PHASE I LITERATURE SEARCH AND EVALUATION

U. S. Department
of Transportation

**Federal Railroad
Administration**

Office of Research and
Development
Washington, D. C. 20590

DOT/FRA/ORD-No number assigned May 1997

DISCLAIMER

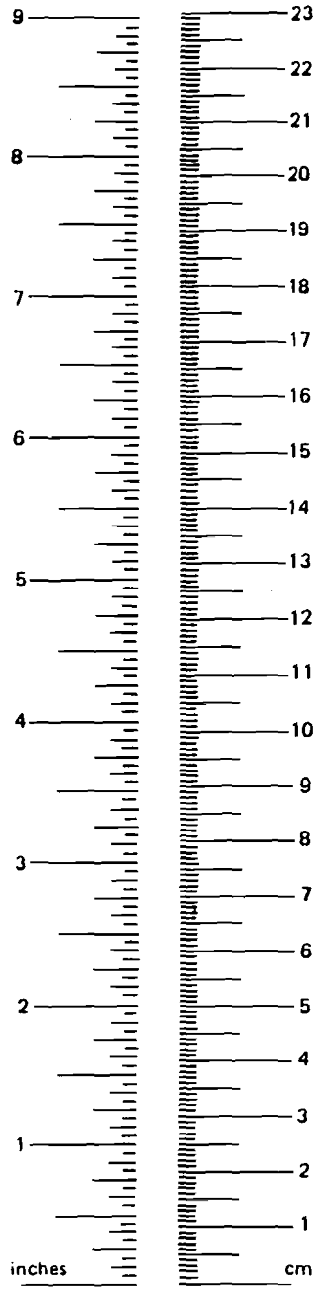
This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof. The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

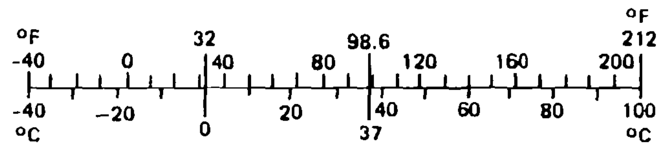
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km
		AREA		
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	m^2
mi^2	square miles	2.60	square kilometers	km^2
	acres	0.40	hectares	ha
		MASS (weight)		
oz	ounces	28.00	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.90	tonnes	t
		VOLUME		
tsp	teaspoons	5.00	milliliters	ml
Tbsp	tablespoons	15.00	milliliters	ml
fl oz	fluid ounces	30.00	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.80	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in. = 2.54 cm (exactly)



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.40	inches	in
m	meters	3.30	feet	ft
m	meters	1.10	yards	yd
km	kilometers	0.60	miles	mi
		AREA		
cm^2	square centim.	0.16	square inches	in^2
m^2	square meters	1.20	square yards	yd^2
km^2	square kilom.	0.40	square miles	mi^2
ha	hectares ($10{,}000\ m^2$)	2.50	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.10	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36.00	cubic feet	ft^3
m^3	cubic meters	1.30	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32	Fahrenheit temperature	°F



1. Report No. FRA/ORD (no report number assigned)	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Phase I Literature Search and Evaluation		**5. Report Date** May 1997
		6. Performing Organization Code
7. Authors K. Scott Pieratt, Jeffery C. Davis, J. Giovanola, and D. Shockey		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Association of American Railroads, Transportation Technology Center, P. O. Box 11130, Pueblo, CO 81001		**10. Work Unit N o. (TRAIS)**
		11. Contract or Grant No. Contract No. DTFR 53-93-C-00001
12. Sponsoring Agency Name and Address U. S. Department of Transportation, Federal Railroad Administration, Office of Research and Development, 400 Seventh Street, SW, Washington, D. C. 20590		**13. Type of Report or Period Covered** Formal
		14. Sponsoring Agency Code
15. Supplemental Notes		

16. Abstract

The Association of American Railroads, Transportation Technology Center is conducting a research project titled, "Damage Assessment of Tank Cars Involved in Accidents." Phase I of the project evaluated the validity of guidelines currently used to assess the severity of damage to pressure tank cars caused by derailments.

A search of the technical literature was performed and subsequently evaluated to identify which of the guidelines can be validated and which require additional modeling and validation in the Phase II effort. In this report and accompanying appendices, the results of the literature search and evaluation are presented and recommendations for the Phase II research are made.

17. Key Words Tank Cars, Damage Assessment, Guidelines		**18. Distribution Statement** None	
19. Security Classification *(of the report)*	**20. Security Classification** *(of this page)*	**21. No of Pages** 57	**22. Price**

Form DOT F 1700.7 (8-72)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYM LIST

FRA	Federal Railroad Administration
AAR	Association of American Railroads
TTC	Transportation Technology Center
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
SRI	Stanford Research Institute
NTIS	National Technical Information Service
DTIC	Defense Technical Information Center
FEA	Finite Element Analysis
HAZ	Heat Affected Zone
LPG	Liquified Petroleum Gas
SGFAS	Slide Graph Fracture Analysis System
LEFM	Linear-Elastic Fracture Mechanics
EPFM	Elastic-Plastic Fracture Mechanics
NDT	Nil Ductility Temperature
NDE	Non-destructive Evaluation
HRC	Hardness Rockwell C Scale
CTOD	Crack-tip Opening Displacement

1.0 INTRODUCTION

Under Federal Railroad Administration (FRA) Contract No. DTFR 53-93-C-00001, Task Order 115, the Association of American Railroads (AAR), Transportation Technology Center (TTC) is conducting a research project titled, "Damage Assessment of Tank Cars Involved in Accidents." Phase I of the project will evaluate the validity of guidelines currently used to assess the severity of damage to pressure tank cars caused by derailments.

