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Federal Railroad Administration

Development and Application of Methodology for Reliability Assessment of Tank Car Structures: Phase I

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Final Report
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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] F = y C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

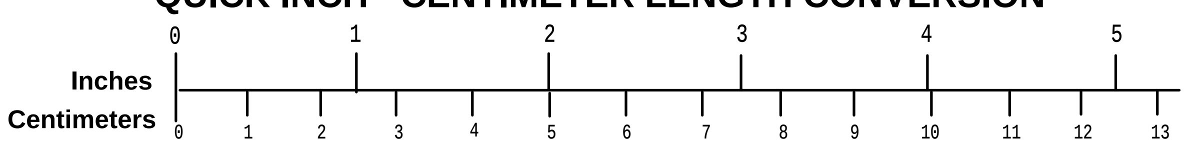
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] C = x F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Safe packaging and transport of hazardous materials is of vital importance to tank car builders, users, Federal regulatory agencies, and the general public. Reliability-centered maintenance (RCM) can be used to effectively maintain the reliability of tank car systems in guarding against lading loss due to equipment failures. Adequate and cost-efficient maintenance decisions depend on the ability to understand the tank car's characteristics and its responses under various service conditions, as well as the ability to analyze and predict the tank car's performance and resistance deterioration as a function of usage.

To support the informed decisionmaking and planning for the RCM through quantitative risk analysis and prediction, this project has developed a methodology that applies modern reliability methods to perform reliability analysis on tank car structures.

Tank car failure with respect to lading loss under service conditions falls into two broad categories:

- Tank car structure failures
- Non-structural failures, such as loading/unloading devices, pressure release devices, and valves

Tank car structure failures occur infrequently but likely with high consequences. It is often age-related and due to structural deterioration, often in terms of corrosion and metal fatigue. This category is the focus of the project. Reliability analysis methodology has been developed for two common failure mechanisms: corrosion and fatigue.

The following partially summarizes achievements as a result of this Phase I effort.

1. A method for tank car reliability analysis against corrosion has been developed. The model includes basic features characterizing the tank car general corrosion process. Reliability analysis performed for a series of tank thickness, corrosion rates, and critical tank thickness predicts reasonable behaviors and trends of tank car corrosion failure.
2. A methodology for tank car fatigue reliability analysis is being developed. It uses commercial reliability analysis software, STRUREL, for the reliability analysis while incorporating FORTRAN routines to perform fatigue crack growth analysis with the Walker crack growth law for a three degrees-of-freedom (dof) surface crack.
3. The methodology is versatile in dealing with a variety of random variables (with or without correlation) and capable of considering various features involved in tank car fatigue crack growth analysis, such as spectrum loading, residual stresses, and an asymmetric, bi-variant stress field, thus offering a state-of-the-art fatigue reliability analysis tool for tank cars.
4. It is clearly demonstrated that the reliability analysis methodology developed in this work can be used to quantify probability of failure for tank cars. Use of the information on the quantified risk allows better risk management through informed decisionmaking on inspection, maintenance, and repair.

A partial list of recommended future work includes the following:

1. What to do in response to a quantified level of risk depends on what is considered an acceptable risk. Therefore, risk criteria or target reliability must be developed for effective and consistent risk management.
2. To promote technology progress and improvement of tank car reliability, exploration should be made to find ways for the industry to share detailed data on lading loss instances with the research community, without concerns of litigation issues or negative impact on business as a result. This will allow specific reliability models to be developed to directly address various problems the tank car industry is facing. In this way, technology transfer can be done more effectively, which will effectively improve the reliability of railroad tank cars.
3. Some failures due to non-structure related non-accident releases (NARs) can also be studied for possible development of reliability analysis models. Since this failure category, though often involving small quantities, accounts for the majority of the lading loss cases, it is very important to the reduction of the total failure rate.
4. The reliability theory and solution methods used for the corrosion and fatigue reliability analysis are generally applicable to other systems and/or components of tank cars (e.g., linings, coatings, valves, pressure relieve devices, and brake systems). Therefore, reliability models can also be developed for such systems and components, if desired and if data is available.

1. Introduction

1.1 Objective

Safe packaging and transport of hazardous materials is of vital importance to tank car builders, users, Federal regulatory agencies, and the general public. RCM can be used to effectively maintain the reliability of tank car systems in guarding against lading loss due to equipment failures. Adequate and cost-efficient maintenance decisions depend on the ability to understand the tank car's characteristics and its responses under various service conditions, as well as the ability to analyze and predict a tank car's performance and resistance deterioration as a function of usage.

To support the informed decisionmaking and planning for the RCM through quantitative risk analysis and prediction, the objective of this project is to develop a methodology that applies modern reliability methods to perform reliability analysis on tank car structures.

1.2 Scope of Work

It is generally recognized that a typical tank car is a complex system involving a variety of components, manufacturing procedures, and operational environments (lading type, car handing, maintenance and repair, and routes and climate). Thus, although the methodology and procedures developed are generally applicable to the entire tank car system, this project focuses on the tank's reliability against lading loss.

Tank car failure with respect to lading loss under service conditions falls into two broad categories:

- Tank car structure failures
- Non-structural failures, such as loading/unloading devices, pressure release devices, and valves

Non-structural failures are often due to reasons such as loose fitting, venting, overloaded cargo, and missing parts. Some of the characteristics of this category include high occurrences, mostly in small quantities, and often human error-related. Thus, it has more bearing on design and training than maintenance.

Tank car structure failures occur infrequently but likely with high consequences. It is often age-related and due to structural deterioration, often in terms of corrosion and metal fatigue. This category is the focus of the project. Thus, this report will emphasize the primary tank structure and its immediate attachments (pads). It is realized that, although non-structural, linings and coatings are also important elements of the tank car system. The methodology and procedures developed will also serve as a good foundation for analyzing such elements.

Phase I effort, as described in this report, focuses on the component reliability problem. Reliability analysis methodology is developed for two common failure mechanisms: corrosion and fatigue. Phase II of the project will analyze system reliability problems (multiple-site damage or multiple failure modes).

1.3 Organization of the Report

This chapter introduces the project objective, scope of work, and organization of the report.

Chapter 2 briefly reviews a few important aspects including primary mechanisms of tank car structural failures, general formulation of structural reliability problems, reliability-centered maintenance, and risk criteria.

Chapter 3 presents reliability methodology development and illustrative analyses for the corrosion failure mode of tank car tank.

Chapter 4 describes reliability methodology development and illustrative analyses for fatigue failure mode of tank car tank structures.

Chapter 5 summarizes major conclusions and recommendations for future study.

2. A Review of Some Important Aspects

2.1 Primary Mechanisms of Tank Car Structural Failures

Based on the experiences and the information known, major causes for structure-related non-accident releases (SR-NARs) can be attributed to the following four primary failure mechanisms. They are fatigue, corrosion, corrosion-fatigue, and fracture, as schematically shown in Figure 1.

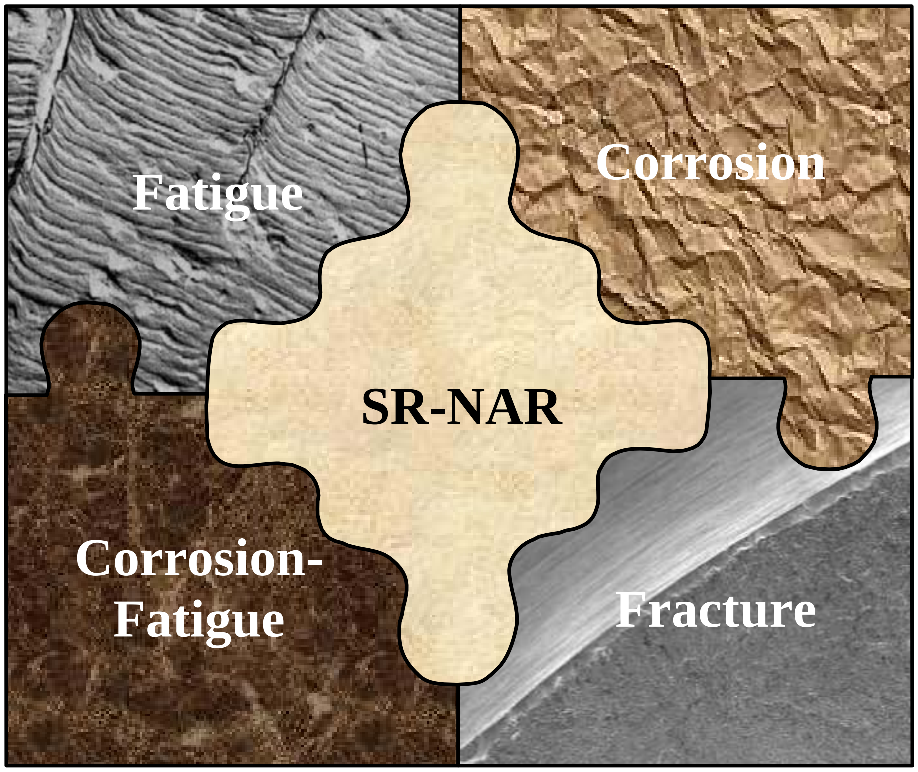

Figure 1. Major failure mechanisms for SR-NARs

In the case of fatigue failure, release results from fatigue crack propagation and penetration through the tank wall. Environmental attack is negligible to crack propagation in this case.

In the case of corrosion failure, release is due to uniform corrosion, which reduces tank wall thickness to such a degree that wall rupture occurs.

In the case of corrosion-fatigue failure, release results from corrosion-assisted fatigue crack propagation and penetration through the wall thickness. In this case, corrosion occurs as pitting or similar localized damages. These damages serve as stress concentrations. Cracks initiate at these sites and propagate under combined action of the fatigue loading and the environmental attack.

In the case of fracture failure, release is due to the tank's separation into two pieces or a large through crack in the tank wall. Fracture may occur by cleavage or rupture, which may initiate from a manufacturing or a material defect, or from a damaged area attacked by one of the above mechanisms.

Table 1 lists cases of SR-NARs reported for 1998 (Association of American Railroads (AAR), 1998).

Table 1. Cases of SR-NARs reported for 1998 (AAR, 1999)

Source of Leak	Commodity	Number of Cases
Cracked Tank Shell	Isobutane	1
Cracked Tank Shell	Acetone	1
Cracked Tank Shell	Corrosive Liquid N.O.S.	1
Broken Tank Shell	N.O.S.	1
Broken Tank Shell	Sodium Hydroxide	2
Corroded Tank Shell	Molten Sulfur	1
Corroded Tank Shell	Phosphoric Acid	2
Rusted Tank Shell	Phosphoric Acid	1
Rusted Tank Shell	Methanol	1
From Report BOE 98-1, "Report of Railroad Tank car Leaks of Hazardous Materials by Commodity by Source of Leak for the Year 1998 (Non-Accident Releases)"		

2.2 General Formulations Based on the Structural Reliability Theory

Recognizing the four failure mechanisms, the event of the SR-NARs occurs if any one or more of the four mechanisms causes a failure. Therefore, the event of the SR-NARs is a union of one or more individual failure events, as shown in Figure 2.

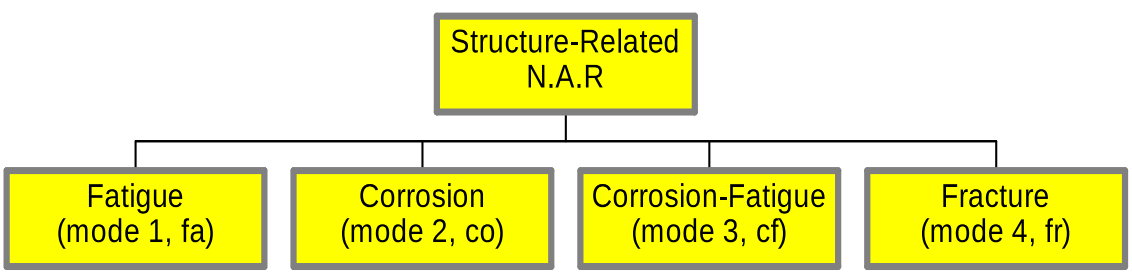

Figure 2. Event of SR-NARs is a union of individual failure modes

Mathematically, this is:

$$E_f = E_{fa} \cup E_{co} \cup E_{cf} \cup E_{fr} \quad (1)$$

$$P_f(E_f) = P_f(E_{fa} \cup E_{co} \cup E_{cf} \cup E_{fr}) \quad (2)$$

where E_f stands for an event of failure leading to SR-NAR. Similarly, E_{fa} stands for an event of failure due to fatigue, E_{co} due to corrosion, E_{cf} due to corrosion-fatigue, and E_{fr} due to fracture. P_f is the probability of failure. In addition to the system reliability problems resulting from the multiple failures modes as shown, each failure mode can also pose system reliability problems due to multiple-site damages. For example, a number of fatigue critical locations (FCLs) may exist in a tank car structure, designated as $F_{aj,}$ j=1, 2, … j_0. The following notations are used:

E_{faj}	Event of failure at F_{aj}
$g_{faj}(X_{faj})$	Performance function for F_{aj}
X_{faj}	Vector of random variables for F_{aj}

Thus, the probability of failure at F_{aj} can be expressed as:

$$P_{faj}(E_{faj}) = P[g_{faj}(X_{faj}) \leq 0]$$

The event of the tank car failure due to fatigue, E_{fa}, is the union of the events E_{faj} at each $F_{aj:}$

$$E_{fa} = \cup_{j=1,j0} E_{faj}$$

where $\cup_{j=1,j0} E_{faj} \equiv E_{fa1} \cup E_{fa2} \cup \ldots\ldots \cup E_{faj0}$. Therefore, the probability of failure due to fatigue is:

$$P(E_{fa}) = P(\cup_{j=1,j0} E_{faj}).$$

2.3 RCM

United Airlines initially developed RCM during 1970s (Nowlan and Heap, 1978). Now it has become an industry standard (Society of Automotive Engineers, 1999). Basically, it is a logical and systematic approach for effective and cost-efficient maintenance of any physical assets. As shown in Figure 3, RCM has the following seven aspects (Moubray, 1997):

1. Functions and Performance Standards–Identifying functions and the associated performance standards of the physical asset.
2. Functional Failures–Determining in what ways it may fail to fulfill its functions.
3. Failure Modes–Determining what causes each functional failure.
4. Failure Effects–Determining what happens when each failure occurs.
5. Failure Consequences–Assessing in what way does each failure matter.
6. Proactive Tasks–Planning and performing proactive tasks that are technically feasible and worth doing to prevent failure or to reduce its consequences.
7. Default Actions–If no proactive tasks are available, taking default actions, which include redesign, or letting it fail, then fixing it, if the failure consequences can be tolerated.

