INL/CON-07-12265
PREPRINT

Failure Rate Data Analysis for High Technology Components

Eighth International Topical Meeting on Nuclear Applications and Utilization of Accelerators

L. C. Cadwallader

July 2007

FAILURE RATE DATA ANALYSIS FOR HIGH TECHNOLOGY COMPONENTS

L. C. Cadwallader

Idaho National Laboratory, PO Box 1625, Idaho Falls, ID 83415-3860 Lee.Cadwallader@inl.gov

Understanding component reliability helps designers create more robust future designs and supports efficient and cost-effective operations of existing machines. The accelerator community can leverage the commonality of its high-vacuum and high-power systems with those of the magnetic fusion community to gain access to a larger database of reliability data. Reliability studies performed under the auspices of the International Energy Agency are the result of an international working group, which has generated a component failure rate database for fusion experiment components. The initial database work harvested published data and now analyzes operating experience data. This paper discusses the usefulness of reliability data, describes the failure rate data collection and analysis effort, discusses reliability for components with scarce data, and points out some of the intersections between magnetic fusion experiments and accelerators.

I. INTRODUCTION

In the past 50 years, reliability has become an important aspect of the increasingly sophisticated and complex tools being used and designed for modern life.[1] Reliability is also inherent in many aspects of nuclear systems and facility operations. Operational reliability data are the best source of information on component life and health, however, because the components are operating within their planned environment and undergoing their true operational demands.

There are several reasons to study reliability.[2] One key reason is that properly used reliability analyses can make a system or an entire facility more efficient. Modest investment in computerized data collection and analyst time has demonstrably resulted in cost savings, improved operational efficiency, and life cycle planning.[3] Some facilities are now being designed with a facility reliability or operational availability target in mind. For example, the International Fusion Materials Irradiation Facility has a goal of 70% availability and the International Thermonuclear Experimental Reactor (ITER) has a goal of 3,000 pulses per year.[4,5] In addition, operational data aid in determining spare parts inventories and component replacements, establishing preventive maintenance programs, and assessing the strengths and weaknesses of systems, the impact systems have on experiment data, and the number and skills of maintenance personnel needed. In fusion research, reliability affects efficiency because better-operating machines produce higher quality and more timely data than machines that break down often and require venting to atmospheric pressure for repairs.

A second reason for reliability analyses is that data derived from operating experience help designers prevent propagation of operational problems in system or facility retrofits, modifications, or enhancements, as well as new designs to be constructed. For example, when designers determine that parts or components work well, they can confidently use the parts in future designs. When designers learn of deficiencies, they can use more robust parts, alter the design, add redundant or diverse components, de-rate the operation of the component, or use other means to increase the reliability.

The third reason to study reliability is that when safety or environmental issues exist with a system or facility, the collection of operating experience data will support a variety of safety and risk analyses[6] or probabilistic safety assessment of hazardous materials (flammable, toxic, radioactive).[7] For example, in the 1980s the offshore oil and chemical process industries began collecting data for safety assessment after some tragic accidents (the Piper Alpha oil rig explosion in 1988 and the Bhopal pesticide plant disaster in 1984). The chemical and petroleum industries now perform limited probabilistic safety assessments, focused on offsite consequences to the public from energetic events.[8]

A fourth reason for reliability study pertains to radiological safety. Observing the operating experiences of engineered systems, especially near-failures and failures that result in hazardous energy release, is the key to managing production stoppage, substandard quality, facility damage, and injuries to personnel.[9] When facilities use or create radioactive materials, even in small quantities, a safety analysis report or safety assessment document is needed to show that the facility is well designed and is a responsible steward of radiological materials.[10,11] Presently, magnetic fusion is using the traditional, conservative safety analysis[12] combined with risk assessment techniques to address radiological safety.[13–15] For accelerators, the amount of radioactive material created may be only a few grams per year, but hazard, safety, and risk analyses could be called upon to support an application for an operating license.

Particle accelerators have two very important qualities that are quite attractive to reliability studies. The first quality is that accelerators use very high numbers of similar components, often dozens to thousands of one type of component. Because of the cost savings of large vendor orders and simpler maintenance training, accelerator staffs tend to use just one brand of component and subsequently stock only that brand's replacement parts or subcomponents, which creates very large and uniform component "populations." Both of these aspects lead to obtaining good statistical data. The second quality is that accelerators strive to operate in one or more campaigns of several thousand hours per calendar year. Therefore, accelerators can accumulate high-confidence statistics on component and system reliability in just a few years. Smaller experiments with fewer components and less run time, such as magnetic fusion experiments, usually require over a decade of accumulated operating time to produce meaningful component failure rate data.

