough approximation technique, I assume the error factor is about the same as the 95% upper bound divided by the average value.

5.2 Cryogenic Piping

Piping for cryogenic fluids is usually double-walled pipe that contains perlite or another thermal insulation in the annular space between the inner and outer pipes. LNG applications use perlite in a vacuum space, LHe applications would likely use aluminized mylar in a vacuum space. The annular space is also usually pumped down by some type of vacuum pump to low pressures, perhaps as low as 1E-03 Pa, to further reduce heat transfer, especially for LHe at 4.5 K. Short runs of LNG piping may be single walled pipe with external insulating layers of perlite, balsa wood, or even fiberglass insulation. Unfortunately, I find that typical water-cooled fission reactor piping failure rates do not really apply for cryogenic pipes. Water reactor piping carries much higher pressures (up to 16 MPa) and is thicker walled. Cryogenic piping is insulated and thin walled to reduce heat transfer from the system's heat source, such as the magnets, to the fluid. Cryogenic pipe often has thin walls of 2.1 mm (schedule 5) or 3 mm (schedule 10).[5-6] Pressurized water reactor piping is generally 5.5 mm (schedule 40) or

7.6 mm (schedule 80). Cryogenic piping is likely to be 2 to 4 times thinner walled than light water reactor piping, although both may be made of 300 series stainless steel. The LNG industry information is more acceptable for fusion cryogenic system applications than light water reactor data, since the LNG materials are designed to be compatible with the temperature region (about 110 K at atmospheric pressure), and account for the special low heat transfer requirements. While light water reactor data is accessible and has a very large data set, the piping is not similar enough to apply these values to cryogenic systems. Another fact to consider is that light water reactor piping may be only carbon steel with stainless steel lining (cladding) rather than stainless steel throughout. Cryogenic piping is generally stainless steel or aluminum, and its failure rate will vary from that of clad pipe. From LNG experience, the piping failure rate for major failures (breaks or ruptures) is about 5E-9/hour-meter, for all diameters.[5-12] For minor failures like small leakage, the piping failure rate is about 6E-10/hour-meter for all diameters. Another interesting experience from the LNG industry is that pipe insulation has experienced many failures such as cracking, moisture buildup in insulation, and insulation joint seal degradation.[5-12]

To compare the LNG piping experience values with nuclear power plant piping failure rates, for pipes greater than 76-mm diameter, nuclear power plant pipe rupture failure rates are about 3E-11/hour-meter.[5-13] A more recent study[5-14] gave a failure rate of 3E-04/plant-year, or about 3E-12/hour-meter (assuming 12 km of piping per plant, see Appendix D of reference 5-14). Compared to the 5E-9/hour-meter, factors over 1000 in liberalism are assumed when fusion analysts apply water piping failure rates to cryogenic piping. Fortunately, cryogenic piping runs are usually short in length, so these variations in failure rates should not present extremely divergent results in risk calculations.

The failure rates assumed here from LNG experience can serve as a basis for preliminary calculations. I recommend detailed calculations using the Thomas method[5-15] for refined piping failure rate values. This method takes the wall thickness and number of welds into account, based on the idea that more material defects are present when there is more material and more welds. The base probability for the Thomas method multiplier approach should probably be increased an order of magnitude from the water piping value of 1E-09/hour. For our purposes here, a small leakage failure rate of 6E-10/hour-meter and a large leakage (rupture) failure rate of 5E-9/hour-meter will suffice. Error factors of 100 should be applied to these values from the LNG database report,[5-12] due to uncertainties in the LNG system information gathering process.

Bellows failure rates can be set by the manufacturer's requirement on bellows life. If a bellows design lifetime is 7,000 exercises,[5-16] and we assume no failures over its lifetime, then a 50% Chi-square distribution[5-17] for zero failures is 0.455/2(7,000)= 3E-05/demand. An error factor of 8 or perhaps 10, should be applied to this failure rate. Many bellows with damage by scarring and dents still meet their design life, but those repaired by welding have been shown to have life decreases down to 35% of original specifications.[5-16] This failure rate depends on the design life of the bellows under consideration.