In February 1993, the AAR/TTC produced a handbook on emergency response titled, *Field Product Removal Methods for Tank Cars*. The handbook was developed for the FRA under contract DTFR 53-82-C-00282, Task Order 31, and was produced for emergency response personnel who deal with tank cars carrying hazardous materials that have been damaged in accidents. The publication and subsequent use of this handbook has pointed to the need for a companion handbook that identifies proven and reliable damage assessment procedures.

Since 1985, the AAR/TTC and other organizations have used a set of guidelines developed by the AAR in the late 1970's to teach emergency response personnel how to make judgements in the field as to the severity of damage to tank cars involved in accidents. These guidelines were developed to help emergency responders decide when tank cars carrying hazardous materials shipped under pressure can be safely rerailed, unloaded in place, or whether nature should be left to take its course.

Recently, the guidelines were reviewed to determine how or if they were validated. After consulting with experts in the tank car, railroad, and chemical industries, it has been determined that the guidelines were developed by several individuals who are no longer available to substantiate them. To better ensure the safety of emergency response personnel and the public-at-large, responders need some sound, qualitative evaluation techniques which they can safely and reliably use to make these decisions. Compiling this information in an easy to understand handbook to assist emergency response personnel make critical decisions is an important effort that will significantly improve the safety of such operations.

Phase I of the project focuses on evaluating the technical foundation for the guidelines. A search of the technical literature was performed and subsequently evaluated to identify which of the guidelines can be validated and which require additional modeling and validation in the Phase II effort. In this report and accompanying attachments, the results of the literature search and evaluation are presented and recommendations for the Phase II research are made.

2.0 OBJECTIVES

In an attempt to gather pertinent information that would assist in the assessment and validation of the current pressure tank car damage assessment guidelines, the Phase I work was designed to accomplish the following:

- Compile current guidelines for pressure tank car damage assessment.
- Survey individuals from various entities including major railroads, chemical shippers, government agencies, etc., to acquire additional information that might aid in the evaluation of the current damage assessment guidelines.
- Search the technical literature for previously published research, rules, regulations, guidelines and recommended practices which are, or may be applicable to pressure tank cars.
- Review the relevant material identified in the literature search and evaluate to determine if the literature can validate the guidelines.
- Write a report that includes a technical discussion of the applicable portions of the literature that validate the current guidelines and identify areas where additional modeling and validation will be required.
- Circulate the report for review and comment to selected individuals previously surveyed.
- Prepare and submit to FRA a Final Phase I Report which documents the work performed under Phase I, identifies the conclusions drawn, and makes recommendations for modeling and work necessary to validate the guidelines.

3.0 PROCEDURES

The following subparagraphs will identify the procedures used to gather the information presented in this section. These procedures included the collection of current guidelines, administration and evaluation of an industry and government survey, and the identification of methods used to perform the literature search.

3.1 GUIDELINES

While pressure tank cars transporting compressed gases can sustain extensive damage in derailments without releasing their contents, delayed failures are possible and have occurred. During this delay, response personnel are likely to have begun derailment clearing operations, and consequently, risk death or injury should the tank fail.

In the late 1970's, damage assessment guidelines were developed to help emergency response personnel make critical decisions whether tank cars damaged in derailments could be safely up righted and transported (either on their own trucks or on flat cars) for unloading or whether they must be unloaded in place. While these guidelines have been used safely for some years, there is no clear record of what methodology was used to establish the guidelines, and their primary author is no longer available to provide that information.

The following information identifies the specific tools (guidelines) which were extracted from the AAR/TTC Hazardous Materials Training Center *Tank Car Safety Course Manual*, as found in Reference 110 in the bibliography. The glossary found in Section 6.0 of the manual contains definitions of key terms found in this section.

- A crack in the tank base metal indicates serious damage. Cracks in welds used to attach brackets or reinforcement plates are not critical unless the crack extends into the base metal.
- Any crack found in the base metal of a tank, no matter how small, justifies unloading the tank as soon as possible. However, if in a yard, the car may be carefully moved to a designated remote location in the yard for transfer.

- When a crack is in conjunction with a dent, score or gouge, the tank should be unloaded as soon as possible without moving it.
- Scores or gouges crossing a weld and removing only the weld reinforcement are not critical.
- Longitudinal scores are the most dangerous. However, circumferential scores cannot be ignored, for at any given section such scores also constitute a longitudinal notch.
- Longitudinal scores or gouges crossing a weld and affecting the heat affected zones are critical and the contents of the tank car should be transferred immediately.
- Tanks having scores or gouges should be unloaded in place when the internal pressure exceeds half of the allowable internal pressure listed in the tables which follow. Tables 1 and 2 show the allowable pressures for 340W and 400W tanks respectively.