This paper describes ongoing work to support magnetic fusion experiment operations and safety. Parallels exist between fusion and accelerator research in terms of equipment and technologies employed. Operating experience from magnetic fusion components can be applied to accelerator components.

II. DATA GATHERING TASK

In the 1980s, the Fusion Safety Program at the Idaho National Laboratory (INL) recognized the need for probabilistic safety assessment of magnetic fusion experiments that used radioactive, gaseous tritium fuel and created radioactive materials by neutron activation.[16] Work began to assemble sets of generic failure rate data for fusion components.[17,18] Initially, work focused on water, liquid metal, and gas cooling systems, then expanded to include vacuum systems, confinement building components, and some initiating event frequencies for use in risk assessment. These "generic" data typically indicate a reasonable or correct order of magnitude for component failure rates of a particular type of component (e.g., pipe run, valve, tank); the data are useful for comparing design alternatives, using in reliability-availability-maintainability-inspectability (RAMI) and system-level failure modes and effects analysis (FMEA), or applying probabilistic risk assessment techniques during conceptual and preliminary design. A few failure rate values are given in Table I as examples.

TABLE I. Representative Generic Data for Use in Data Analysis[18]

Component and Failure Mode	Average Value (/hr)	Error Factor[a]
Liquid metal pipe, leakage/ rupture	1.6E−09	30
Liquid metal valve, fail to operate	5E−08	30
Liquid metal mechanical pump, fail to operate	3.5E−05	10
Liquid metal electromagnetic pump, fail to operate	1E−06	10
Rupture disk, leakage/rupture	1.9E−04	10
Gas piping, all failure modes	3E−10	100
Gas valve, all failure modes	3E−06	10
Electric drive gas circulator, all failure modes	1E−04	10

a. This error factor is the 90% confidence bound estimate divided by the nominal failure rate value.

After data collection was begun at the INL, an opportunity for collaboration arose among countries researching fusion energy. The International Energy Agency (IEA), based in Paris, France, proposed a cooperative agreement on the environmental, safety, and economic aspects of fusion power (known as IEA-ESE/FP). Within the agreement, task 5 is the assembly of a fusion component failure rate database. Participating countries lend support to the task by having cognizant safety researchers meet to share information and ideas. The task participants have agreed to undertake two paths: a short-term data harvesting path described above where generic sets of data are collected and a longer-term path to perform data analysis from existing facilities.[19]

II.A. Harvesting Generic Failure Rate Data

Moss and Strutt have pointed out the value of data harvesting for design support.[20] These generic data can support system availability assessment and modeling, hazard and operability studies favored in the chemical and petroleum industries, and RAMI and FMEA, which are fundamental reliability analysis tools.

In 1992, IEA-ESE/FP task 5 participants began collaborations and shared handbook and generic data values from the documents listed in Table II and other sources.[19–22] Published fusion and accelerator experiences were surveyed for useful data along with information from other industries. Several of these reports have documented findings on magnets, cryogenic components, vacuum components, in-vessel cooling systems, and alternate coolants.[23–29] The data collection work was later expanded to include more industrial aspects of fusion operations, including various plant sensors, fire protection systems, electrical power distribution, various safety equipment, and aspects of maintenance operations.[30–36] All of these data were placed in a computerized database under IEA task participant care.[37–39] The IEA database is restricted to IEA member country participants, however, and task 5 limits database access to those persons working in magnetic fusion safety. Therefore, analysts outside of fusion should use the individual published data reports, most of which are listed in this paper. Many of these reports are available through www.osti.gov.

The accelerator community has chosen a similar path to examine data from facilities and maintains the Accelerator Reliability Database.[40] Access to this database is also restricted to members.

II.B. Failure Data Collection and Analysis

The second part of IEA-ESE/FP task 5 is to collect and analyze operational data from existing fusion facilities. Most of the tokamaks and other fusion experiments have set up trouble report databases,[41–46] keep logbooks of operations, and document operations in annual reports. The data selected for task 5 collection support any of three attributes that must be studied for fusion experiments: public safety, personnel safety, or fusion experiment operational availability.