Welds in the cryogenic piping should be as carefully made and controlled as those in a nuclear power plant because of the consequences of weld failure. Nuclear fission grade (N-stamp) quality assurance may not be needed because helium will not become radioactive, but high quality must be maintained for the cryogenic system. Buende[5-18] has surveyed weld reliability for fusion blankets and determined average leakage failure rate values to use for various types of welds. These values should apply to cryogenic systems as well. For longitudinal welds, about 6E-08/hour-m, for butt welds, about 6E-09/hour-weld, for circumferential welds, about 6E-10/hour-m, and for pipe fittings, such as bends, etc., 1E-08/hour-fitting. These values are representative for small leakage of shop welds, taken from fusion studies and from the nuclear fission industry. Buende also gives multipliers to treat these failure rates for different weld failure modes and fabrication locations. Large leaks should be 0.1 x the given rates. Weld ruptures should be 1E-02 x the given rates. Maintenance welds should be 10 x the given rates. Field welds should be 3.2 x the given rates. This weld information[5-18] is from the best discussion of weld reliability published in the last several years, and it is applicable to cryogenic system welds that are as important to safety and availability as blanket welds. I assume that leakage refers to leak rates less than 190 l/min, and rupture refers to flows equal to the pipe's normal system flow rate.

5.3 Expansion Engines

These can be either reciprocating or turbomachine units, either gas handling or liquid handling. Fermilab small helium reciprocating expanders had initial runs of only 1,000 hours duration due to broken drive shafts and bad seals. Runs lengthened to 1,300 hours between major equipment downtimes after the shafts were repaired and only the piston seals caused problems. Using new, Nitrile O-rings for piston seals gave much better performance, up to 3,000 hours.[5-19] This equipment break-in period lasted about two years. As we can see from the MTBF increase, the equipment failure rate dropped by a factor of 3 in that time. Therefore, the constant failure rate for a small, dry reciprocating gas expander is on the order of 3E-04/hour. The error factor is probably smaller than 10 for these actual data, perhaps 3 (good data) or 5 (medium confidence in the data) should be used instead. I suggest a factor of 3 for conservatism because the results are from a medium size set of 48 components.

Fermilab's small (95 liters/hour) reciprocating wet expanders showed MTBFs of 2,000 hours over the first 2 years of operation. This gives a failure rate of 5E-04/hour. Later improvements in wet reciprocating expander seals gave MTBFs of 4,200 hours, for a failure rate of 2E-04/hour.[5-19] Again, I suggest an error factor of 3.

Recent work on turbomachine reliability suggests that the axial flow turbomachines as a class perform much more reliably than their predecessors, the reciprocating piston units. Continuous duty run times of years between maintenance outages have been achieved, with strides as long as 10 years between major overhauls.[5-20] Therefore, I suggest that a new fusion facility, needing large quantities of cryogens (thousands of liters per hour, or kilowatts of heat removal) for magnet cooling, should take advantage of newer, more reliable turbomachine technology.

For axial flow air and oxygen turbocompressors, failure rates of about 5E-05/hour are given in the literature.[5-11] For guidance, I consider this to be a conservative estimated failure rate for wet and dry cryogenic turboexpanders. An error factor of 10 is appropriate for these units, since no error factor is reported in reference 5-11. Typical repair times on the order of 18 hours were cited for this equipment.

5.4 Heat Exchangers

LN2 or LHe cryogenic heat exchangers can suffer from small inleakages of air, which freezes and begins to plug up flow in the units, as seen in LCT experiences discussed in Chapter 2. They can also suffer large leakages to the atmosphere or through the plates to the opposite fluid. LNG plate and fin heat exchanger experience gives a major failure rate of 6E-06/hour, and a minor failure rate of about 1E-05/hour. Major failures are those requiring over 24 hours of downtime, or else they are considered as major accidents. Minor failures require repair, but keep the plant down less than 24 hours.[5-12] These values are adequate to apply to other cryogenic heat exchangers because of similar design styles and also that the design choice of low temperature compatible materials has been performed. Error factors of 100 should be used with these values.

5.5 Cryogenic Valves

LNG valve experience with external leakage and freezing in an open position gives a failure rate of about 6E-07/hour. Minor failures, typically small leaks, have a failure rate of 3E-06/hour. Both of these values have an error factor of 100.[5-12] I find these valve failure rates to be lower than I expected. Also, R. Callis[5-21] of the DIII-D experiment has suggested that some of these valves can only be exercised perhaps 10 to 100 times before they significantly leak past the seat because of seat scarring and deterioration.

