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Failure Rate Adjustment Factors for High Technology Components

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Lee C. Cadwallader

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Lee C. Cadwallader
Idaho National Laboratory, Idaho Falls, ID, USA
Corresponding author e-mail: Lee.Cadwallader@inl.gov.

***Abstract*—In nuclear fusion research for power plant applications, experiments have used tritium fuel. With the use of radioactive tritium, the safety issues have increased and so have the safety assessments to demonstrate that safety is incorporated into design. For the ITER International Project, the safety concerns of a high power, tritium-burning experiment are being addressed in design. ITER also has another issue of interest, to give a reasonable forecast of the operational availability of this largest fusion experiment ever built. Both of these needs can require component failure rate data for safety assessment and for reliability availability maintainability inspectability (RAMI) studies. ITER is often using components of greater size, at higher temperatures, and at higher radiation damage levels than past experiments. In some cases, the component failure rates from previous operating experiences can be modified with multiplicative factors, called k factors or adjustment factors, to account for the different operating environments. With the use of k factors, the component failure rates from past operations can be applied to this new design. When the environments are defined, the k factor approach can be used with good effect to give component failure rate estimates. This paper describes recent work in developing k factors to adjust some magnet component failure rates for the ITER International Project.**

***Keywords*—reliability, failure rate, k factor**

I. INTRODUCTION

The basic approach to reliability is to use component operating experiences to calculate component failure rates, and use these failure rates with a model of a new system to predict the reliability of the new system. There are instances when the available component operating experiences are collected under environmental conditions and service parameters that are different than those of the new system to be modeled. The concept of k factors, the multiplicative factors applied to a failure rate to adjust it for varying environments and service conditions, has been used in reliability studies for many years [1]. These multiplicative factors are sometimes called adjustment factors, pi factors, or k factors. The military high technology systems (avionics, guidance, communication, detection, and others) developed the concept of k factors to describe various operating environments such as ground benign, ground mobile, shipboard, airborne, missile, and space flight, as well as other parameters that affect reliability such as operating temperature [2]. The military has also researched mechanical components for service factors [3]. The k factors are based comparing the failure rate, λ, from operating experiences of the same type of component operated in two different environments [4]. The component operating experience in one environment provides a base failure rate, and the different environment could be harsh or more benign than that of the base environment. The basic equation is:

$$\lambda_{\text{new environment}}/\lambda_{\text{original environment}} = k_1 k_2 k_{3\ldots} k_n = k_{\text{total}} \qquad (1)$$

where each k_i value represents an aspect of the change in operating environment.

While k factors are widely used, it is possible that tolerance variations can be masked within the k factor [5], which detracts from understanding the physics of the failures that contribute to the failure rate. Despite this drawback, k factors remain a viable method to adjust failure rate data. When used carefully, these factors give good results.

In the ITER International Project, there is a scarcity of component failure rate data originating in the ITER environment to easily calculate k_{total} using eqn 1. Therefore, another approach is to use physics of failure methods to calculate individual k factors; that is, to estimate the k factors so that component failure rates from a known operating environment can be adjusted to account for the ITER environment. This paper describes generation of individual k factor estimates to account for environments and conditions known to affect reliability: the operating temperature, the wall thickness of varying types of tubing and piping, the coolant and flow conditions of water coolant, radiation damage to metal components, and component vibration.

II. OPERATING TEMPERATURE

Generally, the operating temperature of a component is an important parameter affecting reliability and service life. Mechanical components at elevated temperature experience thermally-induced changes in material properties. These changes must be accounted for in their design. The approach used for developing a k factor model was to apply the Arrhenius equation, which has found many uses in modeling temperature effects. The Arrhenius equation has been used in reliability of electronic and mechanical components [2,6]. The failure rate equation is given below.

$$\lambda = A \bullet \exp(-B/T) \qquad (2)$$

where

A and B are constants and T is the operating temperature in Kelvin. Then,

$$k_{temperature} = \lambda_{new}/\lambda_{original} = \exp[B\bullet(1/T_{original} - 1/T_{new})] \quad (3)$$

For steel, failure rate data at high and moderate operating temperatures from the chemical process industry was used to calculate the A and B constants in the equation. Then, with the B constant known, and the elevated operating temperatures of the original application and the ITER application also known, the k factor for the ITER operating temperature value was calculated for piping [6].