As task 5 has progressed, opportunities have arisen to analyze collected data at some fusion facilities. For example, the Tritium Systems Test Assembly at Los Alamos National Laboratory, a fusion fuel cycle testing and technology demonstration facility, collected their trouble report data.[42,47] From that set of data (system component counts, system operating practices, operating times, and counts of demands for component operation), several statistical analyses have been performed on the trouble report data set.[48–53] Similar analyses have been completed on comparable facilities in the European Union (EU)[54,55] and in Japan.[56,57] Comparisons between these data sets have been made, with fair to good results.[58,59]

TABLE II. Selected Generic Data Sources Available for the IEA Fusion Component Failure Rate Data Bank

International Atomic Energy Agency (IAEA), *Component Reliability Data for Use in Probabilistic Safety Assessment,* TECDOC-478 (1988)
IAEA, *Evaluation of Reliability Data Sources,* TECDOC-504 (1989)
IAEA, *Manual on Reliability Data Collection for Research Reactor PSAs,* TECDOC-636 (1992)
IAEA, *Generic Component Reliability Data for Research Reactor PSAs,* TECDOC-930 (1997)
OREDA, *Offshore Reliability Data Handbook*, Second Edition, DnV Technica (1992)
D. I. GERTMAN, W. E. GILMORE, W. J. GALYEAN, M. R. GROH, C. D. GENTILLON, B. G. GILBERT, W. J. REECE, *Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR)*, NUREG/CR-4639, Volume 5, *Data Manual*, Revision 3, INL (1990)
CENTER FOR CHEMICAL PROCESS SAFETY and SCIENCE APPLICATIONS INTERNATIONAL CORPORATION, *Guidelines for Process Equipment Reliability Data*, American Institute of Chemical Engineers (1989)
ATV OFFICE and STUDSVIK AB, *T-Book, Reliability Data of Components in Nordic Nuclear Power Plants*, Third Edition, Vattenfall AB (1992)
D. C. ARULANANTHAM and F. P. LEES, "Some Data on the Reliability of Pressure Equipment in the Chemical Plant Environment," *Int. J. Pres. Ves. Pip.*, **9**, 327 (1981)
POWER SYSTEMS RELIABILITY SUBCOMMITTEE, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems*, IEEE Std 493-1997, IEEE (1997)
W. DENSON, G. CHANDLER, W. CROWELL, A. CLARK, P. JAWORSKI, *Nonelectronic Parts Reliability Data 1995*, NPRD-95, Reliability Analysis Center (1995)
W. CROWELL, W. DENSON, P. JAWORSKI and D. MAHAR, *Failure Mode/Mechanism Distributions*, FMD-97, Reliability Analysis Center (1997)
G. W. HANNAMAN, *GCR (Gas Cooled Reactor) Reliability Data Bank Status Report,* GA-A-14839, General Atomic Co. (1978)
S. A. EIDE, S. V. CHMIELEWSKI, and T. D. SWANTZ, *Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs*, EGG-SSRE-8875, INL (1990)
A. BLANCHARD and B. N. ROY, *Savannah River Site Generic Data Base Development*, WSRC-TR-93-262, Revision 1, Savannah River Site (1998)

The EU has also begun analyzing data from tokamak experiments.[54,60] Vacuum components were an initial focus of the EU work because fusion devices were growing in size and radiological inventory and the vacuum vessel had become an important radiological confinement barrier. Companion work was performed on the largest U.S. tokamak, the DIII-D experiment, to compare to the EU results.[61,62] Other data analyses have focused on personnel gas safety monitors, power supplies, and other components (see Table III).[63–66] Radiological experiences, including which groups of facility personnel receive the highest doses, have been surveyed and compared between fusion experiments.[67–70] Industrial safety experiences at two major fusion facilities have been surveyed and compared to large particle accelerators.[71,72]

III. RELIABILITY ESTIMATES WITH SCARCE DATA

There are many cases in fusion where few operating experience data exist to support quantitative reliability estimation. Several authors have addressed this dilemma. One of the earliest noted approaches was given by Welker and Lipow,[74] who addressed the failure rate for a component that has not yet failed in service. This approach is to take whatever operating time is available for the unfailed component(s) and estimate a failure rate of 1/3T, where T is the cumulative component operating hours. This simple calculation would give an estimate of the "all modes" component failure rate. Tobias and Trinidade suggested using a Chi-squared distribution and calculating an upper bound failure rate as a realistic estimate that accounts for the number of unfailed components in the system.[75] They warned that using the 50% Chi-squared failure rate as a point estimate should be interpreted carefully; the value is not really an average but rather a failure rate value that will produce zero failures half of the time. The IAEA has also suggested using the 50% Chi-squared average value for a failure rate and calculating the upper bound failure rate using the same distribution.[76]