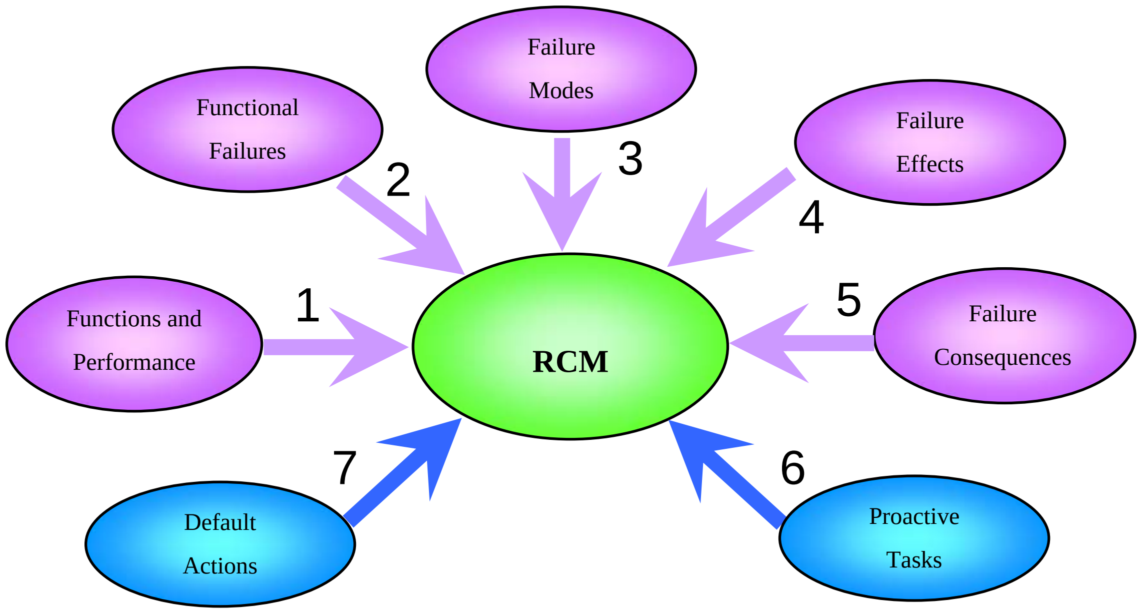

Figure 3. The seven aspects of reliability RCM

So, the first five aspects are about getting to know the assets, their operational environment, and failure consequences. Based on this understanding, proactive tasks are planned to prevent failure or to reduce its consequences if the proactive tasks are technically feasible and worth doing. Otherwise, default actions are taken to redesign, or to let it fail then fix it, if the failure consequences can be tolerated.

Although the logic is simple, when it comes to a tank car structure that is subjected to deterioration due to complex loading and environmental conditions involving various uncertainties, the task to understand the tank car's characteristics and its responses under various service conditions, as well as to analyze and predict the tank car's performance and resistance deterioration as a function of usage, is highly challenging.

To support the informed decisionmaking and planning for the RCM through quantitative risk analysis and prediction, the objective of this project is to develop a methodology that applies modern reliability methods to perform reliability analysis on tank car structures. Specifically, the structural reliability analysis can help identify the most probable failure modes, predict failure effects, and estimate failure consequences. The information on the quantified potential risks helps plan the proactive tasks to reduce or eliminate risks. Or if no suitable proactive tasks are available for a particular failure mode, then it helps take default actions.

2.4 Risk Criteria

Establishment of risk criteria is necessary for effective and cost-efficient management of risks by tank car owners, users, and regulatory agencies. Risk criteria are used to determine acceptable levels of risk or target reliability, with which an assessed risk (e.g., probability of an NAR under a given situation) from analysis can be compared. Thus, a decision can be made as to whether remedial actions need to be taken to reduce the risk. Determination of target reliability, or acceptable risk, is a complicated task that involves social and economical backgrounds and cultures, as people with different social and economical backgrounds and cultures may have different views of acceptable risks. (Some work involving the topic can be found in the following: Wilson and Crouch, 1987; Okrent, 1987; Rackwitz, 2002; Ellingwood, 2000; Ditlevsen, 1997; Ang and Leon, 1997.)

Two approaches exist for establishing risk criteria. One is based on the minimization of the life cycle cost (Menzies, 1996; Mrazik and Krizma, 1997; Elms, 1997; Wen, 2000; Sarveswaran and Roberts, 1999; Singh and Koenke, 2000). The life cycle costs include all costs involved, such as the costs of manufacturing, maintenance and repair, loss of contents, injuries, the loss associated with fatalities, and environmental cleanup. This approach is very appealing and requires extensive data and a high degree of coordination between various aspects and stages of a life cycle. It is an active area of current research and should be a long-term goal for the tank car industry.

The other approach can be well illustrated by the military standard practice for system safety, documented in MIL-STD-882D, February 2000 (Department of Defense, 2000). A risk is an exposure to possible loss or damage. Therefore, risk is measured by a combination of likelihood and consequences. To quantify a risk, it is necessary to quantify the severity of the consequences that a hazard (mishap) may cause and the level of probability with which the hazard may occur.

The MIL-STD-882D classifies the mishap severity, as shown in Table 2.

Table 2. Suggested mishap severity categories

Description	Category	Environmental, Safety, and Health Result Criteria
Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1million, or irreversible severe environmental damage that violates law or regulation.
Critical	II	Could result in permanent partial disability, injuries, or occupational illness that may result in hospitalization of at least 3 personnel, loss exceeding $200,000 but less than $1million, or reversible environmental damage causing a violation of law or regulation.
Marginal	III	Could result in injury or occupational illness resulting in one or more lost work day(s), loss exceeding $10,000 but less than $200,000, or mitigatible environmental damage without violation of law or regulation where restoration activities can be accomplished.
Negligible	IV	Could result in injury or illness not resulting in a lost work day, loss exceeding $2,000 but less than $10,000, or minimal environmental damage not violating law or regulation.

Table 3 shows the classification of the mishap probability levels suggested by the MIL-STD-882D. The quantities shown in these tables are guidelines and need to be adjusted with respect to specific systems.

With the classification of risk severity and probability, the qualitative risk assessment can be made by assigning a risk value to a hazard based on its mishap severity and probability. Table 4 shows an example of a mishap risk assessment matrix. Such a matrix can be used to rank different hazards according to their associated risks.

Such risk assessment values as in Table 4 can be used to group individual hazards into mishap categories, which can then be used to generate specific actions. Table 5 shows an example of mishap risk categories and mishap risk acceptance levels.

Table 3. Suggested mishap probability levels

Description	Level	Specific Individual Item	Fleet or Inventory
Frequent	A	Likely to occur often in the life of an item, with a probability of occurrence (POO) greater than 10^{-1} in that life.	Continuously experienced.
Probable	B	Will occur several times in the life of an item, with a POO less than 10^{-1} but greater than 10^{-2} in that life.	Will occur frequently.
Occasional	C	Likely to occur some time in the life of an item, with a POO less than 10^{-2} but greater than 10^{-3} in that life.	Will occur several times.
Remote	D	Unlikely but possible to occur in the life of an item, with a POO less than 10^{-3} but greater than 10^{-6} in that life.	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a POO less than 10^{-6} in that life.	Unlikely to occur, but possible.

Table 4. Example mishap risk assessment values

Probability	**Severity**			
	Catastrophic	Critical	Marginal	Negligible
Frequent	1	3	7	13
Probable	2	5	9	16
Occasional	4	6	11	18
Remote	8	10	14	19
Improbable	12	15	17	20

Table 5. Example mishap risk categories and mishap risk acceptance level

Mishap Risk Assessment Value	Mishap Risk Category	Mishap Risk Acceptance Level
1-5	High	Component Acquisition Executive
6-9	Serious	Program Executive Officer
10-17	Medium	Program Manager
18-20	Low	As directed

The above approach provides a good framework for establishing risk criteria for tank cars.

3. Reliability Analysis for Corrosion

3.1 Background

As shown in Figure 4 (AAR, 1999), corrosive materials share a significant portion of tank car NAR cases. Although detailed corrosion mechanisms were not reported in the "Annual Report of Hazardous Materials Transported by Rail," nearly half of the cases listed in the AAR report's Table 1 are related to corrosion (classified as corroded tank shell and rusted tank shell) (AAR, 1999). As to specific forms of corrosion, tank car specification (AAR, 1996) uses the following categories to distinguish them: random pits, grouped pits, adjacent to weld, general corrosion, bathtub ring, and blister.

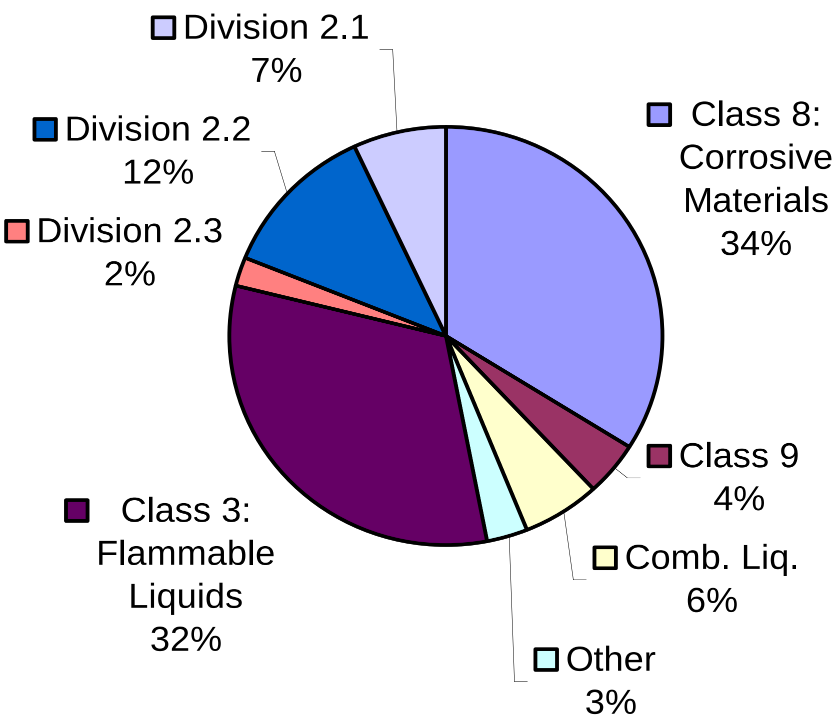

Figure 4. U.S. tank car NARs by hazard class, 1998 (AAR, 1999)

Extensive efforts in understanding and characterizing corrosion behaviors of various material and environment systems can be seen in the literature. For example, Kondo (1989) studied fatigue crack initiation life based on pit growth of NiCrMoV low alloy steels in hot water with dissolved oxygen. A residual life prediction method was proposed that considered transition from pit growth to fatigue crack growth. Bayoumi et al. (1995) reported the effects of pitting on fatigue behavior of plain carbon steels based on numerical simulation using the finite element method to determine pit stress concentration while adopting an empirical stress-life relationship to predict fatigue life. Enright and Frangopol (1998) predicted service life of deteriorating concrete bridges using time-variant reliability methods in which both loads and resistance are time dependent. Effects of variability in various parameters were studied using the Monte Carlo method. Harlow and Wei (1998) proposed a probability model for the growth of corrosion pits in aluminum alloys induced by constituent particles in aqueous environments. They show that pitting was initiated at constituent particles, which were either anodic or cathodic relative to the matrix and involved complex electrochemical processes. Rokhlin et al. (1999) studied the effect of pitting corrosion on fatigue crack initiation and fatigue life in Al 2024-T3 aluminum alloy. They performed experiments using a single artificial pit of different depths. An empirical relationship between pit depth and fatigue life was established. Zhang and Mahadevan (2001) assessed corrosion fatigue life using the reliability method. In-service inspection data was used to update prior reliability analysis. It also showed how the uncertainty in non-destructive inspection techniques affects the prediction.

As well documented in the literature (Van Der Sluys, et al., 1997; ASTM, 1995; ASTM STP 1238, 1995; Ross, 1977; ASM International, 1996), corrosion behavior is very sensitive to material features and environmental variables. Different corrosion behaviors occur for different combinations of material/environment systems and operating conditions. Lacking specific tank car corrosion data, no attempt is made in this work to model and analyze specific cases of tank car corrosion. Instead, a simplified tank car corrosion model is developed for use in reliability analysis. The corrosion model includes basic features for characterizing tank car corrosion behavior. It considers tank wall thinning (material loss) due to general corrosion.

3.2 A Model for Tank Car General Corrosion

Figure 5 shows a schematic of through-thickness tank plate cross section, which is used to develop a simple general corrosion model.

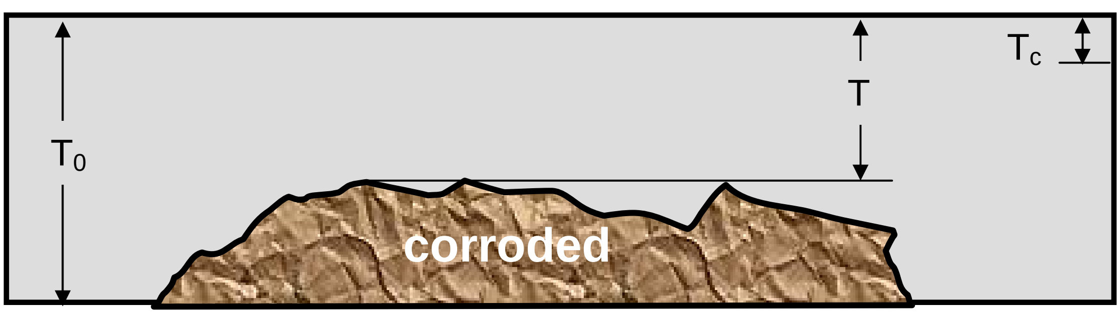

Figure 5. A schematic of tank plate cross section with corrosion damage

The following notations are used:

- T_0: As built or newly repaired tank wall thickness
- T_c: Critical tank wall thickness, at or below which rupture and leakage occur
- T: Time in service (years)
- T: Tank wall thickness at time t

- C_r: Corrosion rate, thickness loss per year (inch/year)
- $N(\mu, \sigma)$: Normal distribution with mean value of μ, and standard deviation of σ
- $LN(\mu, \sigma)$: Lognormal distribution with mean value of μ, and standard deviation of σ

Since leakage or rupture will occur when tank thickness reduces to a critical thickness, the failure criterion is, therefore, defined as:

$$T \leq T_c$$

Tank thickness at time t is equal to initial thickness minus thickness loss:

$$T = T_0 - C_r t$$

Thus, a performance function for reliability against corrosion is:

$$g = T - T_c = (T_0 - C_r t) - T_c$$

In a general situation, T_0, T_c, and C_r are all random variables. For example, T_0 varies within tolerances of the rolling process that produced the steel plate; T_c will vary due to variations in tank radius, lading density, tank pressure, and material properties, as well as uncertainties involved in measurement; C_r is a primary random variable because the corrosion process is influenced by numerous factors related to materials and operating conditions. T_0 may be considered as a constant because the rolling process is capable of limiting the thickness tolerances to very small values per American Society for Testing and Materials (ASTM) standard (ASTM, 2002). Nevertheless, T_0 is treated as a random variable to generally include other factors that may contribute to the variability of the plate thickness, such as a case where T_0 represents a measured thickness after a certain period of service, instead of starting from a pristine condition.

The following lists the assumed random variables and distribution parameters:

- *Critical Thickness*: $T_c \sim N(\mu_{Tc}, 0.01")$, $\mu_{Tc} = 0.1"$ and 0.2"
- *Tank Initial Thickness*: $T_0 \sim N(\mu_{T0}, 5\%)$, $\mu_{T0} = 7/16"$, 9/16", 11/16", and 13/16
- *Corrosion Rate*: $C_r \sim LN(\mu_{Cr}, 0.01)$, $\mu_{Cr} = 0.01$, 0.02, and 0.03 [inch/year]

The standard deviation for T_0 is given as 5 percent of μ_{T0} (coefficient of variation = 5 percent). The parameters used in the example cases are not based on an analysis of actual tank car data. Hence, the results are used to highlight the type of results that can be achieved using the reliability method being developed. Once tank car data is available, prediction regarding trends that may be expected in the tank car fleet can be analyzed using the same methodology. Figures 6, 7, and 8 show the probability density functions (PDF) for the random variables considered. Figure 6 shows the PDF for the four different initial thicknesses considered. Since the same coefficient of variation of 5 percent is assumed for the four different thicknesses, the probability density functions show more scatter for thicker plates.