Table 1: Limiting Score Depths for 340W Tanks

Depth of Score	Maximum Safe Internal Pressure, PSIG
1/16"	191 (89°F for commercial propane)
1/8"	170 (85°F for commercial propane)
3/16"	149 (76°F for commercial propane)
1/4"	127 (65°F for commercial propane

Note: In no case should a tank containing a score in excess of 1/16 inch for 340W tanks be shipped by rail, although the tank could be uprighted and even moved short distances for product transfer.

Table 2: Limiting Score Depths for 400W Tanks

Depth of Score	Maximum Safe Internal Pressure, PSIG
1/16"	228 (108°F for commercial propane)
1/8"	205 (99°F for commercial propane)
3/16"	188 (93°F for commercial propane)
1/4"	162 (82°F for commercial propane)

Note: In no case should a tank containing a score in excess of 1/8 inch for 400W tanks be shipped by rail, although it could be uprighted and even moved short distances for product transfer.

While the values given in Tables 1 and 2 are conservative, they do not include the welded joint efficiency for tanks built prior to 1968. This amounts to an extra 10 percent safety factor.

- If the maximum depth of a wheel burn exceeds 1/8 inch, the tank should be unloaded as soon as possible. If the depth of the wheel burn is less than 1/8 inch, the tank should be emptied at the closest loading facility, provided it is moved with care; not in ordinary train service.

- Sharp dents in the shell of the tank (cylindrical section) which are parallel to the long axis are the most serious as these dents drop the rating of the tank by 50 percent.

- For dents in the shell of tank cars built prior to 1967, the tank should be unloaded without moving it under the following conditions:

  - A minimum radius of curvature of 4 inches or less
  - Have a crack anywhere
  - Cross a weld
  - Include a score or gouge

  Dents with a radius of curvature more than 4 inches are not a problem by themselves.

- For dents in the shell of tank cars built since 1967, the tank should be unloaded without moving it under the following conditions:

  - A minimum radius of curvature of 2 inches or less
  - Have a crack anywhere
  - Cross a weld
  - Include a score or gouge
  - Show evidence of cold work

  Dents with a radius of curvature more than 2 inches are not a problem by themselves.

- Massive dents in heads of the tank are generally not serious unless gouges or cracks are present with the dents.

- Small dents in heads not exceeding 12 inches in diameter in conjunction with cold work in the bottom of the dent are **marginal** if they show a radius of curvature less than 4 inches for tanks built prior to 1967 or less than 2 inches for tanks built since 1967. If at all possible, such tanks should be unloaded in place. In any case, the tank should be moved as little as possible and promptly unloaded.

3.2 SURVEY

A survey was designed, constructed, and administered by the AAR/TTC in May 1995 in an attempt to acquire additional information that might aid in the evaluation of the current damage assessment guidelines. The survey was sent to various representatives of the FRA, National Transportation Safety Board, Canadian Transportation Safety Board, National Research Council of Canada, Transport Canada, AAR, Railway Progress Institute/Association of American Railroads (RPI/AAR) Tank Car Safety Research Project, major railroads, chemical shippers, tank car manufacturers, and others who are or were previously associated with the railroad industry that may have knowledge pertinent to this project. Fifty surveys were sent to representatives of the above referenced entities. Of the 50 surveys sent, 30 responses were received, representing a 60 percent return of the total surveyed. The survey administered and the responses received are summarized below. At the request of several respondents, attribution is not given on direct quotes.

1. **Are you aware of any previously published research, rules, guidelines, or recommended practices which are, or may be applicable to the evaluation of the current guidelines for assessing the severity of damage to pressure tank cars?**

   The responses received were incorporated into the bibliography of references provided to the subcontractor for review during the literature search. Below is a summary of the literature identified by survey respondents.

   - "Phase 18 Study: Integrity of Damaged Tank Cars," Association of American Railroads, Chicago, Illinois (publication date unknown).
   - AAR *Standards and Recommended Practices*, Sec. C - Part III, Specifications for Tank Cars, Specification M-1002.
   - L. S. Beller, J. D. Mudlin, W. G. Reuter, and M. A. Tupper, "Survey of Non-destructive Methods for Evaluating Derailed Tank Cars," US Army Ballistic Research Laboratory Contract Report BRL-CR-539 (November 1984).

- J. L. Hechmer and G. L. Hollinger, "The ASME Code and 3D Stress Evaluation," *Journal of Pressure Vessel Technology*, 113, 481-487 (November 1991).

- National Transportation Safety Board, "Derailment of Burlington Northern Freight Train No. 01-142-30 and Release of Hazardous Materials in the Town of Superior," Hazardous Materials Accident Report NTSB/HZM-94/01, Notation 5842B, Washington, DC (March 1994).