III. Pipe Wall Thickness

A piping reliability study by Thomas [7] has been used to advantage when there has been insufficient piping experience data available for analysts to obtain a statistically significant failure rate. While the piping experience database from fission reactors has increased in the last decades of worldwide operations and now gives good data, the Thomas method is still used today. Employing the Thomas method, the pipe wall thickness equation for the k factor is derived from

$$\lambda_{leakage} \sim L \text{ x } D/t^2$$

where L is the pipe length, D is the pipe diameter, and t is the pipe wall thickness.

$$\lambda_{leakage\ 1} / \lambda_{leakage\ 2} = [L_1 \text{ x } D_1/(t_1^2)\ ]/[\ L_2 \text{ x } D_2/(t_2^2)] \quad (4)$$

When the pipe length L is taken to be a unit length and if the pipe diameter D is constant, then the k factor is

$$k_{wall\ thickness} = \lambda_{new\ thickness}/\lambda_{original\ thickness} = (t_{original})^2/(t_{new})^2 \quad (5)$$

where t is the pipe wall thickness.

This equation is based on Thomas' idea that for prevailing pipe fabrication technology, the pipe has fewer, but larger size flaws as the pipe wall thickness increases. In Thomas' work, the fewer but larger material flaws tended to increase pipe reliability. In general, operating experience shows that pipe failure rates decrease as the pipe wall thickness increases [8], which supports the Thomas model. The wall thickness equation (5) accounts for changes in pipe dimensions.

IV. Coolant and Flow Media

The primary effect of coolant and flow is flow-induced corrosion that has the effect of pipe wall thinning. Chexal [9] is a well-known quantitative study on steel piping corrosion. Chexal's work was used to determine the k factor for flow-induced corrosion, accounting for the coolant type, the mass transfer, and other effects. The operating temperature has an effect on the solubility of the oxide layer that protects the pipe wall; the temperature is accounted for due to chemistry effects while the operating temperature factor above accounts for mechanical effects with temperature. The elements in the pipe metal alloy, such as chromium, also have an effect on flow accelerated corrosion. Mass transfer accounts for flow velocity, pipe diameter, and other hydrodynamic factors. Flow accelerated corrosion varies inversely with the amount of dissolved oxygen present in the water. Some dissolved oxygen is beneficial, oxygen is needed in the fluid to promote formation of a protective oxide layer on the pipe surface. The pH of the coolant and how the pH affects solubility of metal ions in the coolant is taken in to account. The geometry and design of the pipework and how those parameters produce coolant turbulence is recognized. Any two-phase (liquid and gas) flow of the coolant is accounted for. Any reducing agent concentration in the coolant is taken in to account as well. Reference 10 gives examples of applying Chexal's information to estimate a k factor for flow conditions.

V. Neutron Radiation Damage

There are only a few components that reside in high neutron flux environments. One of these components is the metal tube cladding on fission reactor fuel. Stainless steel cladding used for fast fission reactor fuel elements was examined for its breach failure rate to apply to a similar stainless steel piping used for in-vessel coils [10]. For other metals to be used in ITER, a k factor estimate was developed based on radiation environment work by Lauridsen [11]. The formula to express the k factor is given below:

$$\text{Neutron Radiation Damage Factor} = 10^{\Delta} \quad (6)$$

and

$$\Delta = [P_o - P_t]/[P_o - P_f] \quad (7)$$

where
P_o = value of a characteristic parameter of the material before radiation exposure
P_t = value of a characteristic parameter of the material after total radiation dose
P_f = value of the characteristic parameter of the material at failure

The Δ degradation factor varies between 0 and 1, showing the parameter margin remaining in the material under irradiation. This factor assumes that any radiation effect depends on increasing dose level to manifest the change in the characteristic parameter. When P_t is approaching P_f, Δ is approaching 1, meaning the material is radiation degraded. When P_t is much less than P_f, the material in question has seen low dose and is not significantly degraded, so Δ is approaching 0. The neutron radiation damage factor was selected as a factor of ten change in failure rate. It is noted that a factor of ten has been used as the difference between the failure rates of a low mechanical stress and high mechanical stress metal part (shafts, bolts, etc.). Since radiation damage can change stress response of metals, this factor of ten was noted as significant and was used in the equation. For the damage factor, when Δ is a low value, the damage factor is close to 1, and when Δ is a high value, the damage factor approaches 10. The P values were taken from neutron irradiation studies. Whenever possible, the study results of irradiations carried out at the same temperature as the operating temperature were used. When that was not possible, an irradiation temperature below the component operating temperature was used with the assumption that the lower temperature would not allow as much healing of radiation-induced defects – thus the lower temperature would be conservative, giving a poorer reliability result.