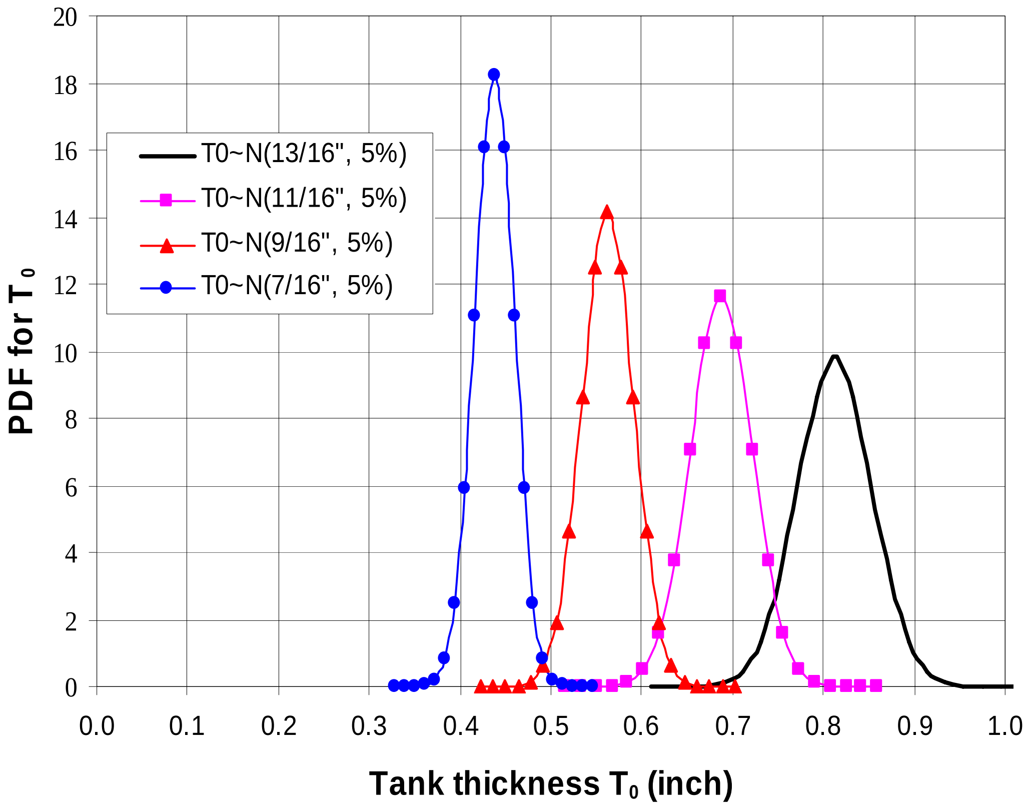

Figure 6. PDF for initial tank thickness, T_0

Figure 7 shows the PDF for the two different critical tank thicknesses considered.

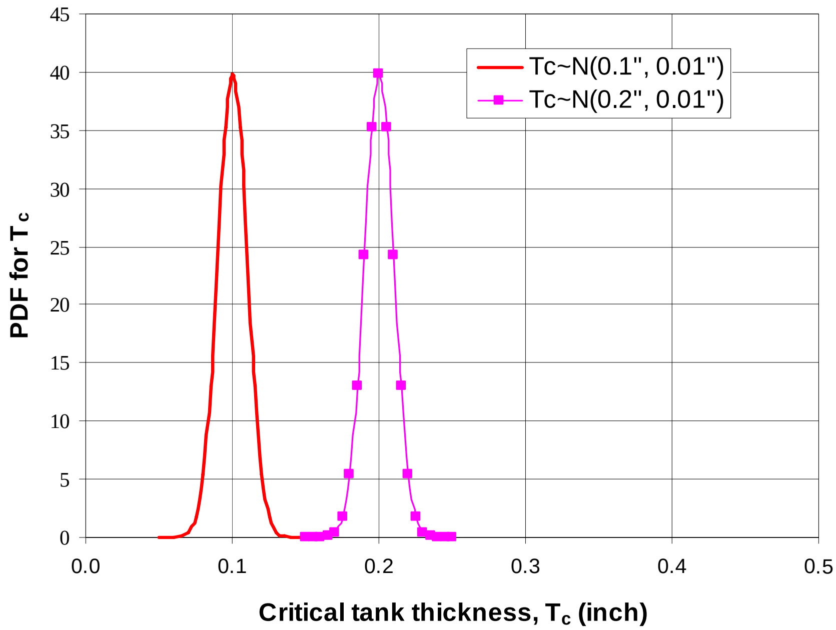

Figure 7. PDF for critical tank thickness, T_c

Figure 8 shows the PDF for the three different corrosion rates considered.

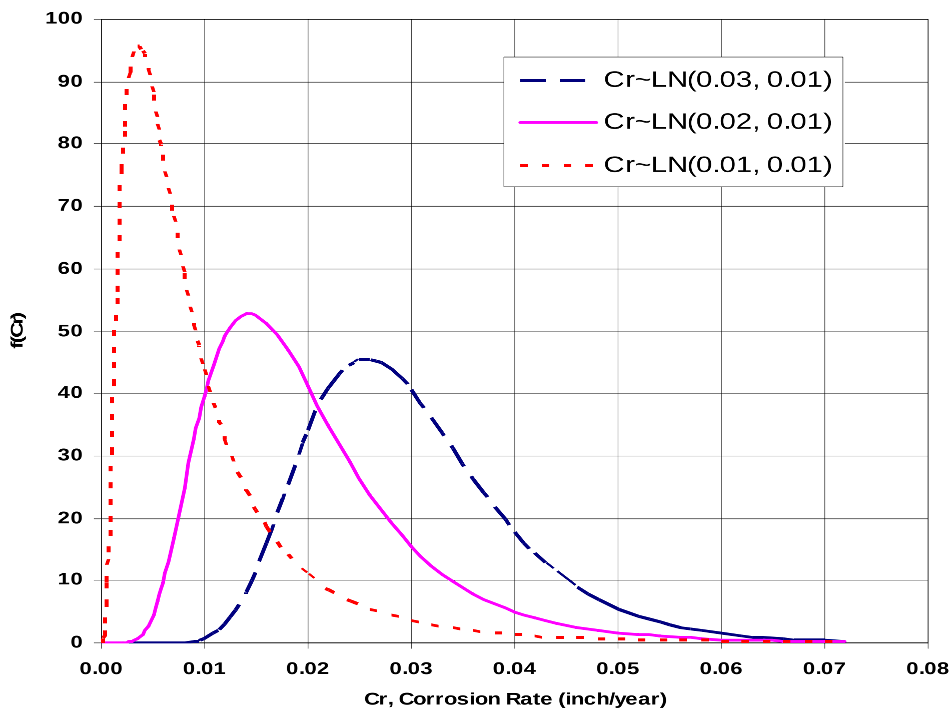

Figure 8. PDF for three different corrosion rates, C_r

3.3 Reliability Analysis Software and Solution Method

Commercial structural reliability analysis software, STRUREL (2000), is employed for the corrosion reliability analysis. First order reliability method (FORM) (Rackwitz and Fiessler, 1978; Chen and Lind, 1983; Wu and Wirsching, 1987; Der Kiureghian and Liu, 1986) has been widely used due to its computational efficiency. As a useful by-product, the method also provides importance measures (ranking) of random variables relative to the failure probability. The specific FORM algorithm offered in STRUREL is based on (Rackwitz and Fiessler, 1978), which is now a standard approach. This FORM is used to locate the most probable point (MPP), or β-point, on the failure surface ($g = 0$). The method produces exact failure probability in cases where failure surface is a (hyper) plane (in standard and independent normal space). Accurate results can be obtained in cases where the curvature of failure surface at the MPP is small or moderate, as is the case for the corrosion model.

3.4 Results and Discussions

Figure 9 gives reliability analysis results for the above corrosion model.

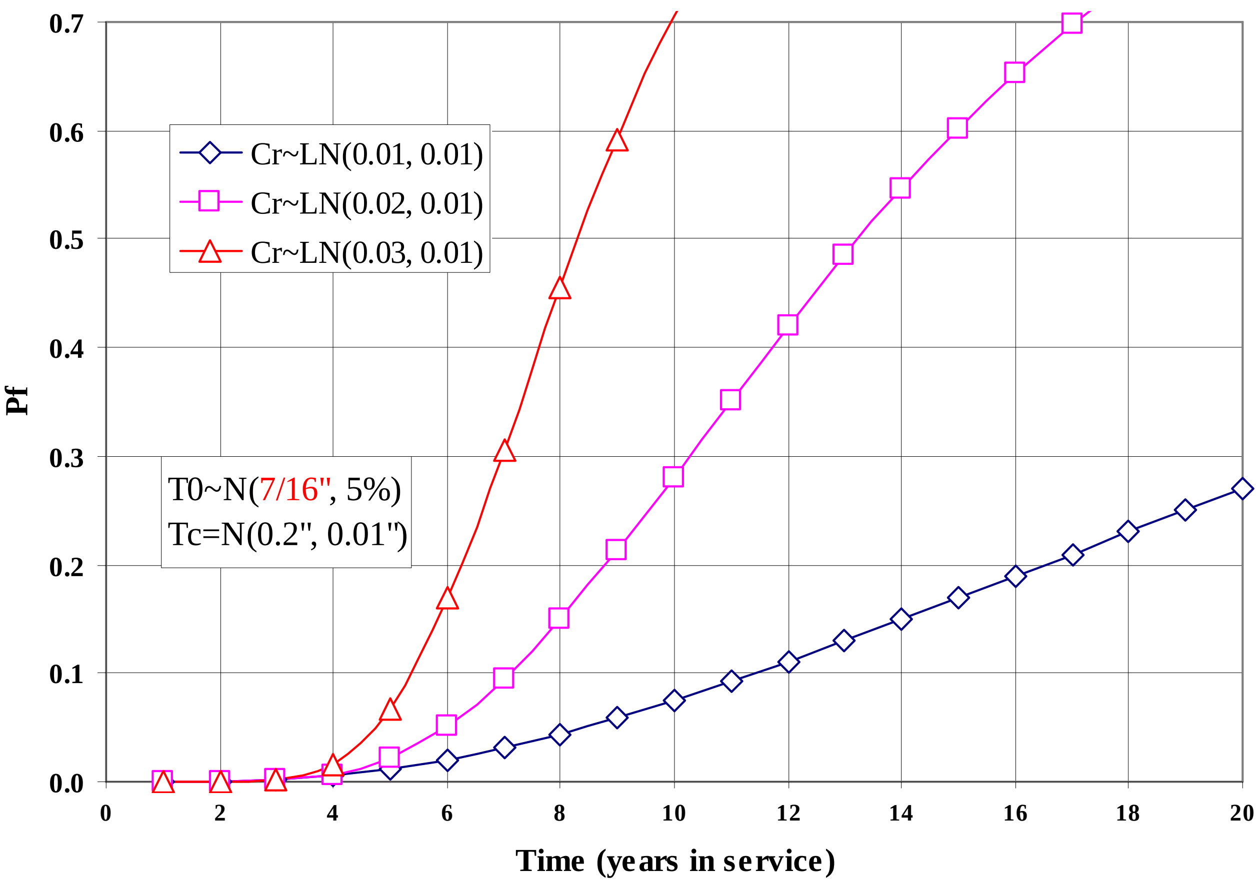

Figure 9. Failure probability versus service time for μ_{T0} = 7/16"

Figure 10 shows the failure probability, P_f, versus service time for the four different values of initial tank thickness with $\mu_{Tc} = 0.2$". Figures 9, 10, 11, and 12 are, respectively, for $\mu_{T0} = 7/16$", 9/16", 11/16", and 13/16".

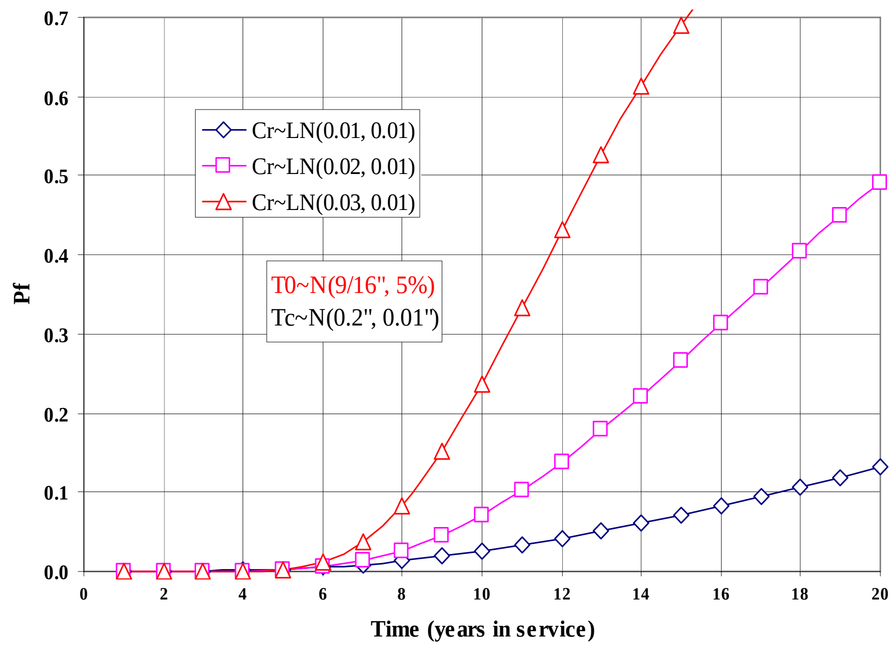

Figure 10. Failure probability versus service time for $\mu_{T0} = 9/16$"

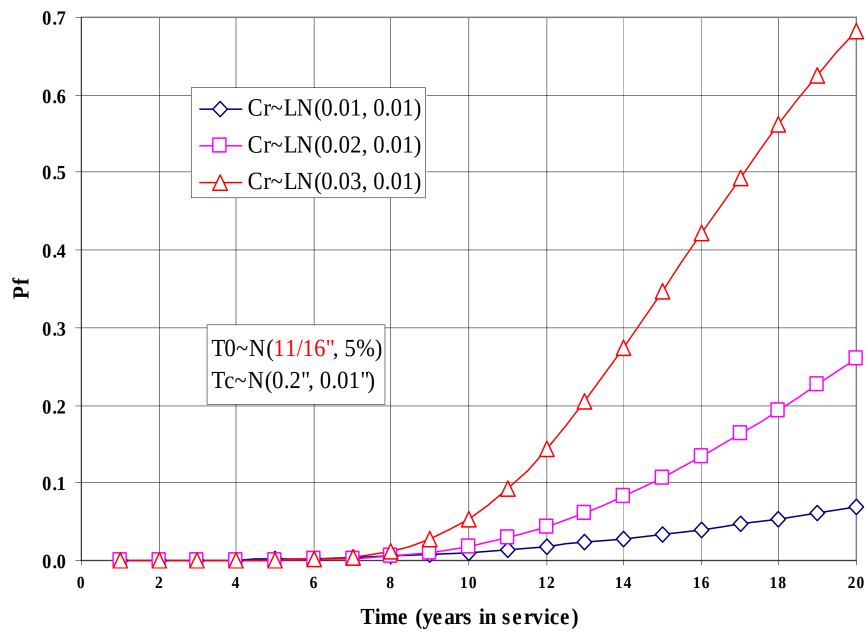

Figure 11. Failure probability versus service time for $\mu_{T0} = 11/16$"

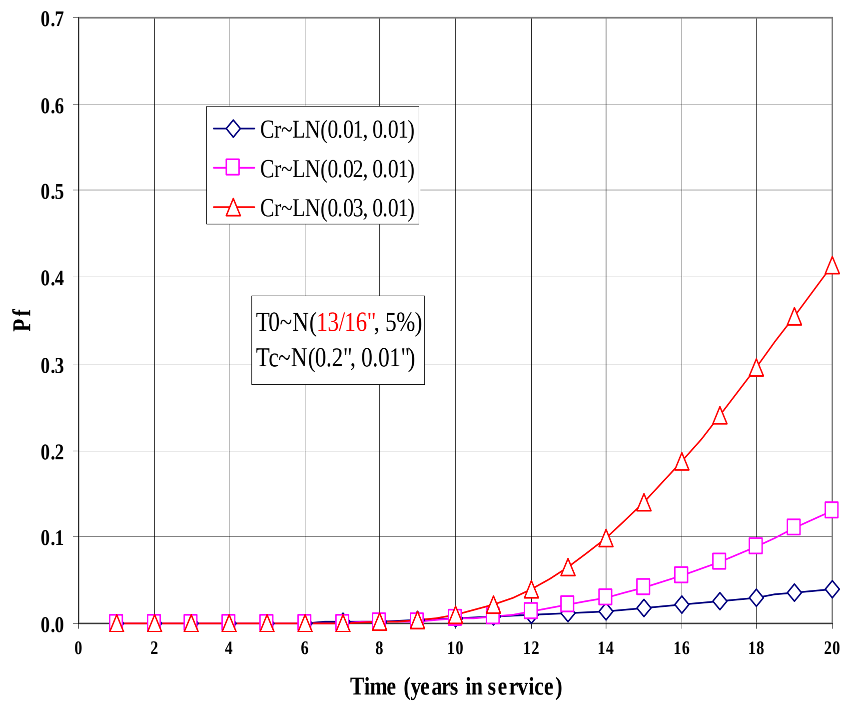

Figure 12. Failure probability versus service time for μ_{T0} = 13/16"

The failure probability increases as service time increase. The higher the corrosion rate is, the higher the failure probability. The thicker the tank plate is, the lower of the failure probability. Although these trends are well within the expectation without analysis, the analysis does quantify the amount of the risk involved in each case. Furthermore, the failure probability may increase much more rapidly after a certain period of service time, say t_a. Based on this information, inspection and repair can be scheduled around time t_a, so that a desired level of reliability can be achieved with a minimal frequency of inspection and repair.