- National Transportation Safety Board, "Derailment of Louisville and Nashville Railroad Company's Train No. 584 and Subsequent Rupture of Tank Car Containing Liquefied Petroleum Gas, Waverly, Tennessee," Railroad Accident Report No. NTSB-RAR-79-1, Notation 2313B, Washington, DC (February 22, 1978).

- National Transportation Safety Board, "Special Investigation Report: Tank Car Structural Integrity after Derailments," Bureau of Technology, Report No. NTSB-SIR-80-1, Washington, DC (1980).

- E. A. Phillips and W. A. Pellini, "Phase 03 Report on Behavior of Pressure Tank Car Steels in Accidents," Association of American Railroads, Report No. RA-03-6-48 (June 20, 1983).

- E. A. Phillips and H. Role, "Effectiveness of Shelf Couplers, Head Shields and Thermal Shields on DOT 112 (114) and 105 Tank Cars," Association of American Railroads, Report No. RA-02-5-51 (AAR R-610), Chicago, Illinois (June 13, 1985).

- K. Rahka, "The Anatomy of a Break Before Leak Case," ASME PVP-Vol. 281, *High Pressure Technology*, ASME, 49-54 (1994).

- W. G. Reuter, J. D. Mudlin, R. L. Harris, F. M. Haggag, W. L. Server, and J. S. Epstein, "Evaluation of Damaged Tank Car Structural Integrity," Department of Transportation, Federal Railroad Administration, Office of Research and Development Report DOT/FRA/ORD-88/02 (January 1988).

- Z. Rosenberg, J. Mironi, A. Cohen, and P. Levy, "On the Catastrophic Failure of High-Pressure Vessels by Projectile Impact," *Int. J. Impact Engng.*, 15(6), 827-831 (1994).

- D. K. Shaver, and R. L. Berkowitz, "Guideline Manual, Post Accident Procedures for Chemicals and Propellants," Air Force Rocket Propellant Laboratory Report AFRPL TR-82-077 (January 1983).

- D. K. Shaver, R. L. Berkowitz, and P. V. Washburne, "Accident Management Orientation Guide," Air Force Rocket Propellant Laboratory Report AFRPL TR-82-0075 (October 1983).

- Tank Car Fatigue Crack Growth Test, DOT/FRA/ORD - 93/10.

2. **Do you have any knowledge of unexpected behavior of damaged pressure tank cars that would aid AAR/TTC in evaluating the current tank car damage assessment guidelines?**

- Report RA-03-6-48, Phase 03 Report on Behavior of Pressure Tank Car Steels in Accidents, 6/20/83. The reports cited delayed ruptures in two separate incidents at Cumming, Iowa and Waverly, Tennessee.

- Vinyl Chloride car exploded in Livingston, Louisiana.

- Vinyl Chloride car failed following accident in Flomaton, Alabama, May 1995.

- Several other respondents indicated yes to the questions, however, no specific incidents were noted.

3. **Are you aware of any three-dimensional, finite element computer modeling work that has been done to simulate the behavior of damaged tank cars or pressure vessels (particularly under load)?**

- Transport Canada has developed a complete tank car Finite Element Analysis (FEA) model. Other models have or are being developed as part of a stub sill study being performed in conjunction with the Tank Car Research Committee.

- Battelle may have done an FEA of a tank car.

- Specific packages or companies with capabilities included: NIKE2D, NASGRO, NASCRAC, CRACKS 94, FM, PFRAC, Failure Analysis Associates, and Transoft, Inc.

4. **Are you familiar with the methodology Roy Holden used to develop the current tank car damage assessment guidelines?**

- One respondent indicated that the guidelines may have been based upon coupon samples that were taken from damaged tank cars and from tank cars that had failed.

- Several respondents indicated that the guidelines were developed primarily through the experience Mr. Holden gained attending derailments.

- Another respondent indicated that, through discussions with Mr. Holden, it was indicated that the guidelines were developed from engineering calculations (conservative) with an added "safety" factor.

5. Did you assist Mr. Holden in the development of the current guidelines?

- Several indicated that they had assisted Mr. Holden. Many of those indicated that they were involved in discussions with Mr. Holden regarding the guidelines.

6. Did Mr. Holden consult with you during the development of the current guidelines?

- Response the same as in Question 5.

7. Do you know of anyone that worked with Mr. Holden in the development of the guidelines?

- Gene Kunz
- W. J. Ruprecht
- George Binns
- Mike Miller
- E. A. Phillips
- Pat Student
- Ted Orr

8. Do you have any reason to suspect that the current tank car damage assessment guidelines published by the AAR/TTC may not be reliable?

- One respondent indicated that the guidelines were out of date. "No mention is made of normalized steels mandated in the mid-1980s, and it contains some errors and omissions."

9. Do you have any reason to believe that the current guidelines may be too conservative?

Only two respondents indicated that they felt that the guideline may be too conservative. Their responses are as follows:

- "The descriptions of some of the damage types are not specific enough and to some extent are in error."
- "In today's environment, damaged tank cars are seldom moved when loaded, especially if hazardous materials are involved."