VI. Vibration

Some components are not expected to experience any levels of high vibration. For those components that will experience vibration, a formula for the vibration effects on failure rates was applied from FIDES [12]. This formula is applicable to several engineering materials, including metals (aluminum, copper, etc.), glass, ceramics, and other materials. The formula was applied to ITER metals as a first approximation for the effects of high vibration on the basic failure rate. The formula for the k factor, called the Acceleration Factor (AF) in reference 12, is based on Basquin's law:

$$AF = (g_{rms}/g_{rms0})^{1.5} \tag{8}$$

Where g_{rms} is the root mean square vibration amplitude (measured in gravities) in the operating environment. The g_{rms0} is a reference vibration amplitude; the FIDES recommended g_{rms0}=0.5 for the materials listed above.

VII. Applications

These k factors have been used for ITER support [6,10]. An example is given here for the ITER in-vessel magnet coils (IVCs). The Tokamak Fusion Test Reactor (TFTR) copper magnet conductor experiences were used to calculate a basic 'piping' failure rate value for copper resistive magnets. The conductor failure rate was calculated as 5.2E-09/m-h for all failure modes. That is, this failure rate would be applied to any failure mode, including small and large leakage, rupture, or blockage. Upper and lower bounds are given in Table I. k factor failure rate multipliers were used to adjust the TFTR copper failure rate to the ITER IVC environment [10]. The k factors are also given in Table I. The overall failure rate multiplier, k_{total}, is 0.954. Thus, the "all modes" copper failure rate to apply to the ITER IVC conductor is (0.954)(5.2E-09/m-h) or 4.96E-09/m-h. This is rounded up to 5E-09/m-h.

VIII. Conclusions

These k factor equations provide estimates of adjustment factors, and they are highly useful in reliability prediction to adjust failure rates from known data sets to apply to the ITER operating environment. When more detail is required, the reliability analyst can use computer predictions of reliability, including monte carlo predictions, or a combination of past operating experience and test stand data.

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References

[1] "Reliability Prediction," MIL-STD 756, US Department of Defense, October 1961.

[2] "Reliability Prediction of Electronic Equipment," MIL HDBK 217F, US Department of Defense, December 1991.

[3] "Handbook of Reliability Prediction Procedures for Mechanical Equipment," NSWC-2011, Naval Surface Warfare Center, Carderock Division, US Departmentof Defense, 2011.

[4] E. L. McCabe, W. B. Pearce, G. D. Rise, "Method for Developing Equipment Failure Rate K Factors," report D180-17674-2, Boeing Company, Seattle, Washington, January 1975.

[5] J. R. Fragola, "Reliability and risk analysis data base development: an historical perspective," Rel. Eng. Sys. Safety, vol. 51, pp. 125-137, 1996.

[6] L. C. Cadwallader, "Vacuum Bellows, Vacuum Piping, Cryogenic Break, and Copper Joint Failure Rate Estimates for ITER Deisgn Use," INL/EXT-10-18973, Idaho National Laboratory, June 2010.

[7] H. M. Thomas, "Pipe and vessel failure probability," Rel. Eng., vol. 2, pp. 83-124, 1981.

[8] K. N. Fleming and B. Lydell, "Pipe Rupture Frequencies for Internal Flooding PRAs," revision 1, EPRI-TR-1013141, Electric Power Research Institute, Palo Alto, CA, 2006.

[9] B. Chexal et al., "Flow-accelerated Corrosion in Power Plants," EPRI TR-106611, revision 1, Electric Power Research Institute, 1998.

[10] L. C. Cadwallader, "In-Vessel Coil Material Failure Rate Estimates for ITER Design Use," INL/EXT-13-28031, Idaho National Laboratory, January 2013.

[11] K. Lauridsen, P. Christensen, H. E. Kongso, "Assessment of the reliability of robotic systems for use in radiation environments," Rel. Eng. Sys. Safety, vol. 53, pp. 265-276, 1996.

[12] "FIDES guide 2009, Edition A, Reliability Methodology for Electronic Systems," September 2010, FIDES Group, p. 44-45.

TABLE I. Copper Piping Failure Rates and Adjustment Factors

Calculated Failure Rate and Failure Mode (/h-m)	**Operating Temperature Factor (unitless)**	**Wall Thickness Factor (unitless)**	**Flow and Flow Media Factor (unitless)**	**Radiation Factor (unitless)**	**Vibration Factor (unitless)**	**Resulting Failure Rate for IVC Use (/h-m)**
Mean for all failure modes 5.2E-09	1.0	0.49	0.183	6.34	1.68	4.96E-09
95% upper bound, all modes 3.1E-08	1.0	0.49	0.183	6.34	1.68	3E-08
5% lower bound, all modes 5.3E-10	1.0	0.49	0.183	6.34	1.68	5.1E-10