Figure 13 shows the influence of the critical tank thickness, μ_{Tc}, on the failure probability versus service time for initial tank thickness μ_{T0} = 11/16". The smaller the critical tank thickness is the lower the failure probability, as expected, because a smaller critical thickness means a larger material loss can be tolerated.

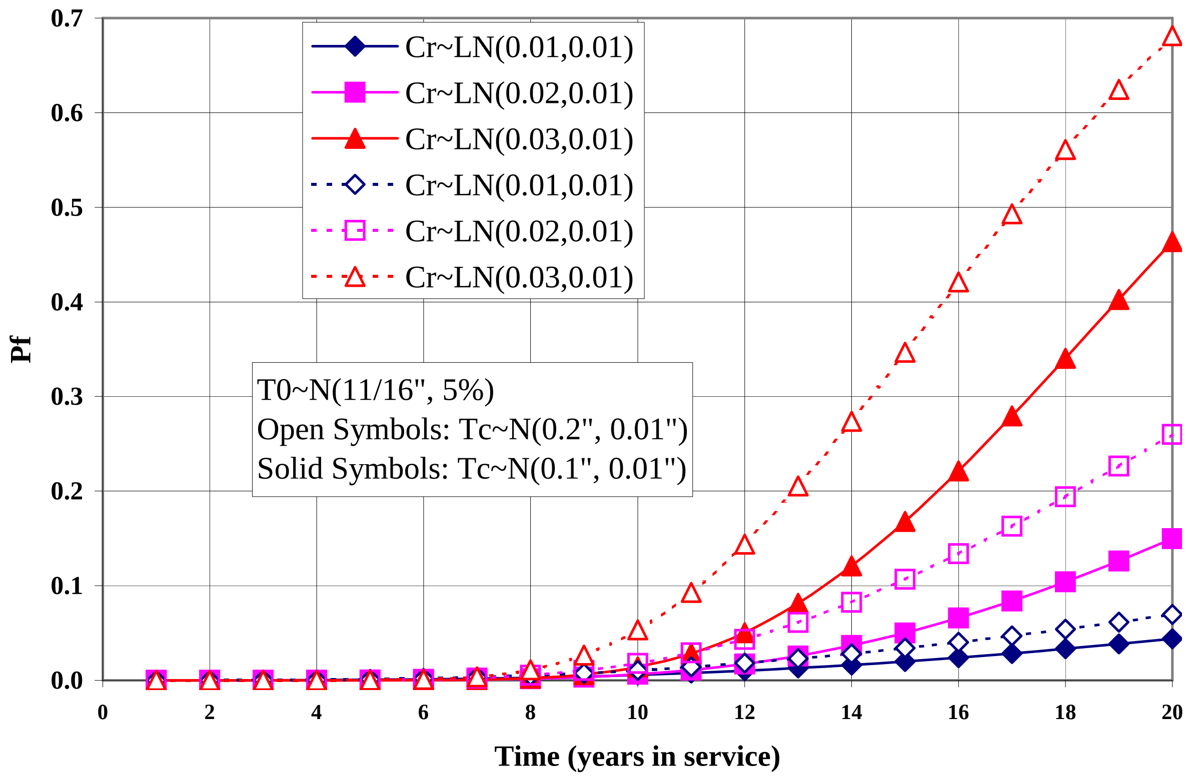

Figure 13. Influence of μ_{Tc} on the failure probability versus service time for nominal tank thickness μ_{T0} = 11/16"

Figures 14, 15, and 16 compare the effect of different μ_{T0} on the failure probability versus service time, for the three different corrosion rates: μ_{Cr} = 0.01"/year, 0.02"/year, and 0.03"/year.

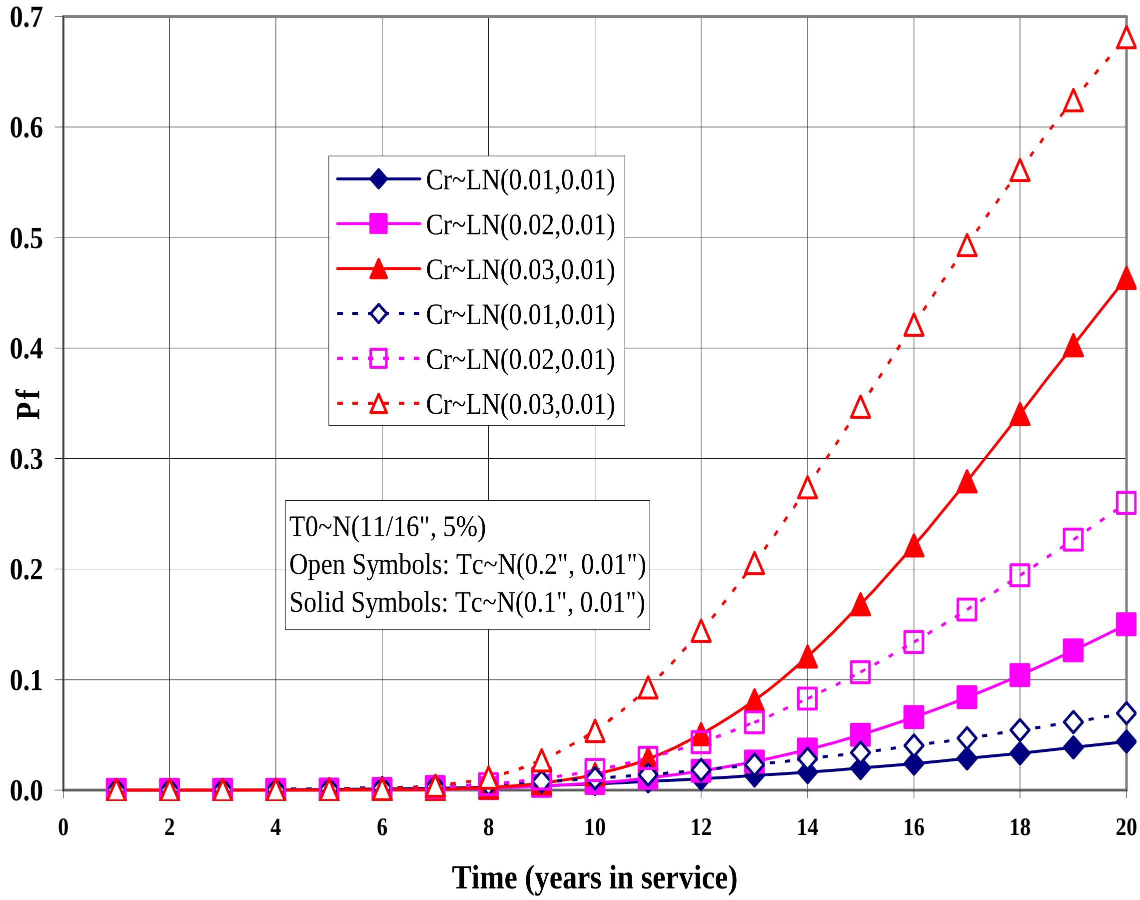

Figure 14. Corrosion failure probability as a function of service time for corrosion rate C_r = 0.01"/year

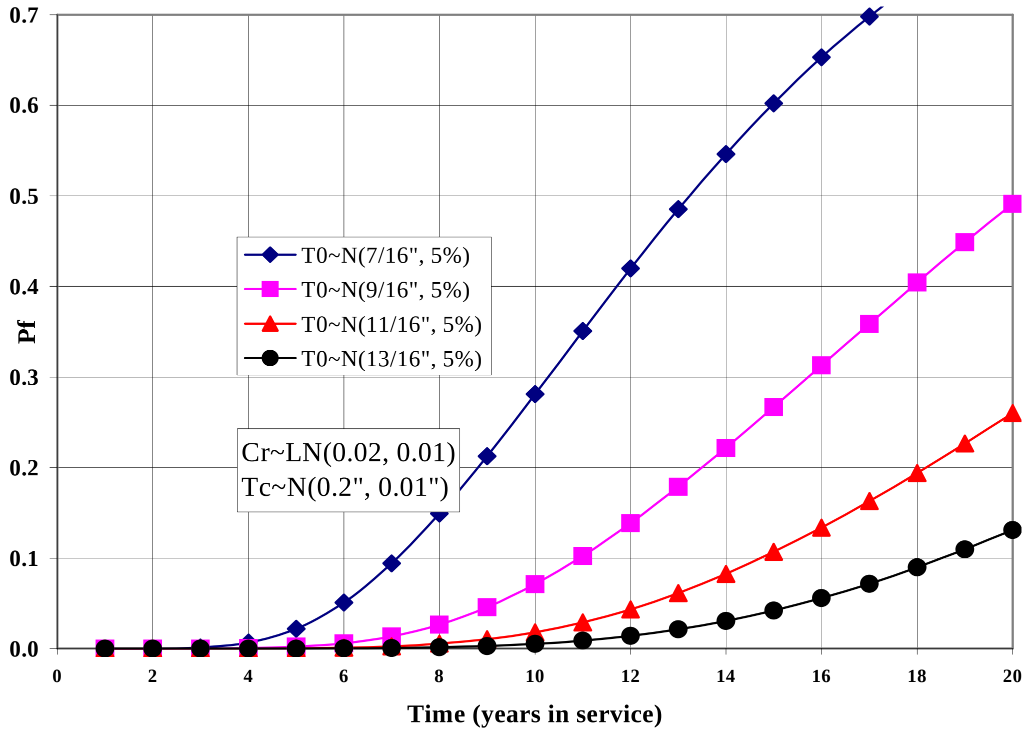

Figure 15. Corrosion failure probability as a function of service time for corrosion rate C_r = 0.02"/year

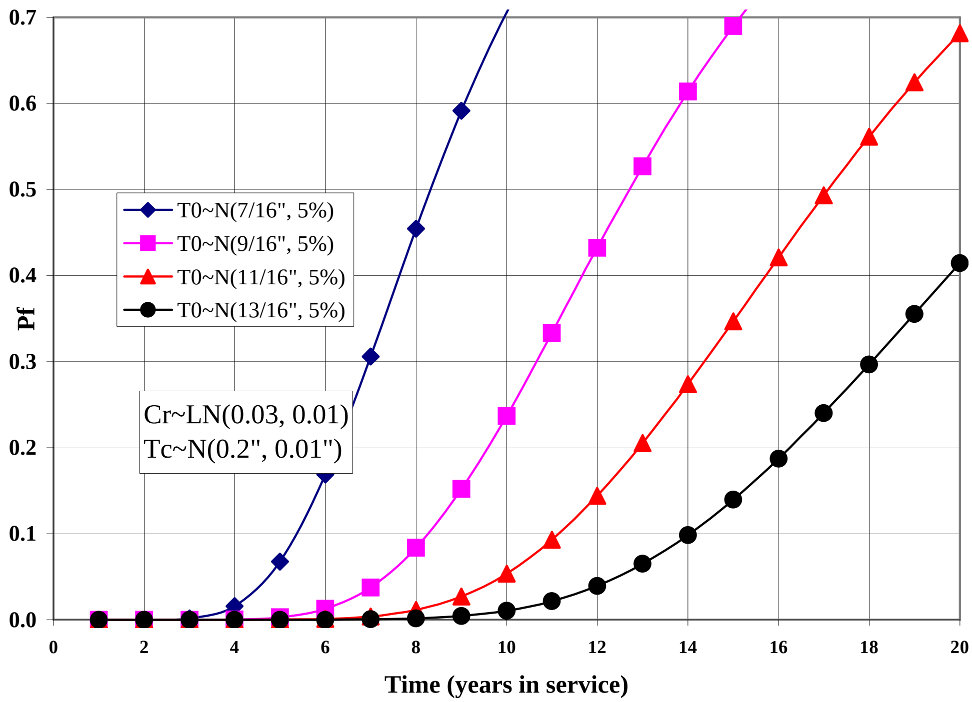

Figure 16. Corrosion failure probability as a function of service time for corrosion rate C_r = 0.03"/year

Figures 14, 15, and 16 provide a convenient form for design in determining how a thicker tank can reduce failure probability. The information can be useful to arrive at an optimal design by minimizing the life cycle cost when incorporating costs of manufacturing, maintenance and repair, and risk of failure.

3.5 Summary of Corrosion Reliability Analysis

The following summarizes the points regarding the above corrosion analysis.

A method for tank car reliability analysis against corrosion has been developed. Lacking specific tank car corrosion data, a simplified corrosion model for the case of general corrosion is developed. The model includes basic features characterizing the tank car's general corrosion process.

Reliability analysis using assumed random variables and distribution parameters has been performed for a series of tank thickness, corrosion rates, and critical tank thickness. The results show reasonable behaviors and trends for the effects of tank thickness, corrosion rates, and critical tank thickness.

The model and method can be used to analyze specific tank car corrosion problems once the relevant data is available.

Models for other forms of corrosion can also be developed once relevant tank car data is available.

4. Reliability Analysis for Fatigue

4.1 Introduction

After a series of tank car fractures occurred under normal service conditions in the aging U.S. tank car fleet, fatigue cracking has emerged as a primary safety concern. To effectively deal with the problem, damage tolerance analysis (DTA) has been performed on the tank car stub sill underframe (Cardinal, et al., 1998) and on the tank structure itself (Zhao, et al., 2000) to determine inspection intervals. It is widely realized that the DTA process, due to complexities involved, is subject to uncertainty arising from incomplete knowledge and/or intrinsic variability of parameters, such as material properties, defect location and geometry, load spectrum, service history or usage projection, and inspection and manufacturing variability.