I suggest in this case that light water reactor valve information be used for these cryogenic components, since it will be conservative. Also, conservative values will be used to address the leak-past-the-seat operating concerns. From fission experiences, motor operated valve failure rates are on the order of 1E-03/demand for failure to operate, and 1E-04/demand for plugging up (failing to remain open), with error factors of 3.[5-13] Also for conservatism, I will use the 6E-07/hour for an external rupture failure rate from the LNG data,[5-12] since it is a factor of 60 larger than the light water valve failure rate for that failure mode. The fission reactor value for check valve leakage past the seat is given as 3E-07/operating hour,[5-13] but due to the differences between actuated valves and the concerns over cryogenic valve seat durability, I suggest using 3E-03/operating hour for cryogenic service motor operated valve leakage past the seat. Pneumatic or air operated valve failure rates are on the order of 3E-04/demand for failure to operate, and the same values for plugging up, rupture, and leakage past the seat as given above. An error factor of 5 should be applied to these values. These valve failure rates are factors of 300 and higher than the LNG valve experience values, but are much more reasonable for order-of-magnitude data when one considers that the type of operations (number of demands, etc.) at a fission plant will be closer to a fusion cryogenic system than that of LNG facilities. Also, the LNG component failure experience report did suggest that the questionnaires might not have been filled out accurately for valves.[5-12]

Cryogenic overpressure relief valve failure to open rates from accelerator helium system experience are 1E-02/demand.[5-22] I suggest an error factor of 5 for this value. Reasons for this high failure rate are that the valves would get plugged with foreign materials from the helium coolant in the magnet cases, from materials loose within the magnet cases, and valve faults. This is a good example of actual operations experience amending a failure rate. For example, a spring loaded safety relief valve failure rate for failing to open might be 1E-05/demand, and premature opening might be 1E-05/hour for a light water reactor.[5-13] I also assume relief valve body ruptures are about the same value as the LNG valve external leakage rate, at 6E-07/hour. That assumption is conservative, since relief valves are usually smaller than process valves and therefore have a somewhat smaller chance of material flaws included in them during manufacture.

5.6 Cryogenic Pumps

The LNG study[5-12] gave a major failure rate for centrifugal pumps of about 3E-04/hour, with most failures being in the bearings and the drive motors. I assume that this failure rate is in the failure to run category. Failure to start on demand was not covered, since LNG facilities typically operate in a continuous manner. Therefore, I assume a fission reactor value for pump failure to start on demand on 3E-03/demand, with an error factor of 5.[5-23] LNG minor failures had a failure rate of about 2E-05/hour, which I assumed meant running in off-normal parameters, typically underspeeding. I assume that pump casing breach failures have a failure rate of 1E-09/hour, with an error factor of 30.[5-24]

5.7 Pressurized Cryogenic Liquid Storage Tanks

Failures of these large tanks can have great consequences, as discussed in Chapter 3 for the NASA storage tank failure that released 2,755 m^3 of LOx. Storage tanks for LNG and LPG have been examined for their accident consequences, and will be discussed in the next chapter. Briefly, the breach failure rates appear to be on the order of 1E-06 to 1E-07/year.[5-25] These very low failure rates are intended to indicate that there is very low risk from the storage tanks. Indeed, with concrete bund walls and some tanks themselves being made of cryogenically stable concrete, they are very solid structures, capable of withstanding normal operational events, such as overpressure. For earthquakes, a large storage tank breach failure rate of 1E-04/year is suggested.[5-25] If a fusion facility storage tank is made of concrete and protected as these tanks are, then these LNG tank failure rates should apply to the fusion tanks.