Component test data can be used to estimate the reliability of a component if the tests have been extensive enough to approximate a component lifetime and the test conditions are approximate to actual operating conditions. An example is high heat flux testing of wall armor tiles with the use of electron beams. Tiles of different materials have been fixed to substrate materials with a variety of processes (e.g., brazing, hot isostatic pressing, and diffusion welding) and these have been tested under vacuum with rapid electron beam heat deposition at magnitudes 2 to 10 times higher than would be expected in the operating tokamak. The reliability premise is that the excessively rapid heatup and cooldown cycles on the tile and its bond are the most harsh conditions the tile unit will experience. Therefore, testing at thousands of short-duration heat loading/unloading cycles will provide relevant data. Thus far, such testing results have proven to give favorable reliability estimates when compared to the positive operating experiences of deployed tiles.[77]

TABLE III. Overall Failure Rates for Resistive Magnet Coil Power Supplies

Power Supply System	Number of Faults in Trouble Reports	System Run Time (hr)	Failure Rate (/hr)	±Standard Error
DIII-D magnetic fusion experiment data from 1987–2004 (Ref. 65)				
DIII-D All Coil Power Supply Systems—All Modes or Generic Trouble	1,422	13,150	1.1E–01	2.9E–03
DIII-D All Coil Power Supply Systems—Alarm/Erratic Alarm/Fail to Preset	181	13,150	1.4E–02	1.0E–03
DIII-D All Coil Power Supply Systems—Fail to Operate and Spurious Operation	1,241	13,150	9.4E–02	2.7E–03
Joint European Torus magnetic fusion experiment data from 1997-2003 (Ref. 65)				
JET Coil Power Supply Systems—Generic Trouble	990	14,864	6.7E–02	2.1E–03
JET Coil Power Supply Systems—Alarm/Erratic Alarm/Fail to Preset	534	14,864	3.6E–02	1.6E–03
JET Coil Power Supply Systems—Fail to Operate and Spurious Operation	456	14,864	3.1E–02	1.4E–03
DAΦNE accelerator power supplies, from 1997–2002 (Ref. 73)				
DAΦNE Coil Power Supplies—All modes	535	39,984	1.3E−02	5.8E−04

When no operating experience data exist for a component, such as a component in the design phase, the analyst has several options:[78]

- Decomposition—deconstructing a component into its constituent parts and then assigning handbook failure rates to the parts. If the analyst is confident in the accuracy of part data, this technique is tedious but useful; if the data on parts are not accurate, other techniques should be used.
- Analyst judgment—may call for reverse estimation based on a system availability requirement or simply engineering judgment of the generic failure rates for that class of component.
- Expert opinion—obtaining qualitative opinions from subject matter experts and combining those to develop an order-of-magnitude failure rate.
- Component-specific techniques—for example, the Thomas method for piping.[79]

V. FUTURE PLANS

The IEA task agreement is being renewed for another 5-year term. The renewal serves as a vehicle for continued collaboration between task participants. At present, plans are for the data analysis of DIII-D and Joint European Torus (JET) operating experience data to continue indefinitely and perhaps to add other tokamaks as well.

The INL Fusion Safety Program work on system reliability analysis continues with the DIII-D fusion experiment operated by General Atomics in La Jolla, California. Promising amounts of DIII-D data have been collected for instrumentation and controls and computer control systems. Another future study will focus on the personnel safety systems, including radiation area monitors and personnel safety interlock systems. All of these systems are shared with accelerators, and collaboration is always possible. Certainly, any already-published accelerator component failure rate data will be used in comparison with the fusion component data analysis results. The EU continues to analyze operations data from the JET experiment near Oxford, UK.

Other U.S. systems under analysis are the neutral beam injectors and radiofrequency plasma heating systems at DIII-D; results will be compared to results of EU analyses completed on the JET data.[61,80] Comparisons of these independent data sets from the two tokamak experiments have been promising and serve to be the first steps toward data validation, at least on the order of magnitude level. Comparison to accelerator radiofrequency systems could prove to be useful as well.

As the fusion machines under study continue to operate, some of the initial data analyses can be updated to verify that the failure rates are constant values as expected. If the rates deviate and are lower, then further investigation will be needed to determine if the values are indicating a new equilibrium; if higher values are found, then investigation will determine if this is an indication of the beginning of equipment wearout.

The harvesting of generic data for design tradeoff or scoping studies, FMEAs, RAMI, and other system reliability uses will continue on an ad hoc basis to support fusion operations and new designs.

ACKNOWLEDGMENTS

The data analysis work discussed here would not have been possible without the support from machine operations personnel who collected the data and supported the analysts with system and operations information. The IEA provided a framework for collaboration between analysts to allow sharing and validation of independent data sets. This work was prepared for the U. S. Department of Energy, Office of Fusion Energy Sciences, under the DOE Idaho Field Office contract number DE-AC07-05ID14517.