Built on the probability and statistics concepts, reliability methods based on limit-state formulation provide a useful tool to quantitatively assess uncertainties involved in the DTA process, which, in turn assists in better risk management. Indeed, a rich literature documents development and applications of reliability methods to various problems involving DTA or fatigue crack growth analysis. For example, Sutharshana et al. (1992) presented a probabilistic fracture mechanics approach for predicting the fatigue life distribution using Monte Carlo simulations and used it to perform probabilistic fatigue crack growth analysis on a welded tube in a space shuttle main engine. Manning et al. (1992) proposed a reliability-centered maintenance analysis method based on a simple stochastic fatigue crack growth approach. To account for uncertainties in various parameters, they applied a single random factor (dispersion parameter) to a deterministic fatigue crack growth law. The method was demonstrated using a cutout in a fuselage bulkhead.

Harkness et al. (1992) combined FORM with a finite element method (FEM) to perform fatigue crack growth reliability analysis for two-dimensional cracks obeying the Paris law (1963). Relative to the PDF for initial crack length, they noted that only the portion corresponding to the largest cracks has a significant effect on reliability. Millwater et al. (1994) integrated a fatigue crack growth life assessment methodology with finite element analysis and advanced probabilistic algorithms. The weight function method was implemented for efficient computation of stress intensity factors (SIF). An application example of a blade attachment steeple in a steam turbine also demonstrated the accuracy and efficiency of the proposed probabilistic life assessment method. Tryon et al. (1996) performed a detailed study of fatigue crack growth reliability of a disk rim in a high pressure turbine using FORM and Monte Carlo methods. For computational efficiency, they used a response surface approach to construct a fatigue performance function. The Paris law was adopted to describe fatigue crack propagation. Both component and system reliability problems were analyzed. Berens (1996) used a probabilistic fracture mechanics approach to perform risk analysis of aging military aircraft. Berens considered four types of problems: (a) cracking at a single critical location, (b) material thinning effects due to corrosion, (c) multiple element damage, and (d) expected costs of inspections and repairs. Cardinal and Enright (2001) performed sensitivity studies on tank car stub sill DTA to various parameters involved by interfacing the fatigue crack growth software, NASGRO (Forman, et al., 2000), with probabilistic analysis software, NESSUS (Riha et al., 2000). Among other things, the results showed that the vertical coupler force (VCF) scale factor had the most significant influence on crack growth life, indicating the importance of accurate determination of the VCF spectrum and the associated tank car stresses.

In this work, a methodology for assessing structural reliability of railroad tank cars undergoing fatigue crack growth is being developed. Significant statistical parameters affecting fatigue crack growth life predictions are treated as random variables. A surface crack with 3-dof is employed in fatigue analysis to account for the asymmetric stress field that may exist at a fatigue critical location in tank car structures. A three-dimensional weight function method (3D-WFM) developed based on the work of Zhao, et al. (1997a) and Zhao, et al. (1997b), was used to determine the SIF for the 3-dof surface crack. A fatigue life prediction program using the Walker equation (1970) to account for stress ratio effects was developed for the 3-dof surface crack model. The component reliability problem is formulated as a limit-state function and solved using FORM along with the importance sampling method within the commercial software for reliability analysis, STRUREL (2000). Without losing generality, the methodology is developed in reference to a fatigue critical location at a weld between the tank head and the front sill pad.

4.2 Key Elements Characterizing Tank Car Fatigue Crack Growth

To facilitate understanding of structural issues related to the reliability analysis, the following section presents a brief account of the structural features of a typical railroad tank car, followed by a description of a few important elements characterizing tank car fatigue crack growth. These elements include stress distributions, load spectrum, welding residual stresses, fatigue crack growth law, and life prediction algorithm.

4.2.1 Structural Features of Railroad Tank Cars

The majority of tank cars in service are stub sill tank cars that utilize a stub (short) sill at each end of the tank, with the tank acting as a structural component to transfer in-train loads. Figure 17 shows a half model of a non-pressure, general purpose, stub sill tank car (cut along the symmetry plane). The figure does not show running gears (trucks) supporting the tank car at each end since they are not a subject of the current analysis. The supporting actions of the trucks are simulated by springs at each end. The primary fatigue loads for tank cars are those transferred through couplers and are classified as the VCF and longitudinal coupler force (LCF). As shown in Figure 17, the VCF is either in the upward direction or in the downward direction. The LCF is either in tension (draft) or in compression (buff).

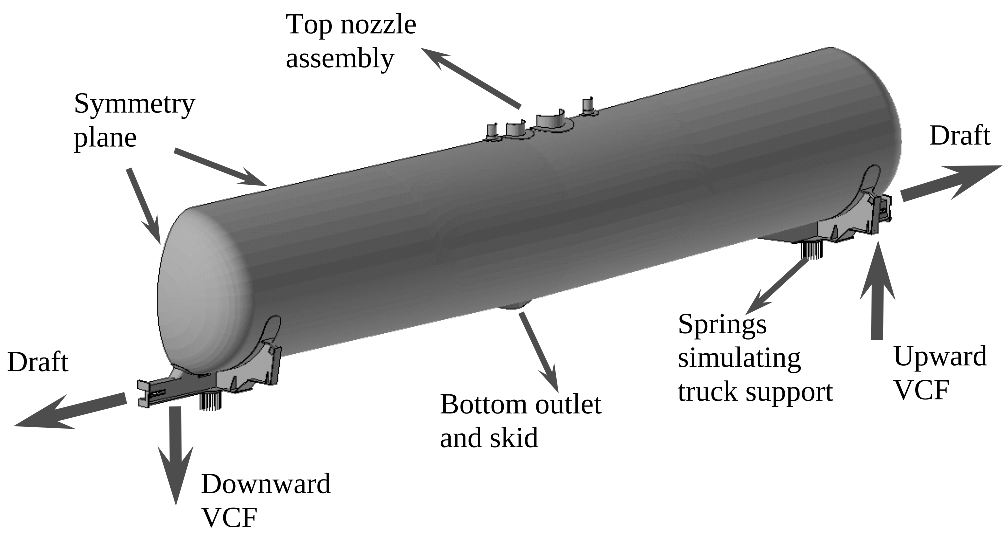

Figure 17. Half model of a non-pressure, general purpose, stub sill tank car

4.2.2 Stress Distribution at a Fatigue Critical Location

DTA of the above tank car has identified a fatigue critical location (FCL), as shown in Figure 18 (Zhao et al., 2000). The FCL is located outside the tank along the weld toe between the front sill pad and the tank head, and stress is induced by a downward VCF load.

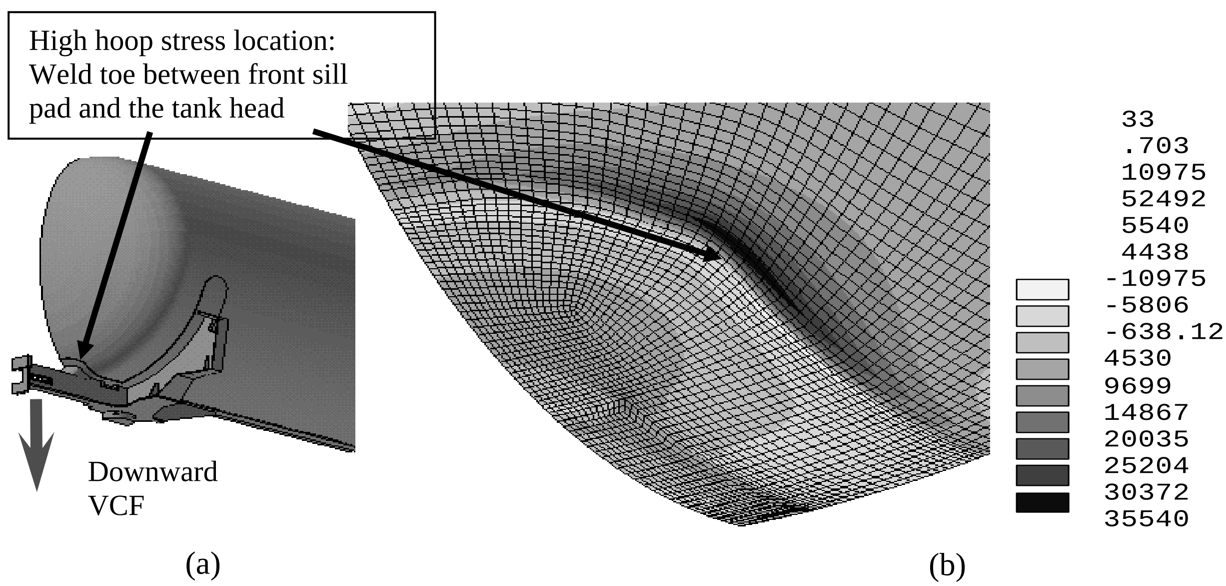

Figure 18. Downward VCF on an empty tank car: (a) location of high stress area and (b) hoop stress on tank's bottom surface around the front sill pad area, psi

Since the process of fatigue crack growth and fracture in tank car structures has been shown to initiate primarily at welds, especially those welds that connect the tank to the underframe structure (the stub sill region), the FCL shown in Figure 18 is a typical one. A surface crack located at this FCL is generally subjected to an asymmetric stress distribution, as shown in Figure 19 (X and Y in inch, with Y = 0 at the outer surface), as well as welding residual stresses, thus covering the practical complexities that may be experienced by tank cars. Therefore, without losing generality, the tank car fatigue reliability analysis methodology is developed in reference to this FCL.

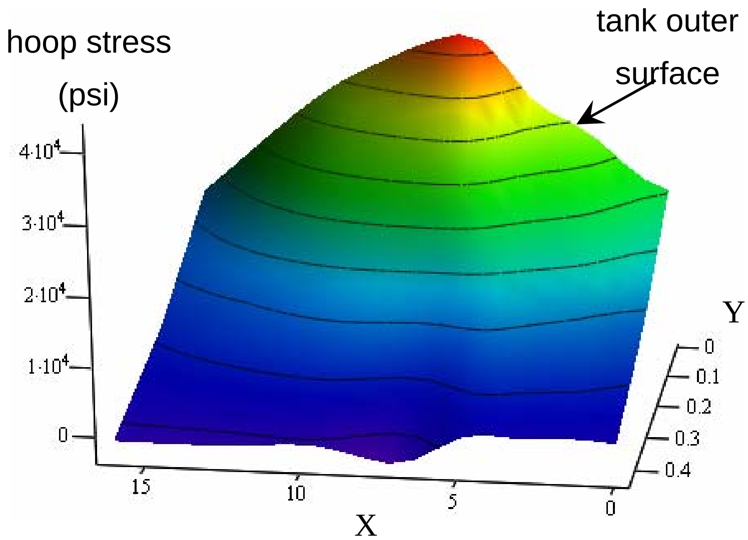

Figure 19. Through-thickness distribution of the hoop stress at the FCL

4.2.3 Tank Car Fatigue Load Spectrum

The load spectrum causing most fatigue damage at the FCL is the one for the downward VCF load. The downward VCF spectrum has two parts: one for a loaded tank car and the other for an empty tank car. The current practice is to assume that the ratio of unloaded (empty tank) mileage to the loaded mileage is $R_{UL} = 1.06$. Figure 20 shows the load step information for the downward VCF spectrum, where the load steps for the unloaded tank car are arranged to follow the loaded portion. Figure 20 does not show the number of cycles at each load step. Sutton and Zhao (2001) have shown, among other things, that load ordering effects are negligible if the spectrum is repeated many (e.g., > 10) times during a life prediction where load sequence effects are neglected.

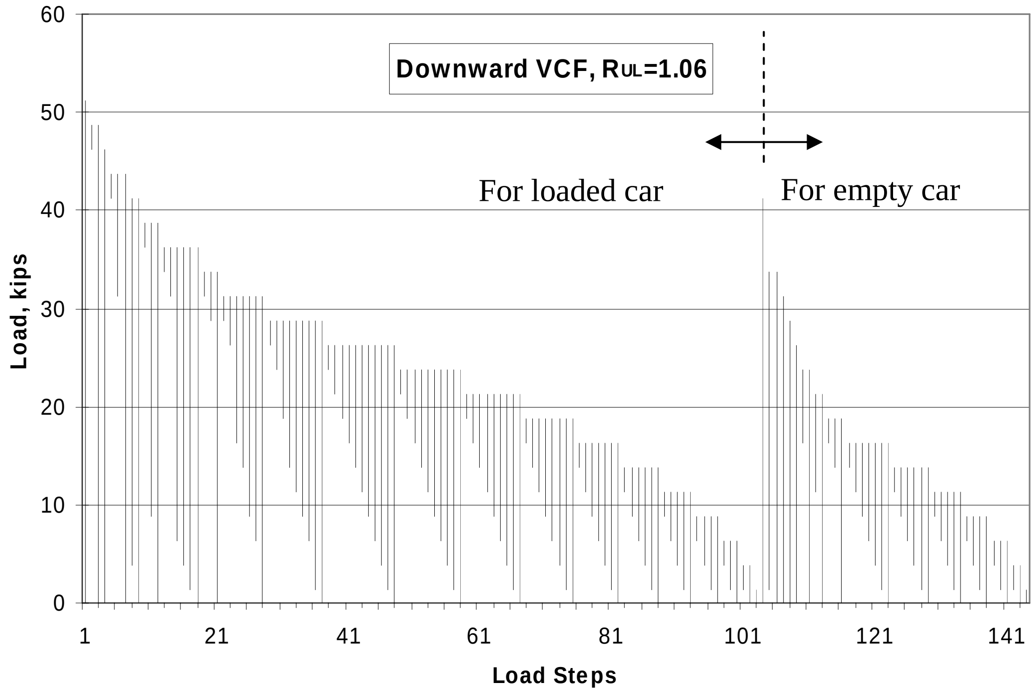

Figure 20. Tank car downward VCF spectrum

Mean loads corresponding to lading and gravity effects at the FCL are added to the above spectrum to obtain a load spectrum specific to the FCL considered.

4.2.4 Welding Residual Stresses

Tank cars are built-up structures of shells and beams through fusion welding. Although post-weld heat treatment is performed, welding residual stresses may not be negligible in fatigue crack growth analysis. Therefore, welding residual stresses are considered in developing the fatigue reliability analysis methodology. This work uses neutron diffraction measurements of welding residual stresses for a butt weld of tank car plates made of TC128-B steel (Sutton, et al., 2002).

For the FCL considered, the responsible residual stress component is in the direction transverse to the weld bead, which is about the same or very close to the second principal stress direction. Figure 21 shows the second principal welding residual stress distributions at various thickness positions (Sutton et al., 2002). The figure shows that the welding residual stress distribution is very complicated. Though the actual residual stress distribution can be implemented in the SIF calculation using the enhanced 3D-WFM, this work made no such attempt for the methodology development. Rather, the residual stress effect on life prediction is assessed by assuming a relevant constant value as described later.