5.8 Cryogenic Instrumentation

Typical instruments for cryogenic systems are liquid level indicators, general pressure transducers, venturi gauges for flow measurement, silicon diode temperature detectors, and cold cathode gauges for vacuum measurement.[5-26] I rely on NASA Saturn rocket part experiences for some of these failure rates.[5-27] Using the failure rate modifiers for liquid helium temperatures, liquid level sensor failure rates are: incorrect output, 2E-03/hour; no output, 6E-04/hour; and erratic indication, 4E-05/hour. These values have an error factor of 2. Pressure transducer failure rates are: low output, 8E-03/hour; high output, 7E-03/hour; erratic output, 6E-03/hour; and external leakage, 7E-04/hour. Again, these values have an error factor of 2. Turning to other data sources, flow-indicator controllers for an ammonia plant have a failure rate of 2.5E-01/year (and we can assume year round operation, or about 3E-05/hour).[5-28] In comparison generic failure rate data for all types of flow measurement devices is 6E-06/hour (reference 5-12, page 573). I suggest using 1E-05/hour with an error factor of 10 to account for possible venturi plugging and any low temperature effects in the instrument. I anticipate that silicon diode temperature detectors will have operational problems due to impurities in the flow stream, such as metal shavings, noncondensible gases, etc. Typical silicon diode failure rates are on the order of 1E-06/hour for short circuits, intermittent circuits, and open circuits.[5-29] To account for the rest of the instrument and the low temperature effects, I suggest a failure rate of 1E-05/hour with an error factor of 10. Cold cathode gauges, or Penning gauges, are rather simple devices. They consist of anode and cathode arranged in a low strength permanent magnet field.[5-30] Such simple meters should not have many failure modes, and should be reliable. Of course, these gauges cannot be used near the fringe field from the fusion magnets. I suggest a failure rate of 1E-03/year for these gauges, since this failure rate is the mid-point of the range of events commonly regarded as unlikely events. For a continuously operating unit (as we would find in a cryogenic system because significant downtimes are realized when warming and cooling the system) the failure rate would be about 1E-07/operating hour. I also assume a conservative error factor of 10 for the cold cathode gauge failure rate.

5.9 Gas Handling Plant Equipment

The warm gas handling subsystem duplicates some of the same equipment from the cryogenic temperature side of the plant, namely compressors and storage tanks. Another component to consider here is the gas storage cylinder. These steel cylinders generally have a 24 year imposed life, to keep wall thinning from creep due to pressure loads and internal corrosion problems from causing a breach event.[5-31] If we consider that these cylinders are maintained well, cleaned regularly, and handled carefully, then the assumption of no failure over service life is reasonable. Therefore, using a 50% Chi-Square distribution[5-17] on zero failures and 24 operating years gives 0.455/2(24 years) = 9.5E-03/year, or about 1E-02/year. A 95% upper bound failure rate would be 3.841/2(24 years) = 8E-02/year.

Other warm gas handling plant component failure rates have been taken from the literature on natural gas, and ammonia facilities. While these failure rates are not from the exact same equipment, they are from the correct industrial application of gas handling, and serve in analogous functions in their respective plants. These failure rates are indicative enough for our fusion facility order-of-magnitude analyses. The warm gas plant component failure rates are given in Table 5-1.

5.10 Unpressurized Storage Containers

Small 'dewar' cryogenic storage containers are simply unpressurized, insulated containers to limit the amount of heat inleakage boiloff. Larger cryogenic containers, usually referred to as cryostats, generally utilize pressure to suppress boiling. The cryostat containers are actually only as good as their ability to maintain an effective vacuum insulation space. Once that space is filled with either the cryogen or air, heat transfer into the inner vessel increases and boiling can no longer be suppressed. Therefore, since failure of either the inner or outer wall will fail the unit, the failure rate for either the inner chamber or the outer chamber (whichever is larger) is used for the entire cryostat.

For dewars, Tantam[5-34] states that the vacuum space between chambers lasts 7 years or perhaps longer. If we consider that these dewars are well cleaned and maintained, do not form ice plugs, are not abused, etc., then a 50% Chi-square distribution failure rate with zero faults in seven years is 0.455/2(7 years) = 3E-02/year. The 95% upper

TABLE 5-1. WARM GAS PLANT ORDER-OF-MAGNITUDE COMPONENT FAILURE RATES APPLICABLE TO FUSION FACILITIES

Component Description	Failure rate	Error factor	Reference
Gas-operated shutoff valve, fail to operate	0.2/year	3	5-32
Turbine flow meter (reads high or low)	0.06/year	3	5-32
Resistance temperature detector (reads high or low)	0.07/year	3	5-32
Pressure transmitter (reads high or low)	0.2/year	3	5-32
Gas density meter (reads high or low)	0.06/year	3	5-32
Process control computer system fail to operate	100/year	3	5-32
Gas compressor (assumed to be turbo unit) fail to operate	5E-03/hour	3	5-32
Solenoid valve, fail to operate	5E-02/year	5	5-28
Control valve, fail to operate	3E-02/year	5	5-28
Uninterruptible power supply system fail to operate	3E-02/year	5	5-28
Large compressor, fail to operate (assumed to be turbo unit)	5E-02/year	5	5-28
Gas Piping, all diameters, catastrophic failure (taken from natural gas pipe data)	2E-11/hr-m	4	5-33
Piping connection leakage	6E-07/hour	4	5-33

bound failure rate is 3.841/2(7 years) is about 3E-01/year. Considering some of the abuse that these dewars survive when subjected to rigorous testing, this is a conservative failure rate.[5-35]