10. In your opinion, do the current tank car damage assessment guidelines published by the AAR/TTC meet the needs of emergency response personnel?

Most respondents indicated that, in their opinion, the current damage assessment guidelines do meet the needs of emergency response personnel. The following comments were supplied by those who did not agree.

- "Secure the advice of someone with tank car experience...is vague. The appropriate contacts are the designated shipper and carrier emergency response personnel."
- "The guidelines should be reviewed and definitions revised to meet the current regulations. Fractures and creases should also be discussed in greater detail."
- "They point a direction, but if this is all emergency response personnel have to go on, people are going to get hurt."

11. What other topics of concern to emergency response personnel would you like to see addressed by the guidelines?

- What lifting configurations can responders use to safely lift, roll, or drag a damaged pressure tank car considering different damage types and locations of damage.

- Responders are concerned over the inability to apply the damage assessment guidelines to jacketed tank cars short of physically removing the jacket. By removing the jacket using a cutting torch or other mechanical means, the responder may be introducing additional hazards that raise critical safety concerns.

- The guidelines should address what conditions responders should look for that may contribute to the delayed failure of a tank car.

- Responders would like to see a means of remotely inspecting a damaged tank car to assess the criticality of damage (i.e. Non-Destructive Evaluation techniques).

- "Responders need guidelines to perform damage assessment on general service tank cars."

- "Engineering calculations and data verification must be performed on current guidelines and then a statistical margin of safety must be added to the findings."

- A concern was raised over the affect of damage to pressure relief systems and applicability of guidelines under these conditions.

- Several comments identified a need within the guidelines for training requirements and available resources.

- "The guidelines do not appear to address the current problem of fatigue in the stub sill tank cars."

- "Fractures and creases are not discussed in great enough detail in the current guidelines."

- What effect does the increasing age of the tank car fleet have with respect to application of the guidelines (i.e. double diameter tank cars built in early 1960s).

Several respondents also identified concerns that may not be appropriate to cover within this handbook, but more appropriately under the handbook titled, *Field Removal Methods for Tank Cars.* The comments are included here merely as information.

- Responders need a tool or method to dislodge or move the excess flow check valve on pressure tank cars in order to allow responders to remove the liquid without moving a severely damaged tank car.

- "Liquid flaring of LPG from tank cars should be addressed identifying the limitations, capabilities, and advantages of the technique." This topic was covered in the Field Removal Methods for Tank Cars handbook. However, more study would be required to fully address this individual's concerns.

3.3 LITERATURE SEARCH METHODS

T. objective of the literature search was to identify technical literature from previously published research, rules, guidelines, and recommended practices which are, or may be applicable to pressure tank cars or pressure vessels. Several methods were employed to perform this search. These included searches of catalog files for applicable documents from AAR libraries in Chicago, Pueblo and Washington, national and international computer searches of various libraries, technical information services, and professional organizations, as well as responses from surveys sent to various government and industry representatives. The search was performed by both AAR and subcontract personnel hired to assist with the search and review of the information.

3.3.1 Institutions and/or Sources Investigated

Using advances in computer technology to perform literature searches allowed the AAR to search for applicable documents in numerous locations. Many libraries were searched, including AAR libraries in Chicago, Pueblo, and Washington, University of Colorado, Colorado School of Mines, Colorado State University, and other nationally known libraries. Computer searches were also made of the Technical Research Information Services, Engineering Index databases, National Technical Information Service (NTIS), Defense Technical Information Center (DTIC), ASME Journal of Pressure Vessel Technology and conference proceedings of the ASME Pressure Vessel and Piping Division. Survey respondents were also a useful source of identifying technical literature and other contacts.

3.3.2 Bibliography of Literature Reviewed

A bibliography of literature reviewed during the Phase I portion of this project is contained in the Appendix A. References 1 through 33 were documents supplied to the subcontractor by the AAR. References 34 through 37 were obtained from NTIS and DTIC. References 38 through 76 were obtained through the Technical Research Information Services and Engineering Index databases. A review of the abstracts for these 39 references showed that the documents did not contain any substantially new information compared with the information in References 1 through 37. References 77, 79 through 85, and 89 were obtained through the ASME Journal of Pressure Vessel Technology. Reference 78 was from a recent conference proceedings of the Pressure Vessel and Piping Division of ASME. References 86 through 88, 90, and 92 through 109 were obtained from a bibliography established by the subcontractor over the years.

4.0 RESULTS

AAR/TTC retained a subcontractor with expertise in metallurgy, finite element analysis, and fracture mechanics to assist in the literature search and review of relevant material. Upon completion of the review, a report was prepared to document the methods by which materials were collected to discuss the applicable portions of the literature, to provide an assessment of the guidelines and the degree of validation, and to discuss their conclusions and recommendations for Phase II modeling and validation. Sections 4.1, 4.2, and 4.3 were extracted from the report titled, "Literature Search and Evaluation Pertaining to Damage Assessment of Tank Cars Involved in Accidents," prepared by Stanford Research Institute (SRI), International. These sections discuss the findings of the SRI evaluation.