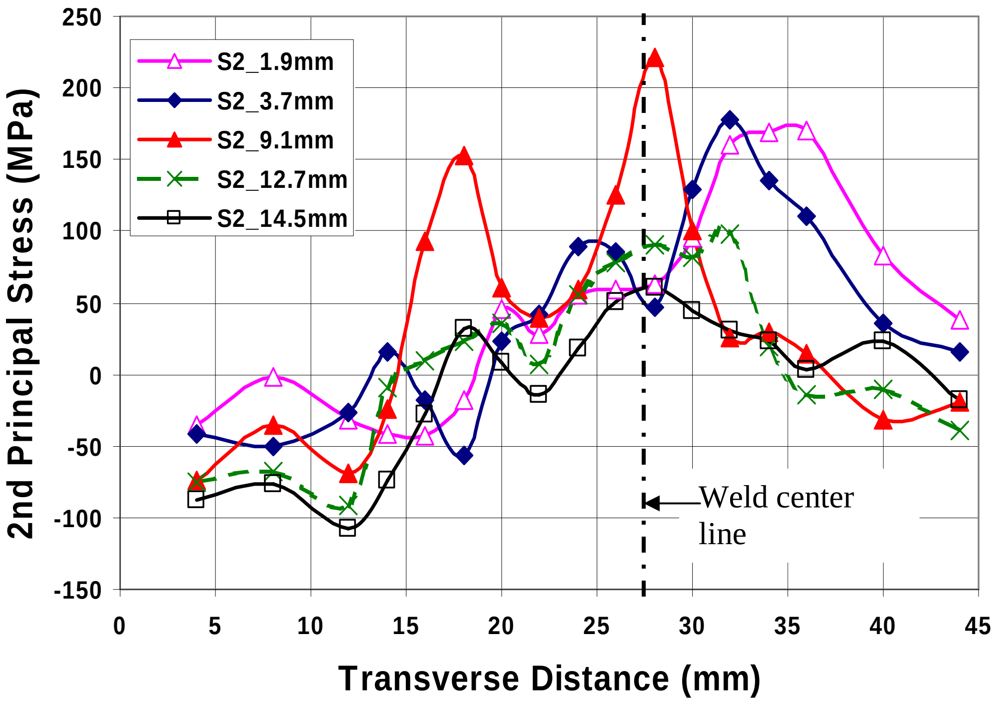

Figure 21. Welding residual stress in transverse direction for a butt weld of tank car plates made of TB128-B (Sutton, et al., 2002)

4.2.5 Fatigue Crack Growth Law

Commonly used fatigue crack growth laws vary from Paris equation (Paris and Erdogan, 1963) to those applicable to the entire fatigue crack growth process from the threshold regime to the rapid fracture regime, such as the NASGRO equation (Forman, et al., 2000) and the FASTRAN equation (Newman, 1992). Since the available fatigue crack growth data for the tank car steel A516-70 (Suresh and Ritchie, 1982) is too limited to determine parameters needed for description of the entire fatigue crack growth process, the Walker equation (Walker, 1970) is adopted for this work. The Walker equation is simple, yet it incorporates the stress ratio (R-ratio) effect, a desirable feature for spectrum loading, as is the case for tank cars. No load sequence effects (retardation and acceleration) are considered since neither load sequence information for the tank car load spectrum nor material response data is available. The Walker equation can be expressed as follows:

$$\frac{da}{dN} = C_W(R)[\Delta K]^m \qquad (3a)$$

$$C_W(R) = \frac{C}{(1-R)^q} \quad for\ R < R_{co} \qquad (3b)$$

$$C_W(R) = \frac{C}{(1-R_{co})^q} \quad for\ R \geq R_{co} \qquad (3c)$$

where R_{co} is the cutoff value of the R-ratio above which the R-ratio effect diminishes in Paris regime. Based on the limited fatigue crack growth data for A516-70 (Suresh and Ritchie, 1982), along with data for structural and low alloy steels (Hudak, et al., 1985), the parameters in Eq. (3a, 3b, and 3c) are estimated as follows: C = 1.36×10^{-10}, q = 2.09, m = 3.15, and R_{co} = 0.5, with crack growth rate, da/dN, expressed in inch/cycle. Figure 22 shows the resulting $C_{w,}$ where the low R (R = 0.2) and high R (R = 0.5) values for C of Paris equation used for tank car stub sill DTA (Cardinal et al., 1998) are shown as triangles. The advantage of using the Walker equation is the ability to use the actual R-ratios of the tank car spectrum in fatigue life prediction, instead of assuming a fixed R-ratio for high R (Cardinal et al., 1998) or for a dominating R-ratio (Zhao, et al., 2000).

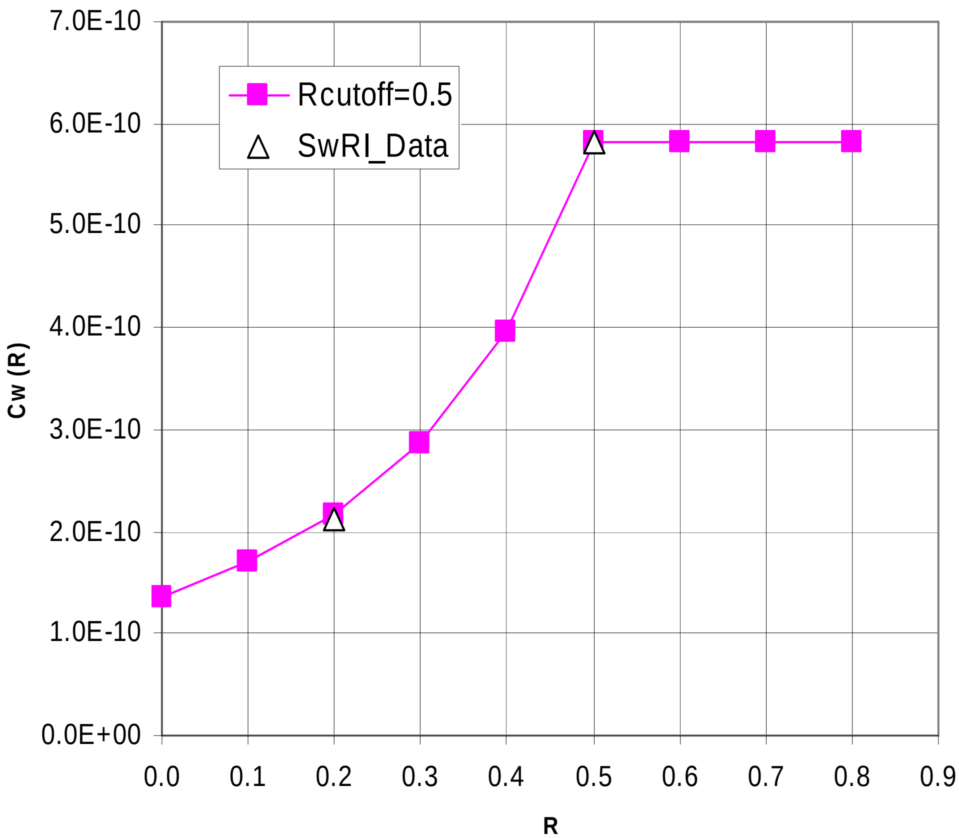

Figure 22. Walker equation coefficient as a function of R-ratio for A516-70

4.2.6 *Life Prediction Algorithm for the 3-dof Surface Crack*

Figure 23 defines geometrical parameters for the 3-dof surface crack considered in this work. The 3-dof surface crack is more general because it does not require symmetry of geometry and load with respect to the crack's a-axis, as does a 2-dof surface crack. Therefore, it allows a better representation for cracks involving asymmetric load and/or geometry.

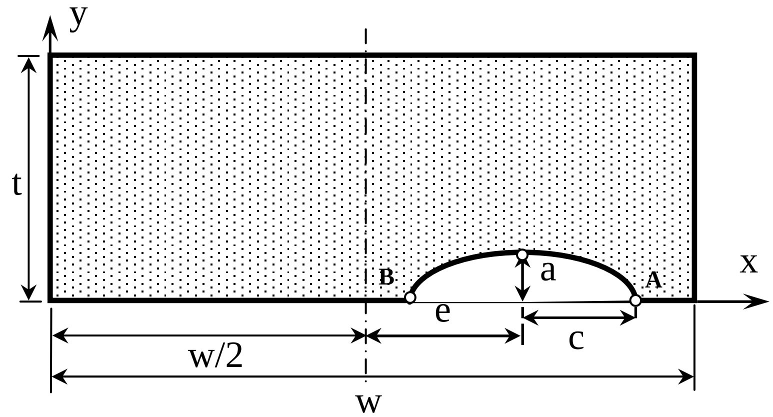

Figure 23. A 3-dof surface crack

The capability of the 3D-WFM (Zhao, et al., 1997a; Zhao, et al., 1997b) has been enhanced to analyze off-center surface and embedded cracks[1]. The enhanced 3D-WFM is adapted for use in this work to determine SIFs for the 3-dof surface crack.

The fatigue life prediction for the 3-dof surface crack under downward VCF spectrum is performed as follows. First, the SIF range for load step i of the spectrum is determined as:

$$\Delta K_i = \Delta S_i f_i \left[a_{i-1},\ c_{i-1},\ e_{i-1},\ w,\ t,\ \varphi,\ S(x,y) \right] \quad (4)$$

where ΔS_i is the stress range at the FCL; S(x,y) is the stress distribution at the FCL due to a unit downward VCF load; φ is a parametric angle of the crack with φ = 0° at point A in Figure 23, φ = 90° at point B, and φ = 180° at point C; f_i is SIF due to the unit downward VCF load. Then, the crack growth increments are calculated according to Eq. (5):

[1] The work was done in cooperation with Dr. G. Graham Chell and Mr. Yi-Der Lee, Southwest Research Institute (SwRI), while Dr. Zhao worked as a subcontractor to SwRI through funding of Pratt & Whitney (P&W). SwRI's contribution to the enhanced 3D-WFM and P&W's kind permission for the authors to use the enhanced 3D-WFM are gratefully acknowledged.

$$\Delta a_i = C(R_i)\left[\Delta K(90^0)_i\right]^m \Delta N_i \quad (5a)$$

$$\Delta c_{A_i} = C(R_i)\left[\Delta K(0^0)_i\right]^m \Delta N_i \quad (5b)$$

$$\Delta c_{B_i} = C(R_i)\left[\Delta K(180^0)_i\right]^m \Delta N_i \quad (5c)$$

$$\Delta e_i = \Delta c_{A_i} - \Delta c_{B_i} \quad (5d)$$

where R_i is the stress ratio for load step i and ΔN_i is the number of cycles at load step i. Sub-incrementation of ΔN_i will be performed if a large crack growth increment may occur during ΔN_i load cycles. Lastly, the crack size and eccentricity are updated as follows:

$$a_i = a_{i-1} + \Delta a_i \quad (6a)$$

$$c_{A_i} = c_{A_{i-1}} + \Delta c_{A_i} \quad (6b)$$

$$c_{B_i} = c_{B_{i-1}} + \Delta c_{B_i} \quad (6c)$$

$$e_i = e_{i-1} + \Delta e_i \quad (6d)$$

The procedure starts from initial crack size and continues until either crack penetrates tank or final fracture occurs.

4.3 Fatigue Reliability Analysis

4.3.1 Performance Function

A performance function for fatigue reliability can be defined as:

$$g_0 = N_P - N_D \quad (7)$$

where N_P is the predicted fatigue life, N_D is the demanded fatigue life during which a tank car is expected to perform without leakage or fracture due to fatigue crack growth (i.e., failure in this case is defined as leakage or fracture due to fatigue crack growth). Therefore, two failure criteria exist:

$$a \geq t \cdots \text{ for leakage} \quad (8a)$$

$$K_{\max}(\varphi) \geq K_c \cdots \text{ for fracture} \quad (8b)$$

For practicality, the leakage criterion is implemented as a $\geq$0.985t. Failure occurs when predicted fatigue life fails to meet the demanded life (i.e., $(N_P - N_D) < 0$). The probability of failure, P_f, is thus expressed:

$$P_f = P(g_0 < 0) = P[(N_P - N_D) < 0] \quad (9)$$

4.3.2 Basic Random Variables and Deterministic Parameters

This study considered six basic random variables. They are:

1. Initial crack depth, a_0
2. Initial crack aspect ratio, $(a/c)_0$
3. Coefficient of fatigue crack growth law, C (Equ.(3))
4. Stress uncertainty factor, S_{uf}, which represents the combined influence of uncertainty in amplitudes for the load spectrum and stress analysis
5. Cutoff value of R-ratio effect, R_{co}
6. Initial crack eccentricity, e_0

The statistic nature of the first four basic random variables is well recognized, and they are routinely considered in probabilistic analysis of fatigue crack growth, (e.g., Sutharshana, et al., 1992; Harkness, et al., 1992; Millwater, et al., 1994; Tyron, et al., 1996; Cardinal and Enright, 2001).

The R_{co} is assumed to be a random variable based on the observation that the R-ratio effect in the near-threshold to Paris regimes is primarily attributed to various crack closure mechanisms, which, in turn, may be sensitive to material microstructure, mechanical properties, and environment, as well as the statistical nature of measuring the crack opening load.

The e_0 is assumed to be a random variable since a crack initiation site is dependent on features, such as welding details and material microstructures, which apparently are statistic in nature, in addition to being in a high-stress area as determined by structural finite element analysis.

No sufficient data is available to establish probabilistic distribution types and parameters for the tank car material considered. Based on experiences and engineering judgment, Table 6 lists the distribution types and parameters assumed for this methodology development work.

Table 6. Probabilistic distributions for the basic random variables

Name	Symbol	Probabilistic Density Function	Parameters
Initial crack depth	a_0	U(0.0125", 0.2")	Distribution interval
Initial crack aspect ratio	$(a/c)_0$	U(0.1, 1)	Distribution interval
Crack growth coefficient	C	LN(1.36e-10, 0.272e-10)	Mean, standard deviation
Stress uncertainty factor	S_{uf}	N(1, 0.08)	Mean, standard deviation
R-ratio cutoff value	R_{co}	N(0.5, 0.03)	Mean, standard deviation
Initial crack eccentricity	e_0	U(0", 3")	Distribution interval

In Table 6, U, LN, and N stand for uniform (rectangular), lognormal, and normal distributions, respectively. The dimensions for C correspond to crack growth rate expressed in inch/cycle.

In addition, the effects of welding residual stresses, S_r, are considered through deterministic parameter studies.

The fracture toughness, K_c, is another legitimate random variable but intentionally treated as a deterministic parameter of $K_c = 250$ ksi√in (roughly a mean value for data from a range of steels and conditions). This K_c value essentially suppresses the fracture failure (leak before break), thus avoids dealing with system reliability problems (multiple failure modes in this case), which will be covered in the next phase of the project.

4.3.3 Reliability Analysis Software and Solution Methods

Reliability analysis software. Commercial structural reliability analysis software, STRUREL (2000), is employed for the fatigue reliability analysis. To do so, FORTRAN subroutines and a static library have been developed to interface with STRUREL. Figure 24 shows a flow chart for the fatigue reliability analysis process. The fatigue life calculation (in the dashed rectangle) is carried out from initial crack size to failure (leakage) or to a pre-determined run-out life, for each realization (sample) of the set of random variables.