For large metal cryostats, I assume that they are built similar to low temperature, unfired pressure vessels used in the chemical industry. A reliability survey of these and other thin walled, unfired pressure vessels[5-36] shows that an average failure rate for breaches is 1E-03/year, under normal service conditions. An error factor of 4 applies to this failure rate. Seismic responses must be judged separately. If the cryogenic cryostat has many penetrations, such as those with flexible bellows, then the failure rate of penetrations must be assessed. Also, if the cryostat is not thick walled or robust enough to handle small pressure transients, then the 1E-03/year value may be too liberal.

Large, thick-walled concrete cryostats, are very similar to the LNG storage tanks mentioned in section 5.7. Therefore, an order-of-magnitude breach failure rate for such a tank in a fusion facility is probably 1E-06/year, without consideration of seismic, impact, or crane operations induced failures.

Table 5-2 gives a summary of the failure rates cited in this chapter for cryogenic components. These failure rates can be used for fusion cryogenic system risk assessment, reliability analysis, design trade-off studies, and availability analyses. Table 5-3 gives some average hands-on component repair times from the referenced accelerator discussions and other data sources.

TABLE 5-2. SUMMARY OF ORDER-OF-MAGNITUDE FAILURE RATES FOR CRYOGENIC SYSTEM COMPONENTS APPLICABLE TO FUSION FACILITIES

Component Description	Failure Rate	Error Factor
Small reciprocating compressor		
all failure modes	3E-03/hour	10
Large reciprocating compressor		
all failure modes	5E-05/hour	100
Large turbo-compressor		
all failure modes	1E-04/hour	10
Small, dry reciprocating gas expander		
all failure modes	3E-04/hour	3
Small, wet reciprocating expander		
all failure modes	2E-04/hour	3
Axial flow turbo-compressor	5E-05/hour	10
all failure modes		
Plate and fin heat exchanger		
major failures (breach)	6E-06/hour	100
minor failures (leakage)	1E-05/hour	100
Motor-operated valve (all sizes)		
fails to operate on demand	1E-03/demand	3
plugging	1E-04/demand	3
external rupture	6E-07/hour	5
leak past the seat	3E-03/hour	5
freezing up in position	6E-07/hour	100
Air-operated valve (all sizes)		
fails to operate on demand	3E-04/demand	3
plugging	1E-04/demand	3
external rupture	6E-07/hour	5
leak past the seat	3E-03/hour	5

TABLE 5-2. SUMMARY OF ORDER-OF-MAGNITUDE FAILURE RATES FOR CRYOGENIC SYSTEM COMPONENTS APPLICABLE TO FUSION FACILITIES (Continued)

Component Description	Failure Rate	Error Factor
Pressure relief valve (all sizes)		
fail to open on demand	1E-02/demand	5
external rupture	6E-07/hour	5
premature opening	1E-05/hour	3
Motor-driven centrifugal pump (all sizes)		
fail to continue to run	3E-04/hour	100
fail to start on demand	3E-03/demand	5
fail to run at rated speed	2E-05/hour	100
external breach failure	1E-09/hour	30
Large cryogenic storage tank breach	1E-06/year	10
Liquid level sensor		
incorrect output	2E-03/hour	2
no output	6E-04/hour	2
erratic indication	4E-05/hour	2
Pressure transducer		
low output	8E-03/hour	2
high output	7E-03/hour	2
erratic output	6E-03/hour	2
external leakage	7E-04/hour	2
Venturi flow meter, all modes	1E-05/hour	10
Silicon diode temperature detector		
all failure modes	1E-05/hour	10
Cold cathode vacuum gauge		
all failure modes	1E-07/hour	10
Steel gas cylinder breach	1E-02/year	8

TABLE 5-2. SUMMARY OF ORDER-OF-MAGNITUDE FAILURE RATES FOR CRYOGENIC SYSTEM COMPONENTS APPLICABLE TO FUSION FACILITIES (Continued)