4.1 ANALYSIS OF THE LITERATURE

After searching the literature, the identified references were sorted into five general categories, as indicated in Table 3. Some references are listed under more than one category. Although the largest number of references falls in the category "Structural and Fracture Analysis Methods," many of the references in this category do not deal specifically with tank cars.

Table 3: Scope of Literature Review

Category	Total No. of References	Specific References
Structural and fracture analysis methods	35	1, 2, 6, 30, 36-42, 77, 79-81, 82, 85, 87, 88, 90, 92-105, 106
Material properties and specifications	20	4, 5, 7, 11, 12, 21, 43-54, 83, 84
Tank car accident reports	25	3, 8, 13, 15, 23, 25, 26, 27, 29, 55-70
Tank car failure analyses	17	2, 9, 10, 14, 16, 17, 18, 19, 20, 24, 28, 31, 32, 76, 78, 86, 89
Miscellaneous	10	33-37, 71-75

After reading the AAR/TTC guidelines on "Tank Car Damage Assessment," SRI reviewed the identified references to:

- Retrace the genesis of the guidelines and determine on what basis they were established.
- Obtain physically accurate descriptions of the types of damage incurred by tank cars.
- Establish the failure scenarios that have resulted from tank car damage.
- Identify the analytical tools that have been used to explain tank car failures associated with accidental damage.
- Identify the loading and stress levels to which damaged tank cars may be subjected.
- Assemble information from other engineering fields that may be useful in assessing tank car damage.

4.1.1 Findings and Relationship to Guidelines

The literature reviewed did not specifically mention the establishment of the guidelines or indicate the basis on which they were established. SRI's review suggests that they may have been prompted by recommendations issued by the National Transportation Safety Board to the Association of American Railroads on August 30, 1978 (I-78-14, I-78-15, and I-78-16) and to the Federal Railroad Administration (FRA) in the Spring of 1979 (I-79-13), see Reference 26, Page 3. According to AAR personnel, the guidelines were developed by Roy Holden, former AAR Bureau of Explosives engineer, and were based on (1) experience gained attending derailments and (2) the inspection of specimens from damaged or failed tank cars.[91] The guidelines are discussed in some detail in Reference 34, which indicates the rationale for a few specific recommendations.

Most of the available fracture analyses for tank cars are based on the work of William S. Pellini, who, after a career at the Naval Research Laboratory, acted as a consultant to AAR for many years.[2,5,6,13,17-19,30,40] The guidelines appear to be based, at least in part, on these analyses. Mr. Holden reportedly interacted extensively with Mr. Pellini during the drafting of the guidelines.[91] References 2, 6, 17, and 30 give descriptions of Pellini's "Slide Graph Fracture Analysis System" (SGFAS), and of its use for the analysis of tank car failures and tank car safety.

The approach applies to structures made of low to medium strength carbon steels and operating on the lower shelf or the low transition region. It combines experimental data and service experience accumulated since the late 1940s with Linear Elastic Fracture Mechanics (LEFM) to establish (1) whether a freshly nucleated crack* will arrest before unstable catastrophic failure occurs, and (2) whether a pre-existing crack will initiate and lead to unstable fracture.[92-94]

Pellini used the SGFAS to develop guidelines for the fracture-safe and fatigue-reliable design of steel structures.[18,19] The historical evolution of these fracture guidelines is presented in Reference 6, pages 51-53. Pellini used the SGFAS to explain the good safety record of tank cars,

*In this report the terminology "nucleate a crack" is used to indicate the formation of a sharp macroscopic crack in a material that was previously pristine. SRI refers to "initiate a crack" as the process of extending a preexisting stationary sharp macroscopic crack (e.g. a fatigue crack) by increasing applied loads and/or displacements.

and the few occurrences of arrested or catastrophic brittle fracture (in particular, the two known cases of catastrophic **delayed** fracture in tank cars containing extensive rail burn damage).[2] Because it underlies many of the more recent safety studies undertaken by AAR, a short desciption of the SGFAS is given in the next section.