REFERENCES

1. C. E. EBELING, *An Introduction to Reliability and Maintainability Engineering*, Ch. 1, McGraw Hill Book Company, New York, New York (1997).
2. CENTER FOR CHEMICAL PROCESS SAFETY, *Guidelines for Improving Plant Reliability through Data Collection and Analysis*, American Institute of Chemical Engineers, New York, New York (1998).
3. A. J. ALEXANDER, *The Cost and Benefits of Reliability in Military Equipment*, accession number ADA-207344, Rand document number P-7515, Rand Corporation, Santa Monica, California (1988).
4. C. PIASZCZYK and M. RENNICH, "Reliability Analysis of the IFMIF," *Proceedings of the 2nd International Topical Meeting on Nuclear Applications of Accelerator Technology*, Gatlinburg, Tennessee, September 20–23, 1998, pp. 572–579, American Nuclear Society (1998).
5. ITER JOINT CENTRAL TEAM, Y. SHIMOMURA, and G. SAJI, "ITER Safety and Operational Scenario," *Fusion Eng. Des.*, **39–40**, 17 (1998).
6. M. HOUTERMANS, T. VANDE CAPELLE, and M. AL-GHUNGHAM, "Reliability Engineering & Data Collection to Improve Plant Safety and Availability," *Proceedings of the Second International Conference on Systems (ICONS'07)*, Sainte-Luce, Martinique, France, April 22–28, 2007, Session SAFESYS II,

Institute of Electrical and Electronics Engineers (2007).
7. M. MOOSEMILLER, "Avoiding Pitfalls in Assembling an Equipment Failure Rate Database for Risk Assessments," *J. Hazard. Mater.*, **130**, 128 (2006).
8. U.S. ENVIRONMENTAL PROTECTION AGENCY, *Chemical Accident Prevention Provisions*, 40 Code of Federal Regulations (CFR) 68, Subpart B, "Hazard Assessment" (2007).
9. U. KJELLEN, *Prevention of Accidents through Experience Feedback*, Ch. 1, Taylor & Francis, London, England (2000).
10. OFFICE OF SCIENCE, *Safety of Accelerator Facilities*, DOE O 420.2B, U.S. Department of Energy, Washington DC (2004) reviewed 2006.
11. OFFICE OF FUSION ENERGY SCIENCES, *Safety of Magnetic Fusion Facilities: Requirements*, DOE STD-6002-96, U.S. Department of Energy, Washington DC (1996).
12. H.-W. BARTELS, et al., "ITER Reference Accidents," *Fusion Eng. Des.*, **42**, 13 (1998).
13. T. PINNA, R. CAPORALI, G. CAMBI, L. BURGAZZI, A. POUCET, and M. T. PORFIRI, "Failure Mode and Effect Analysis on ITER Heat Transfer Systems," *Fusion Eng. Des.*, **42**, 431 (1998).
14. L. C. CADWALLADER, N. P. TAYLOR, and A. E. POUCET, "Preliminary Master Logic Diagram for ITER Operation," *Proceedings of the 4th International Conference on Probabilistic Safety Assessment and Management*, New York, New York, September 13–18, 1998, pp. 253–258, Springer-Verlag Limited (1998).
15. J. IZQUIERDO, N. P. TAYLOR, J. DIES, J. GARCIA, and F. ALBAJAR, "Progress in the Development of a PIE-PIT for the ITER Tokamak," *Fusion Eng. Des.*, **75–79**, 1145 (2005).
16. S. J. PIET, "Implications of Probabilistic Risk Assessment for Fusion Decision Making," *Fusion Technol.*, **10**, *1*, 31 (1986).