Component Description	Failure Rate	Error Factor
Insulated dewar boils dry	3E-02/year	10
Metal cryostat inner or outer shell breach	1E-03/year	4
Concrete cryostat breach	1E-06/year	10
Cryogenic pipe (all diameters)		
breaches	5E-09/hour-m	100
leakage	6E-10/hour-m	100
Metal bellows breach failure (based on 7000 operating cycles)	3E-05/demand	10
Weld, small leakage failure		
Longitudinal weld	6E-08/hour-m	5
Butt weld	6E-09/hour-m	5
Circumferential weld	6E-10/hour-weld	5
Pipe fitting weld	1E-08/hour-fitting	5

Note: gas handling plant component failure rates are given in Table 5-1 Weld multipliers: large leak failure rate is 0.1 x given values, field weld failure rates should be 3.16 x given values, and maintenance welds should be 10 x given values. Weld ruptures should be 1E-02 x the given values. I estimate that small leaks can range from drops per minute to 5% of pipe flow, or 190 l/min, whichever is larger. Large leaks likely range from 5% up to 50% of pipe flow, and ruptures are taken to be 100% of pipe flow.

TABLE 5-3. TYPICAL HANDS-ON COMPONENT REPAIR TIMES FOR CRYOGENIC COMPONENTS WITH APPLICABILITY TO FUSION FACILITIES

Equipment item to be repaired	Repair time, hours	Reference
Small cold box (warmup, entry, and cooldown)	146	5-10
Cryogenic transfer line	1	5-10
wet reciprocating expander	1	5-10
dry reciprocating expander	1	5-10
Plug leaky heat exchanger u-tube	0.1	5-10
Compressor	60	5-10
Recovery from a gas explosion in a compressor	3 to 6 days	5-12
Air compressor	18	5-11

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6. Cryogenic System Initiating Events for Fusion Facilities

This chapter gives a summary of published risk assessment initiating event (IE) frequency information relating to cryogenic systems. This information is from superconducting magnet cooling system safety assessments and safety analyses performed for other industries. Chapter 5 gave suggested component failure rates for analysts to use when building IE fault trees. IEs are the initial failure events that lead to an undesired system or facility condition, such as release of radioactive materials or destructive release of energy. As in other chapters, other industry information, such as that from liquefied natural gas (LNG), liquefied ammonia, and liquefied petroleum gas facilities (LPG), has been reviewed along with magnetic fusion safety work to compile the information discussed here.

These frequencies can be used as initial numbers in a scoping study of the risks from possible hazards. IE frequencies for large scale industrial operations should be larger than those for a fusion facility's more modest operations. A large LNG facility might handle 100 to 1,000 tons/day, while a fusion facility might handle quantities up to 100 tons of LHe/day. Fusion LHe systems will be operated more in the refrigerating mode, removing kilowatts of heat from the magnets (without continuous liquefication). A fusion facility's LN2 needs are likely to be higher than LHe, but also in the heat removal mode. The LN2 might be allowed to boil and be re-liquefied. Later, when detailed safety work is done for fusion, the initiating event values given here can be used for comparison to the calculated IE frequencies, to provide a check against other, independent work from other industries.

Table 6-1 gives order-of-magnitude IE frequencies reported in the literature. These values can be used for fusion facilities. I have assumed that the variety of cryogenic systems are similar enough in design to fusion facilities that the IE values reported for these different industries will be indicative of conservative frequency magnitudes for fusion facilities. All industries using cryogenic fluids need to take similar design precautions, such as retarding heat transfer into the fluid by insulation and optimized pipe design. Cryogen transfers to trucks or rail cars will also likely be similar for all facilities, except for the

TABLE 6-1. CRYOGENIC SYSTEM INITIATING EVENT FREQUENCIES FROM VARIOUS INDUSTRIES APPLICABLE TO FUSION

Initiating Event Description	Frequency	Reference
Large LHe magnet coolant loss-of-coolant accident	1E-04/yr	6-1
Loss of fusion magnet insulating vacuum	3E-03/yr	6-2
Cryogen terminal spills and incorrect transfers (assume error factor of 10)	1E-06/yr to 1E-07/yr	6-3
Primary failure of refrigerated cryogen storage tank	1E-07/yr	6-4
Failure of refrigerated cryogen storage tank due to overfill	1E-10/yr	6-4
Refrigerated cryogen storage tank collapse due to vacuum creation inside tank	1E-15/yr	6-4
Inadvertent gaseous release from rail car during unloading (assume 1500 cars/year)	1E-06/car	6-5
Driver moves cryogen truck while it is still connected to unloading arm, following completion of unloading, a large release results (assume 1000 trucks/year)	1E-04/truck	6-5
Cryogen release from truck unloading arm if truck shifts position while still connected (medium release, 1000 trucks/year)	1E-05/truck	6-5