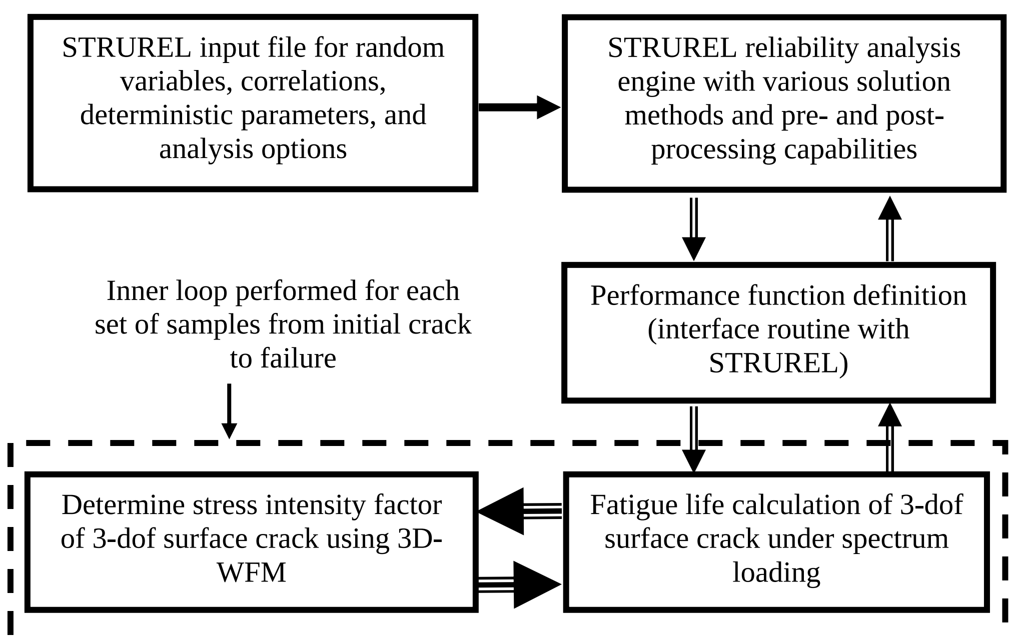

Figure 24. A flow chart of the fatigue reliability analysis process

Solution methods. FORM (Rackwitz and Fiessler, 1978; Chen and Lind, 1983; Wu and Wirsching, 1987; Der Kiureghian and Liu, 1986) has been widely used due to its computational efficiency. As a useful byproduct, the method also provides importance measures (ranking) of random variables relative to the failure probability. The specific FORM algorithm offered in STRUREL is based on Rackwitz and Fiessler (1978), which is now a standard approach. This

FORM is used to locate the most probable point (MPP), or β-point, on the failure surface (g_0=0). The method produces exact failure probability in cases where failure surface is a (hyper-) plane (in standard and independent normal space). Accurate results can be obtained in cases where the curvature of failure surface at the MPP is small or moderate. Preliminary tank car reliability analyses, however, have clearly demonstrated that the failure surface is highly nonlinear. To reduce the nonlinearity, the following equivalent performance function (logarithmic transformation of Eq.(7) is used:

$$g = Ln(N_P) - Ln(N_D) \tag{10}$$

Furthermore, after locating the β-point using FORM, importance sampling (Hohenbichler and Rackwitz, 1988) is performed based on the β-point information to improve the accuracy of the FORM solution. This approach allows arbitrarily accurate solutions to be obtained as more and more importance samples are used. This work used 75~150 importance samples in most of the cases, which generally gives a failure probability with a coefficient of variation less than 15 percent, which is considered reasonable for illustrating the methodology.

4.4 Results and Discussion

To illustrate the fatigue reliability analysis methodology, probabilistic analyses are performed using the random variables given in Table 6, along with parametric studies for the deterministic parameter, S_r. Five different values are considered for residual stresses, S_r. They are S_r = 0 (no residual stresses), 3.24, 6.47, 10.9, and 15.33 ksi (22.3, 44.5, 75, and 105.5 MPa, respectively). The residual stress effect is considered by applying a mean load of Q_r = 3.8, 7.6, 12.8, and 18 kip in the load spectrum. This mean load is determined such that it corresponds to a tensile residual stress given above.

Figure 25 shows the probability of failure, P_f, as a function of mileage traveled for the four cases considered. Instead of using the number of load cycles, the usage is expressed as a number of passes through the tank car spectrum that represents 10,000 miles of service. Figure 25 clearly shows the following:

- In all the cases, P_f increases as mileage increases.
- Welding residual stress can significantly increase $P_{f.}$
- The residual stress effect on P_f tends to saturate above S_r = 10.9 ksi (75 MPa), which corresponds to a load level of Q_r = 12.8 kip in the downward VCF spectrum.

The saturation behavior is related to the R-ratio cutoff effect of the material. The saturation behavior observed from the analysis has a practical implication that post-weld heat-treatment for reducing welding residual stresses can be effective in increasing fatigue crack growth resistance only if it reduces the residual stresses to well below the saturation level. The residual stress saturation level depends on load spectrum and stationary (non-alternating) stress distribution, as well as materials' R-ratio cutoff values.

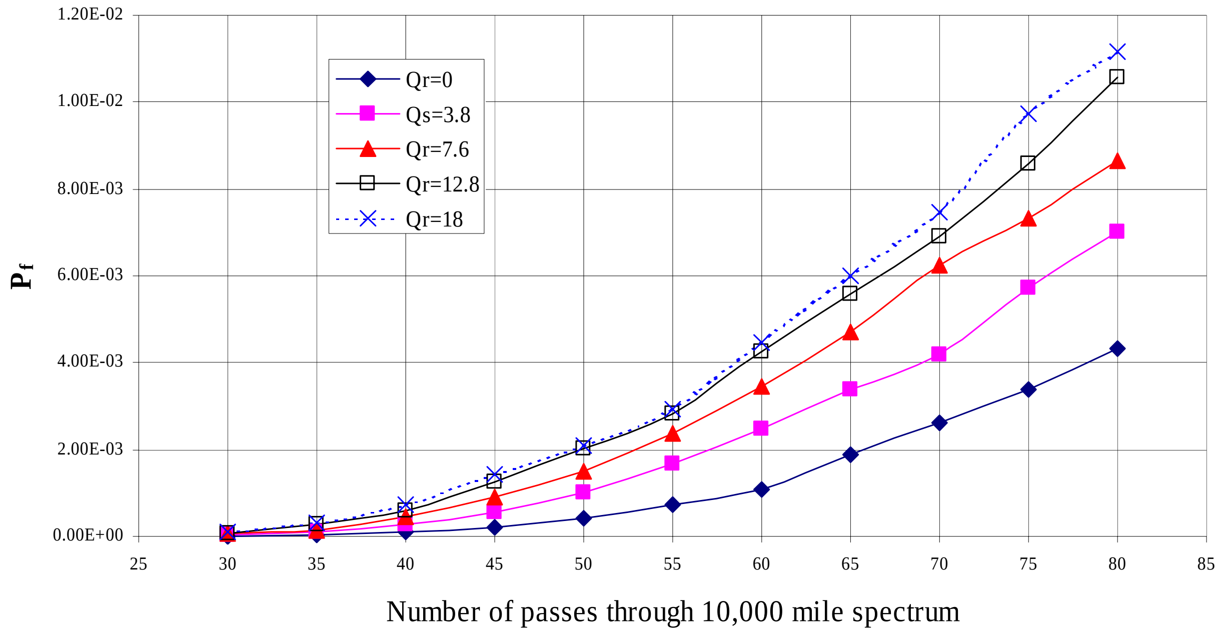

Figure 25. Failure probability versus mileage for the five different values of the welding residual stresses

The information provided in Figure 25 should be useful in managing risk. For example, inspections and repairs can be scheduled at a certain mileage interval to satisfy a given target reliability (reliability = $1-P_f$).

In DTA (Cardinal, et al., 1998; Zhao, et al., 2000; Zhao and Sutton, 2001), all parameters are deterministic. To be conservative, a common practice is to use upper bound values for loads and lower bound values for material properties. Figure 26 compares the effect of assuming S_{uf} as (a) a random variable of $N(\mu, \sigma)$ with mean $\mu = 1$ and standard deviation $\sigma = 0.08$ and (b) a deterministic parameter with three different values equal to μ, $\mu+2\sigma$, and $\mu-2\sigma$. In this case, it can be seen that assuming an upper bound value ($\mu+2\sigma$) for S_{uf} is overly conservative, while using mean value of S_{uf} will be unconservative. In other words, adopting a reliability approach may reduce the conservativeness while still maintaining adequate reliability, thus reducing the life cycle cost.

Figure 26 also shows the results obtained using Monte Carlo simulation (5000~9000 samples) for $S_{uf} = 1.16$. Good agreement observed between Monte Carlo and FORM, plus importance sampling, provides additional verification that the FORM, plus importance sampling, produced correct results in the case of the highly nonlinear performance function analyzed.

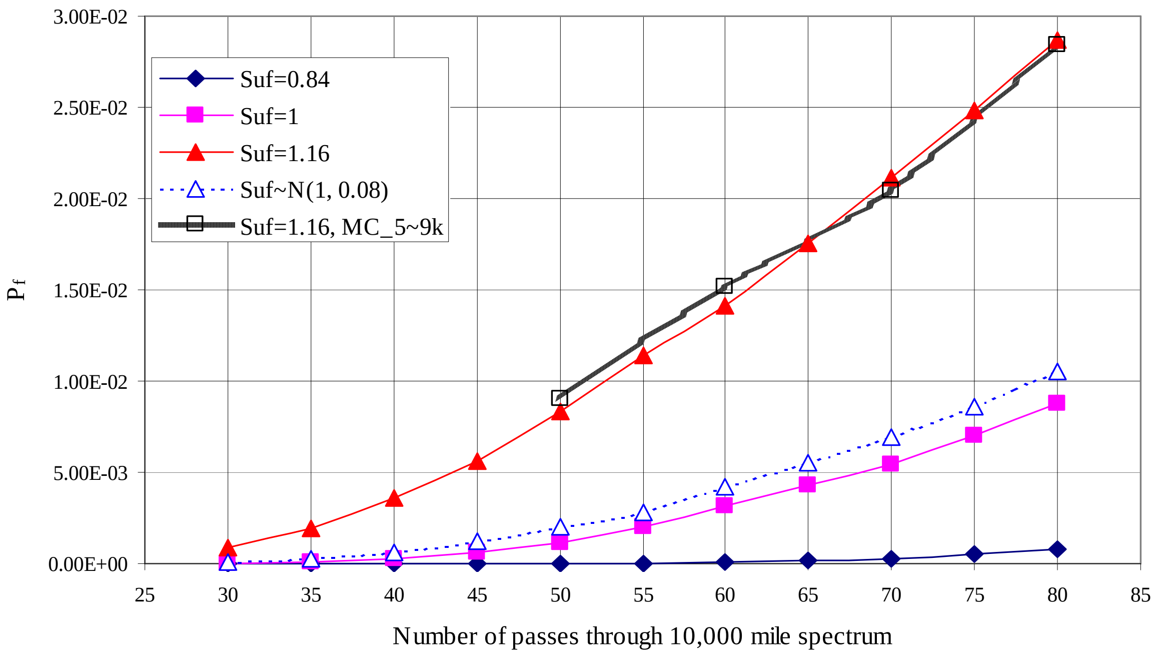

Figure 26. Comparison of stress uncertainty factor as a random variable and as a deterministic parameter with three different values

In the above analyses, all the random variables are assumed to be independent. In reality, the initial crack depth, a_0, and the initial crack aspect ratio, $(a/c)_0$, are probably correlated, such that a crack with a larger surface length will be shallower (a larger *c* corresponds to a smaller *a*). For example, a crack initiating from weld porosity may have a smaller surface length and a larger aspect ratio, while a crack initiating from a weld undercut may have a larger surface length but a smaller aspect ratio. Thus, a_0 and $(a/c)_0$ may be positively correlated. As an illustrative example, the study considered two correlated cases between a_0 and $(a/c)_0$, with a correlation coefficient of 0.25 and 0.5, respectively (i.e., $C_c[a_0, (a/c)_0] = 0.25$ and 0.5). Figure 27 compares results with and without correlations. All three cases have residual stresses. The solid symbols are for the case without correlation. The open ones are for the cases with correlation. It is clear that correlation between a_0 and $(a/c)_0$ has a significant effect on the failure probability, even in a weakly correlated case ($C_c = 0.25$, triangles).

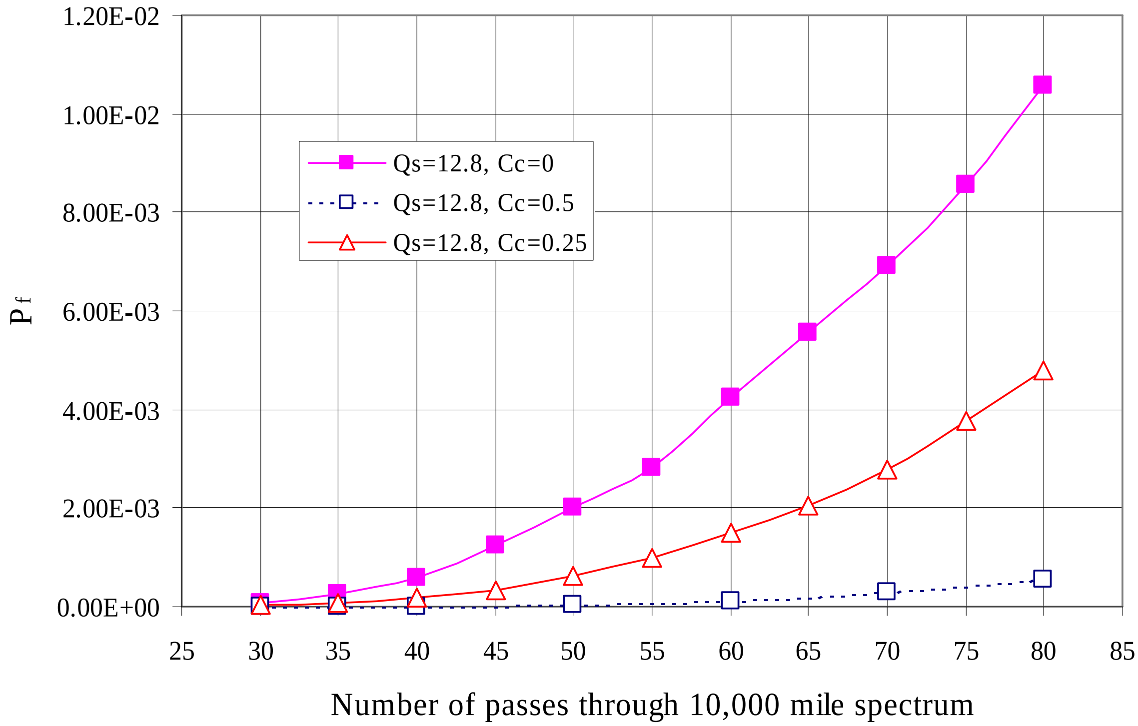

Figure 27. Comparison of failure probabilities with and without correlation between initial crack depth and initial crack aspect ratio

The positive correlation reduces P_f significantly because the chances to have simultaneously long and deep surface cracks are reduced. Figures 28 and 29 show this where samples for a_0 and $(a/c)_0$ from Monte Carlo simulation (5000 samples) are compared between correlated and uncorrelated cases. The correlation effect boils down to the fact that SIF is a function of both crack depth and crack aspect ratio.