17. L. C. CADWALLADER and S. J. PIET, *1988 Failure Rate Screening Data for Fusion Reliability and Risk Analysis*, EGG-FSP-7922, INL (1988).
18. L. C. CADWALLADER and S. J. PIET, *1989 Failure Rate Screening Data for Fusion Reliability and Risk Analysis*, EGG-FSP-8709, INL (1989).
19. L. C. CADWALLADER and T. PINNA, "Progress Toward a Component Failure Rate Data Bank for Magnetic Fusion Safety," *Proceedings of the International Topical Meeting on Probabilistic Risk Assessment (PSA '99)*, Washington, DC, August 22–26, 1999, pp. 11–17, American Nuclear Society (1999).
20. T. R. MOSS and J. E. STRUTT, "Data Sources for Reliability Design Analysis," *Proceedings of the Institution of Mechanical Engineers*, **207 E1**, 13 (1993).
21. C. L. ATWOOD, J. L. LaCHANCE, H. F. MARTZ, D. J. ANDERSON, M. ENGLEHARDT, D. WHITEHEAD, and T. WHEELER, *Handbook of Parameter Estimation for Probabilistic Risk Assessment*, NUREG/CR-6823, U.S. Nuclear Regulatory Commission (2003).
22. H. PROCACCIA, S. P. ARSENIS, P. AUFORT, *EIReDA 1998, European Industry Reliability Data Bank*, Crete University Press, Iraklion Crete, Greece (1998).
23. L. C. CADWALLADER, *Magnet Operating Experience Review for Fusion Applications*, EGG-FSP-9977, INL (1991).
24. L. C. CADWALLADER, *Cryogenic System Operating Experience Review for Fusion Applications*, EGG-FSP-10048, INL (1992).
25. L. C. CADWALLADER, *Vacuum System Operating Experience Review for Fusion Applications*, EGG-FSP-11037, INL (1994).
26. T. D. MARSHALL and L. C. CADWALLADER, *In-Vessel Tubing Failure Rates for Selected Materials and Coolants*, EGG-FSP-10928, INL (1994).
27. A. MOSSO, A. PONTA, and T. PINNA, *Screening of Failure Data for Component Typically Used in Fusion Facilities*, ENEA FUS TECN S&E 6/96, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA) (1996).
28. T. PINNA, C. RIZZELLO, and R. CAPORALI, *Failure Data for Cryostat Penetrations*, ENEA FUS TECN S&E 21/94, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA) (1994).
29. L. C. CADWALLADER, *Liquid Metal, Gas, Molten Salt, and Organic Cooling System Operating Experience Review for Fusion Applications*, INEEL/EXT-99-00144, INL (1999).
30. L. C. CADWALLADER, *Ventilation Systems Operating Experience Review for Fusion Applications*, INEEL/EXT-99-01318, INL (1999).
31. L. C. CADWALLADER, *Fire Protection System Operating Experience Review for Fusion Applications*, INEL-95/0396, INL (1995).
32. L. C. CADWALLADER, *Operating Experience Review of In-Plant Electrical Distribution Systems for Fusion Applications*, INEEL/EXT-01-01558, INL (2001).
33. L. C. CADWALLADER, *Selected Component Failure Rate Values from Fusion Safety Assessment Tasks*, INEEL/EXT-98-00892, INL (1998).
34. L. C. CADWALLADER, "Compressed Gas Safety for Experimental Fusion Facilities," *Fusion Sci. Technol.*, **47**, *4*, 989 (2005).
35. L. C. CADWALLADER, *Reliability Estimates for Selected Sensors in Fusion Applications*, INEL-96/0295, INL (1996).