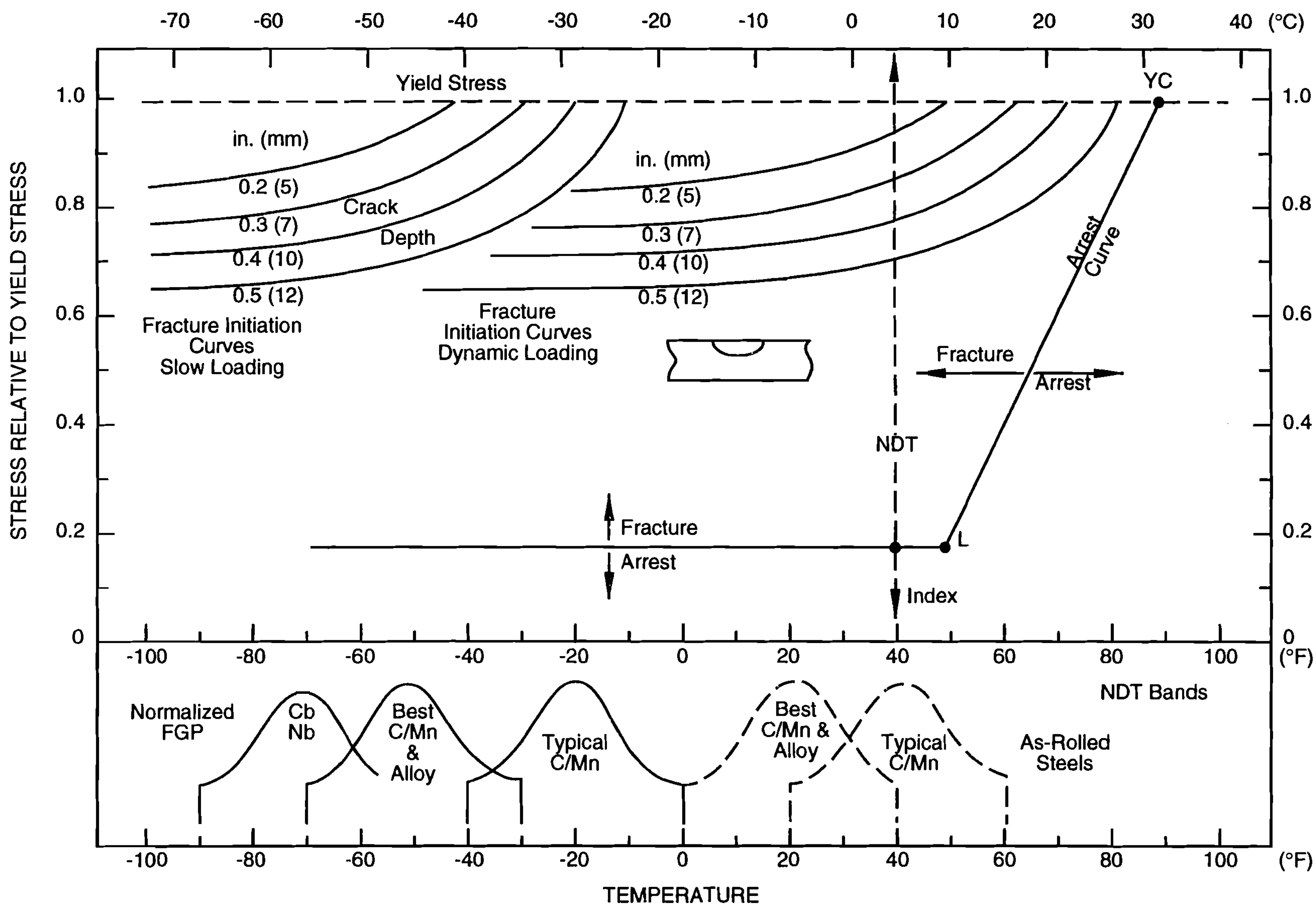
4.1.2 The Pellini SGFAS

Figure 1 illustrates Pellini's SGFAS. The abscissa plots a relative temperature scale and the ordinate plots the normalized applied stress. This graph is indexed with respect to the nil ductility temperature (NDT) of the steel considered for a specific structure. The crack arrest analysis is based on the concepts of NDT and fracture mode transition. Below the NDT, fracture occurs entirely by brittle microscopic cleavage, with the steel behaving essentially elastically on the macroscopic level. In the temperature range for fracture mode transition defined by

$$\mathrm{NDT} < T < \mathrm{NDT} + \Delta T \tag{1}$$

two microscopic modes of fracture coexist (brittle cleavage and ductile void growth), with the proportion of brittle cleavage gradually decreasing and the extent of macroscopic plastic deformation increasing with increasing temperature. Above the transition range, fracture occurs in a microscopically, fully ductile (void growth) mode. The material undergoes extensive macroscopic, plastic deformation (that is, the fracture driving stress is equal to or higher than the yield stress).

The NDT is established with such standard fracture tests as the drop weight test performed over a range of temperatures bracketing the transition region.[107] Pellini selected 50°F (28°C) as the value of ΔT for shells of thickness corresponding to the thickness range of tank cars (0.5 to 0.75 in. or 12.7 to 19.1 mm), based on experimental data and service experience. The points L and YC in temperature versus applied stress space define the crack arrest line.



CM-7483-1

Figure 1. Slide-graph analysis. (From Reference 6)

The index is located at the average NDT temperature for the old tank car steels.

According to the SGFAS, service conditions to the left of this line will lead to instability of a nucleated crack, whereas a crack nucleated for service conditions to the right will always arrest and lead to a leak-before-break situation.

The crack initiation part of the analysis is a straightforward application of LEFM to the case of a semi-elliptical surface crack. The effect of dynamic loading has been approximately accounted for by a shift in the toughness versus temperature curve toward higher temperatures.