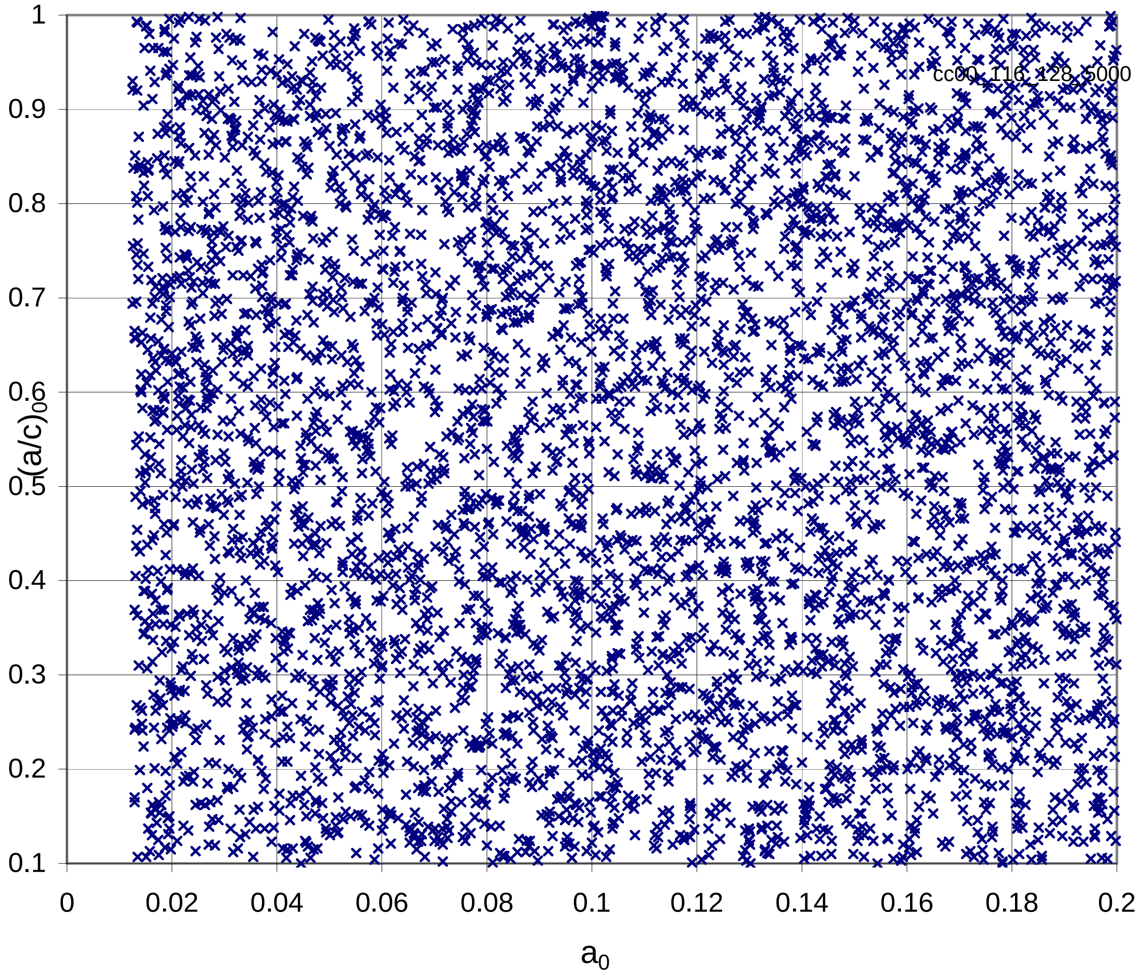

Figure 28. Samples for a_0 and $(a/c)_0$ from Monte Carlo simulation (5000 samples), (a) $C_c[a_0, (a/c)_0] = 0$

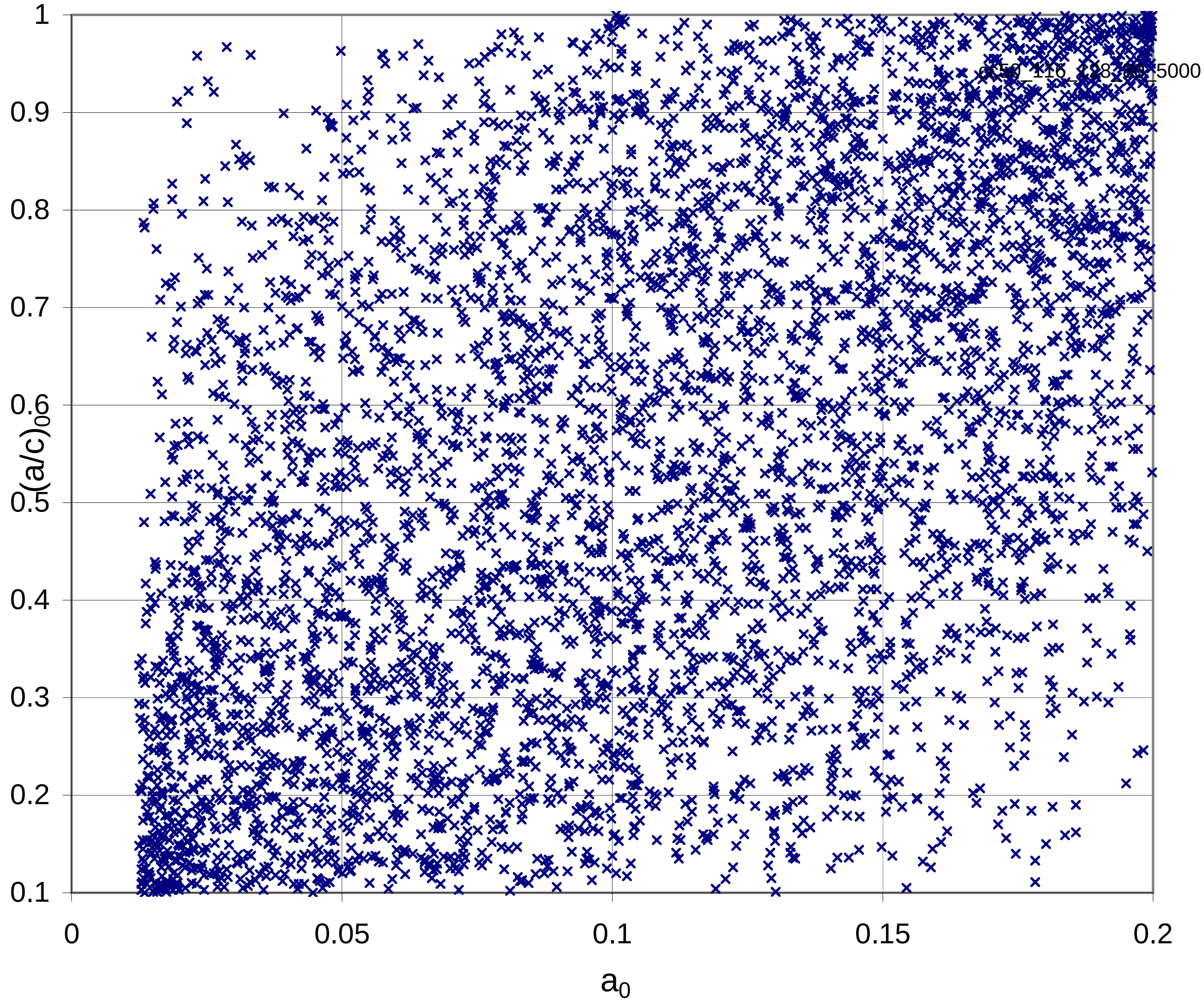

Figure 29. Samples for a_0 and $(a/c)_0$ from Monte Carlo simulation (5000 samples), (b) $C_c[a_0,(a/c)_0] = 0.5$

Though considered as deterministic parameters in the above analysis, S_r and other parameters can be easily treated as random variables. Different probability density distributions, or distribution parameters, can also be considered for the variables listed in Table 6, so that the effects of distribution types and parameters on the failure probability can be studied. In this regard, the sensitivity measures obtained as a byproduct of FORM can provide guidance in determining the relative importance of random variables on failure probability. Figure 30 shows such an example, which is for $Q_r = 7.6$ kip. In the order of decreasing importance (sensitivity) of the six random variables to the failure probability, they are $(a/c)_0$, a_0, S_{uf}, C, R_{co}, and e_0. In fact, based on the information that the sensitivity of P_f to e_0 is nearly zero, e_0 may well be treated as a constant, instead of as a random variable. The information is of practical interest in design because the effect of changing design variables on P_f can be evaluated.

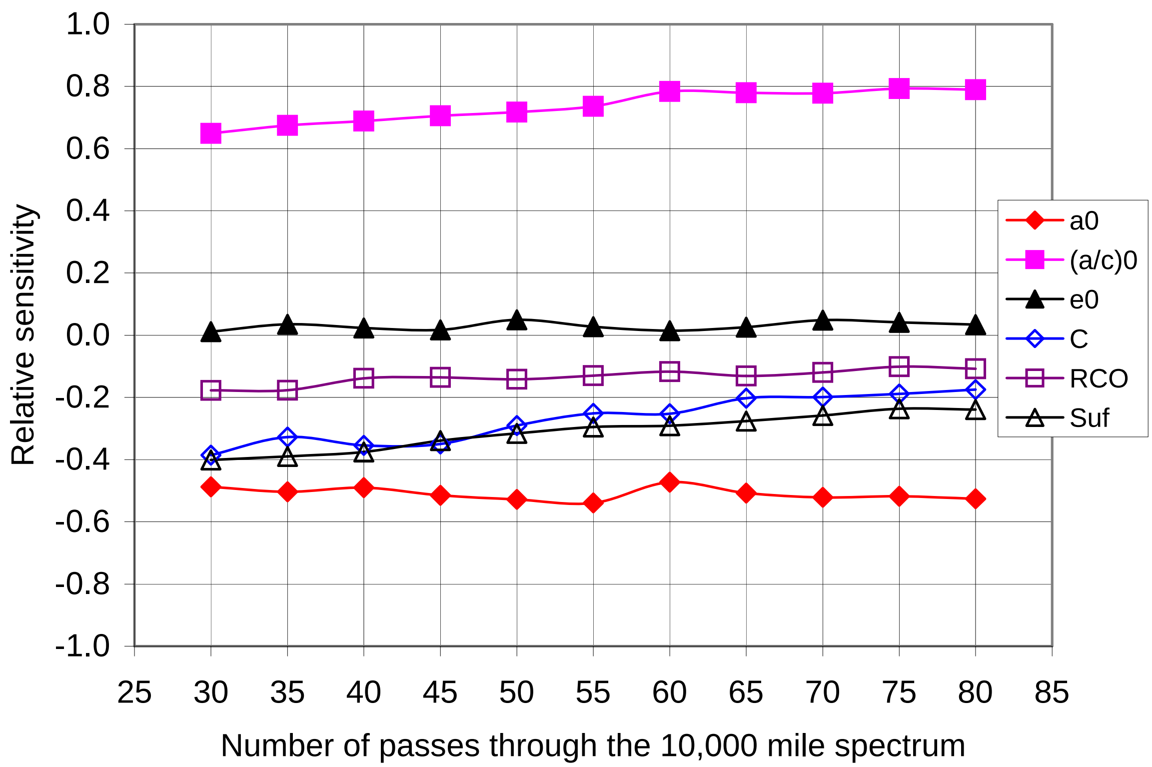

Figure 30. Relative sensitivities of P_f to the basic random variables

Finally, the Walker equation is implemented for a 3-dof surface crack. Other crack growth laws and crack configurations can be added in parallel to the existing models. For example, by utilizing the weight function methods (Zhao, et al., 1997a; Zhao, et al., 1997b; Wu and Carlsson, 1991), various 2D and 3D cracks can be efficiently analyzed.

4.5 Concluding Remarks

A methodology for tank car fatigue reliability analysis is being developed that uses a commercial reliability analysis software, STRUREL, for the reliability analysis, while incorporating FORTRAN routines to perform fatigue crack growth analysis with the Walker crack growth law for a 3-dof surface crack.

Feasibility of using the commercial reliability software for tank car fatigue reliability analysis is demonstrated. The methodology is versatile in dealing with a variety of random variables (with or without correlation) and capable of considering various features involved in tank car fatigue crack growth analysis, such as spectrum loading, residual stresses, and asymmetric, bi-variant stress field.

Results from the illustrative examples show that P_f increases as mileage increases, welding residual stresses can significantly increase $P_{f,}$ uncertainty in the stress amplitude has a significant effect on $P_{f,}$ and the correlation between initial crack depth and initial crack aspect ratio is an important parameter.

5. Conclusions and Future Work

5.1 Conclusions from the Corrosion and Fatigue Reliability Analysis

A method for tank car reliability analysis against corrosion has been developed. Lacking specific tank car corrosion data, a simplified corrosion model for the case of general corrosion is developed. The model includes basic features characterizing tank car general corrosion process.

Reliability analysis with assumed random variables and distribution parameters has been performed for a series of tank thickness, corrosion rates, and critical tank thickness, using the commercial reliability analysis software, STRUREL. The results show reasonable behaviors and trends for the effects of tank thickness, corrosion rates, and critical tank thickness.

The model and the method can be used to analyze specific tank car corrosion problems once the relevant data is available. Models for other forms of corrosion can also be developed once relevant tank car data is available.

A methodology for tank car fatigue reliability analysis is being developed that uses the commercial reliability analysis software, STRUREL, for the reliability analysis, while incorporating FORTRAN routines to perform fatigue crack growth analysis with the Walker crack growth law for a 3-dof surface crack.

The FORTRAN routines developed for the tank car fatigue crack growth analysis can be extended to include various other crack configurations and crack growth laws as more tank car material data becomes available.

Feasibility of using the commercial reliability software for tank car fatigue reliability analysis is demonstrated. The methodology is versatile in dealing with a variety of random variables (with or without correlation) and capable of considering various features involved in tank car fatigue crack growth analysis, such as spectrum loading, residual stresses, and asymmetric, bi-variant stress field.

Results from the illustrative examples of fatigue reliability analysis show that probability of failure, P_f, increases as mileage increases; welding residual stresses can significantly increase $P_{f;}$ uncertainty in the stress amplitude also has a significant effect on P_f; and the correlation between initial crack depth and initial crack aspect ratio is an important parameter.

The observed saturation behavior of the welding residual stress effect on fatigue crack growth life suggests that post-weld heat-treatment for reducing welding residual stresses can be effective in increasing fatigue crack growth life, but only if it reduces the residual stresses to well below the saturation level.

It is clearly demonstrated that the reliability analysis methodology developed in this work can be used to quantify probability of failure for tank cars. Use of the information on the quantified risk allows better risk management through informed decisionmaking on inspection, maintenance, and repair.

5.2 Future Work

Tank car corrosion failure mechanisms are manifold. It is of practical interest to develop reliability models for other forms of corrosion failure, such as pitting.

The possibility may exist that at certain stages and locations, fatigue crack growth will be accelerated by wall thinning effect due to tank car general corrosion. The current fatigue reliability model can be extended to incorporate the general corrosion effect.

System reliability models must be developed to consider multiple failure modes and multiple site damage. In fact, the two failure criteria, fracture and leakage, encountered in the fatigue reliability analysis, pose a system reliability problem in general.

What to do in response to a quantified level of risk depends on what is considered an acceptable risk. Therefore, risk criteria, or target reliability, must be developed for effective and consistent risk management.

To promote technology progress and improvement of tank car reliability, exploration should be made to find ways for industry to share detailed data on lading loss instances with the research community, without concerns of litigation issues, or negative impact on business as a result. This will allow specific reliability models to be developed to directly address various problems that the tank car industry is facing. In this way, technology transfer can be done more effectively, which, in turn, will effectively improve the reliability of railroad tank cars.

Reliability analysis method accounting for inspection and repair (both have their own uncertainties) needs to be developed, so that reliability models can be updated based on inspection and repair information, once available.

Some failures due to non-structure related NARs can also be studied for possible development of reliability analysis models. Since this failure category, though often involving small quantities, accounts for the majority of the lading loss cases, it is very important to the reduction of the total failure rate.

The reliability theory and solution methods used for the corrosion and fatigue reliability analysis are generally applicable to other systems and/or components of tank cars (e.g., linings, coatings, valves, pressure relieve devices, brake system). Therefore, reliability models can also be developed for such systems and components, if desired and data is available.

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Abbreviations and Acronyms

3D-WFM	three-dimensional weight function method
dof	degree-of-freedom
DTA	damage tolerance analysis
FCL	fatigue critical location
FEM	finite element method
FORM	first order reliability method
MPP	most probable point
PDF	probability density function
POO	probability of occurrence
NAR	non-accident release
RCM	reliability-centered maintenance
SIF	stress intensity factor
SR-NAR	structure-related non-accident releases
VCF	vertical coupler force