36. L. C. CADWALLADER, *Lift Truck Safety Review*, INEL/EXT-97-00178, INL (1997).
37. T. PINNA and L. C. CADWALLADER, "Component Failure Rate Data Base for Fusion Applications," *Fusion Eng. Des.*, **51–52**, 579 (2000) 579-585.
38. T. PINNA, *Fusion Component Failure Rate Database (FCFR-DB), Vers. Dec. 2001: User's Manual and Collected Data*, FUS-TN-SA-SE-R-43, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA), Frascati, Italy (2002).
39. T. PINNA, J. IZQUIERDO, M. T. PORFIRI, and J. DIES, "Fusion Component Failure Rate Database (FCFR-DB)," *Fusion Eng. Des.*, **81**, 1391 (2006).
40. C. M. PIASZCZYK, "Accelerator Reliability Database," *Proceedings of the 1999 Particle Accelerator Conference*, New York, New York, March 29–April 2, 1999, pp. 1465–1467, Institute of Electrical and Electronics Engineers (1999).
41. K. M. GRUETZMACHER and R. C. WILHELM, "Data base for Failure/Maintenance at the Tritium Systems Test Assembly," *Fusion Technol.*, **10**, 1596, (1986).
42. P. I. PETERSEN and S. M. MILLER, "The DIII-D Tokamak Trouble Report Database," *Proceedings of the 14th IEEE/NPSS Symposium on Fusion Engineering*, San Diego, California, September 30–October 3, 1991, pp. 776–778, Institute for Electrical and Electronics Engineers (1991).
43. S. SENGUPTA and G. OLIARO, "The NSTX Trouble Reporting System," *Proceedings of the 19th Symposium on Fusion Engineering*, Atlantic City, New Jersey, January 21–25, 2002, pp. 242–244, Institute of Electrical and Electronics Engineers, (2002).
44. K. ARAKAWA, et al., "JT-60 Operational Experience and Trouble Analysis," *Proceedings of the 13th Symposium on Fusion Engineering*, Knoxville, Tennessee, October 2–6, 1989, pp. 1072–1075, Institute of Electrical and Electronics Engineers (1989).
45. B. J. GREEN, et al., "Machine Utilisation and Operating Experience with JET from 1983," *Fusion Technology 1988, Proceedings of the 15th Symposium on Fusion Technology*, Utrecht, The Netherlands, pp. 1633–1637, Elsevier (1988).
46. D. VAN HOUTTE, et al., "Availability Analysis of Five Years of Operation of the Superconducting Tokamak Tore Supra," *Fusion Technology 1996, Proceedings of the 19th Symposium on Fusion Technology*, Lisbon, Portugal, September 16–20, 1996, North-Holland Publishing Co. (1996).
47. M. A. CASEY, K. M. GRUETZMACHER, J. R. BARTLIT, and L. C. CADWALLADER, "The Data Collection System for Failure/Maintenance at the Tritium Systems Test Assembly," *Fusion Technol.*, **14**, 962 (1988).
48. L. C. CADWALLADER, M. A. STOLPE-GAVETT, L. QUINTANA, "Estimated Failure Rates for Some Selected Tritium System Components," *Fusion Technol.*, **21**, 518 (1992).
49. L. C. CADWALLADER and M. A. STOLPE-GAVETT, *Tritium Waste Treatment System Component Failure Data Analysis from June 18, 1984 to December 31, 1989*, EGG-FSP-8973, INL (1990).
50. L. C. CADWALLADER and D. P. SANCHEZ, *Secondary Containment System Component Failure Data Analysis from 1984 to 1991*, INEEL/EXT-92-00335(10323), INL (1992).
51. L. C. CADWALLADER, M. A. STOLPE-GAVETT, L. QUINTANA, *Tritium Room Air Monitor Component Failure Rate Data Analysis from January 1, 1984 to December 31, 1990*, EGG-FSP-9450, INL (1991).
52. L. C. CADWALLADER and G. L. TAYLOR, *Experimental Tritium Cleanup System Availability Analysis from 1984 to 1992*, EGG-FSP-10603, INL (1994).
53. L. C. CADWALLADER and G. L. TAYLOR, "Failure Rate Data for Glovebox Components and Cleanup Systems at the Tritium Systems Test Assembly," *J. Fusion Energ.*, **12**, 47 (1993).
54. T. PINNA, G. CAMBI, A. LO BUE, and C. RIZZELLO, "Collection and Analysis of Data Related to Fusion Machines (JET and TLK) Operation Experience on Component Failures," FUS-TN-SA-SE-R-058, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA), Frascati, Italy (2003).
55. T. PINNA, G. CAMBI, S. CIATTAGLIA, A. LO BUE, S. KNIPE, J. ORCHARD, R. PEARCE, and U. BESSERER, "Collection and Analysis of Data Related to Fusion Machines (JET and TLK) Operating Experience on Component Failure," *Fusion Eng. Des.*, **75–79**, 1199 (2005).
56. M. YAMADA, M. ENOEDA, T. HONMA, T. HAYASHI, Y. MATSUDA, K. OKUNO, "Operations Experience on Safety System of Tritium Process Laboratory in Japan Atomic Energy Research Institute," *Fusion Technol.*, **28**, 1376 (1995).
57. M. YAMADA, T. YAMANISHI, W. SHU, T. SUZUKI, H. NAKAMURA, Y. KAWAMURA, Y, IWAI, K. KOBAYASHI, K. ISOBE, and M. NISHI, "Operation Results on Safety Systems of Tritium Process Laboratory in Japan Atomic Energy Research Institute," *Fusion Sci. Technol.*, **41**, 593 (2002).
58. L. C. CADWALLADER, "Comparisons of Facility-Specific and Generic Failure Rates for Tritium-