TABLE 6-1. CRYOGENIC SYSTEM INITIATING EVENT FREQUENCIES FROM VARIOUS INDUSTRIES APPLICABLE TO FUSION (continued)

Initiating Event Description	Frequency	Reference
Refrigerated cryogen storage tank farm failures from events within the plant	1E-06/yr to 1E-07/yr	6-6
Refrigerated cryogen storage tank farm failures from events outside of the plant (earthquake, etc.)	1E-04/yr	6-6
Storage tank farm events (for 18 tanks)		
drainage spill, not following procedure	5E-03/yr	6-7
Tank overfilling	1E-01/yr	6-7
Tank instrument connection breakage	1E-04/yr	6-7
cryogen leakage from flanged joint	1E-02/yr	6-7
cryogen leakage from pump seal	2E-02/yr	6-7
US cryogen spill incidents	1E-05/hr	6-8
cryogen plant small fires	4E-06/hr	6-8
cryogen truck loading and unloading spills (truck value estimated from a Chi-square distribution on zero large failures)	2E-07/hr	6-8
cryogen pipework failure (over whole refinery)	5E-03/yr	6-9
cryogen tank serious fatigue failure	2E-04/yr	6-9
cryogen tank overpressurization by overfilling	1E-04/yr	6-9
Cryogen tank car derailment	1E-06/km	6-9
probability of overturning, given derailment	0.2	6-9
Tank truck road accident involving spill	2E-08/km	6-9

wide variance in the number of transfers per year. Error bounds are not typically reported, since these values should be conservative upper bounds.

Some of the IE frequencies given in Table 6-1 are very low. Frequencies on the order of 1E-10/year are not credible values. Such low frequencies are meaningless, unless the authors are trying an indirect means to illustrate that concern is not necessary for the particular event. I suggest stating such facts in the text, not by using an extremely low value. Such low frequencies are not meaningful and can damage the credibility of the entire analysis.

A failure modes and effects analysis for an MHD experiment gave some qualitative initiating events. These were loss of insulating vacuum, failure of relief valves to open on overpressure (causing burst disks to open and risking an explosion due to liquid oxygen condensation), refrigerating shield overfill, pipe rupture, and high pressure gas explosions.[6-10]

Other events I noted in Chapter 3 that should be considered for inclusion as IEs are ozone explosions, control system errors, and human errors. Since attention has been given to ozone explosions, and reasons for their occurrence are known, I assume that these events can only occur with a low frequency at future fusion facilities. I will set a point estimate IE frequency of 1E-03/year, with an error factor of 10, on ozone explosion events, since that is the midpoint of the probability range generally thought of as unlikely events.

I noted small discussions of control system errors and problems in the literature. Fermilab experiences showed that large cryoplant control systems could cause about 10-15 hours of downtime per month,[6-12] and LNG terminal experiences showed computer control system outage frequencies of 100/year.6-13

Human errors in LHe cryoplant operations have also been noted at Fermilab.[6-12] These were said to account for a few hours of system downtime each month. As a first attempt at estimating human error probabilities, I refer to the Systematic Human Action Reliability Procedure (SHARP).[6-14] This procedure gives coarse estimates, usually overestimates, of human reliability for a variety of tasks, accounting for the task difficulty. SHARP estimates are usually very conservative, but they suffice until such time as detailed human factors Task Analysis can be performed using operator interviews, operating procedure reviews, and other similar information. For a new system, I assume a SHARP 'rule based' midrange error rate of 1E-02/demand for unusual actions where the operator might place the system in a detrimental condition. As the operators familiarize themselves with the system, this value should be reduced to a SHARP 'skill based' midrange error rate of 1E-03/demand. I assume that operator errors which can place the cryoplant in jeopardy will be blocked by the computer interlock system, but, since it could also fail, I assume a conservative IE frequency of 1E-02/year for operator errors harmful to the cryoplant. Maintenance errors should be discovered by system checks or tests prior to returning the system to operation, so I will assume an IE frequency of 1E-03/year for significant maintenance errors. These maintenance errors are those that endanger the system, such as allowing system breaches to the building to occur.

Chapter 6. References

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