Bearing Components used in Fusion Applications," *Fusion Eng. Des.*, **54**, 353 (2001).
59. L. C. CADWALLADER, "Comparison of Tritium Component Failure Rate Data," *Fusion Sci. Technol.*, **47**, 983 (2005).
60. T. PINNA, G. CAMBI, and F. GRAVANTI, "Collection and Analysis of Component Failure Data from JET Systems: Neutral Beam Injectors and Power Supply," *Nucl. Fusion*, **47**, S453 (2007).
61. T. PINNA, F. GRAVANTI, G. CAMBI, and P. POLINARI, *JET Data Collection on Component Malfunctions and Failures of Neutral Injectors and Power Supply Systems*, ENEA FUS TN-SA-SE-R-121, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA), Frascati, Italy (2004).
62. L. C. CADWALLADER and P. I. PETERSEN, "Confinement Reliability Estimates for Vacuum System Components," *Fusion Sci. Technol.*, **44**, 382 (2003).
63. L. C. CADWALLADER and P. I. PETERSEN, "Reliability Estimates for Oxygen Monitors," *Proceedings of the 20th IEEE/NPSS Symposium on Fusion Engineering*, San Diego, California, October 14–17, 2003, pp. 171–174, Institute for Electrical and Electronics Engineers (2003).
64. L. C. CADWALLADER and P. I. PETERSEN, "Reliability Estimates for Power Supplies," *Proceedings of the 21st Symposium on Fusion Engineering*, Knoxville, Tennessee, September 26–29, 2005, pp. 776–778, Institute for Electrical and Electronics Engineers (2005).
65. L. C. CADWALLADER, T. PINNA, and P. I. PETERSEN, "Power Supply Reliability Estimates for Experimental Fusion Facilities," *17th Topical Meeting on the Technology of Fusion Energy*, Albuquerque, New Mexico, November 13–15, 2006, to be published in *Fusion Sci. Technol.*
66. P. I. PETERSEN, "Systematic Characterization of Component Failures for the DIII-D Tokamak," *Fusion Eng. Des.*, **51–52**, 571 (2000).
67. A. NATALIZIO, T. PINNA, J. D. LEVINE, "TFTR Occupational Radiation Exposure Data Collection and Analysis," *Fusion Eng. Des.*, **75–79**, 1187 (2005).
68. A. NATALIZIO, M. T. PORFIRI, and B. PATEL, "Collection and Analysis of Occupational Radiation Exposure Data from the JET Tokamak," *Fusion Eng. Des.*, **75-79**, 1193 (2005).
69. A. NATALIZIO and T. PINNA, *TFTR and DIII-D ORE Data Collection and Analysis*, FUS-TN-SA-SE-R-095, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA), Frascati, Italy (2004).
70. A. NATALIZIO and M. T. PORFIRI, *JET ORE Report*, FUS-TN-SA-SE-R-88, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA), Frascati, Italy (2003).
71. L. C. CADWALLADER, *Occupational Safety Review of High Technology Facilities*, INEEL/EXT-05-02616, INL (2005).
72. L. C. CADWALLADER, "Occupational Injury Rate Estimates in Magnetic Fusion Experiments," *17th Topical Meeting on the Technology of Fusion Energy*, Albuquerque, New Mexico, November 13–15, 2006, to be published in *Fusion Sci. and Technol*.
73. M. INCURVATI, R. RICCI, and C. SANELLI, "DAΦNE Power Supply System: 5 Years of Experience and Statistics," *Proceedings of the 8th European Particle Accelerator Conference*, Paris, France, June 3–7, 2002, pp. 2478–2480, European Physical Society Interdivisional Group on Accelerators and CERN (2002).
74. E. WELKER and M. LIPOW, "Estimating the Exponential Failure Rate from Data with No Failure Events," *Proceedings of the Annual Reliability and Maintainability Symposium 1974*, Los Angeles, California, January 29–31, 1974, pp. 420–424, Institute for Electrical and Electronics Engineers (1974).
75. P. A. TOBIAS and D. C. TRINDADE, *Applied Reliability*, Second Edition, pp. 70–71, Van Nostrand Reinhold, New York, New York (1995).
76. J. HAMMER, *Manual on Reliability Data Collection for Research Reactor PSAs*, IAEA-TECDOC-636, Ch. 9, International Atomic Energy Agency, Vienna, Austria (1992).
77. E. B. DEKSNIS, A. T. PEACOCK, H. ALTMANN, C. IBBOT, and H. D. FALTER, "Beryllium Plasma-Facing Components: JET Experience," *Fusion Eng. Des.*, **37**, 515–530 (1990).
78. L. C. CADWALLADER and T. D. MARSHALL, "Component Reliability Estimation for Fusion Safety and Risk Assessment," *Proceedings of the International Topical Meeting on Probabilistic Safety Assessment*, Park City, Utah, September 29–October 3, 1996, pp. 637–648, American Nuclear Society (1996).
79. H. M. THOMAS, "Pipe and Vessel Failure Probability, *Reliab. Eng.*, **2**, 83 (1981).
80. G. CAMBI and T. PINNA, *JET Data Collection on Component Malfunctions and Failures on Ion Cyclotron Resonant Heating (ICRH) System*, FUS-TN-SA-SE-R-143, Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA), Frascati, Italy (2006).