Fracture safety evaluations with the SGFAS are made by entering in the graph of Figure 1 the service temperature relative to the NDT and the normalized service stress. This procedure is rather simple and requires very little stress analysis because, in most reviewed references, the service stress is taken as either the membrane hoop stress induced by the tank internal pressure or the yield stress. It also avoids the difficulties of dealing explicitly with fracture in the transition region and under elastic-plastic or fully plastic conditions. SGFAS is therefore a useful engineering design tool, even though it is somewhat qualitative and is based on fracture experience and theories dating back to the early 1970s. Since then, several significant advances were made in the field of fracture mechanics that could be applied to the assessment of damaged tank cars. This point vill be addressed further below.

4.1.3 Damage to Tank Cars

The guidelines identify and define six types of tank car damage:

• Cracks	• Scores
• Dents	• Gouges
• Rail burns	• Wheel burns

These types of damage can occur simultaneously and interact in derailments, as will become apparent in the following discussion.

4.1.3.1 Cracks

Cracks in tank cars may be introduced by welding during the fabrication process, by fatigue during service, or by deformation during an accident.

Explosion bulge tests show that it is very difficult to nucleate a crack in the base metal of the tank (see for example Reference 6, pages 78 and 79; or Reference 2, pages 38 and 41). However, plastic denting during accidents can nucleate cracks at tank car welds. In particular, long rail burns can nucleate cracks at girth welds, which caused catastrophic **delayed** fractures in two instances. The guidelines also seem to recognize the possibility of initiating a crack at a sharp dent in the base metal.

Longitudinal cracks (along the axis of the tank) are the most dangerous because they are oriented normal to the hoop stress, which is twice as high as the axial stress for normal-service conditions. The SGFAS provides a rational method to assess the criticality of cracks in tank cars as long as the temperature and stress level allow a linear elastic analysis. The guidelines take a conservative approach and assume that any stationary crack discovered in the base metal of the damaged tank car can always lead to catastrophic failure.

In the reviewed literature, no detailed fractographic information (for instance scanning electron microscope photographs) was found for cracks found in tank cars. This lack of information is particularly unfortunate for failures triggered by rail dents, because fractography could help establish whether the nucleated crack became immediately unstable or was extended first by stable ductile tearing and then switched to brittle cleavage (because of coupled rate and constraint effects).

4.1.3.2 Dents

Dents are formed in accidents by the punching action of an external object, which causes a local decrease or reversal of the tank curvature. Rail burns, discussed below, represent a special type of long narrow dent.

Dents have several effects on the structural integrity of the tank car; they change the mechanical properties of the material in the dent (increase in flow stress and decrease in ductility due to work hardening); they cause a redistribution of the stresses in the tank shell, which may significantly increase the stresses in the dent region; they can lead to nucleation of cracks (for instance at a girth weld); and, in some cases, when dents occur near so-called "hard points" that constrain the displacement of the shell and induce large membrane strains, they may be associated with significant wall thickness reductions (see for example Reference 37, Figure 1, pages 12 and 13).

A decrease in the radius of curvature will make each of the first three effects associated with dents more critical. This is probably why the guidelines require that tanks be unloaded if (1) the radius of curvature of the dent is smaller than a certain limit value, and (2) the dent crosses a weld. Further, a dent will be more threatening to the integrity of the tank if it contains other defect types (such as scores, gouges, or pre-existing cracks). Again, the guidelines recognize the risk associated with the interaction of two types of damage and mandate unloading. Small dents in tank heads (<12 in.) are considered marginal if their curvature is below a certain radius, and the tank should be unloaded in place if at all possible.

Pellini, in Reference 2, states that "...delayed fracture should not be expected for the cases of broad area dents." Here one has to presume that a broad area dent is one with plastic deformation leading to a large radius of curvature and without additional damage in the deformed region. With this understanding, the statement of Reference 2 is consistent with the guidelines. Service experience (for example, hydroforming repairs) supports this assessment, although no analysis is available that would take into account lifting loads during rerailing.

4.1.3.3 Rail Burns

Rail burns are a special type of long dent oriented more or less longitudinally and caused by a rail impacting on the tank. Usually no material is removed in the process of forming a rail burn, except in girth weld regions where the weld reinforcement may be gouged away. Rail burns have the same effects as other dents (see discussion above), but these effects are magnified by the fact that rail burns often have small radii of curvature and extend over a significant portion of the tank shell more or less normal to the hoop stress direction. Therefore, Reference 2 considers rail burns as the most critical damage to tank cars short of a long through-crack in the shell. The following discussion will emphasize this point and indicate the parameters of a rail burn that control the weakening of the tank car.

Figure 2a shows a cross section through a tank shell with a rail burn dent. The radius of curvature ρ of the dent controls the degree of plastic bending that the shell wall undergoes during the denting process. The sharper this radius, the higher the likelihood that a crack will be nucleated, particularly in the region of a girth weld intersected by a rail burn. The depth d of the dent controls, in part, the bending moment imposed by the pressure-induced hoop stresses on the section A-A at the bottom of the dent. The moment the section can support is limited to the fully plastic moment, which is reached rather rapidly as the dent depth increases. Beyond this level, the load must be transferred to the material surrounding the dent.

In other words, the dent acts like a soft bellow or like a hole. If the longitudinal dimension L of the dent is small (Figure 2b), the stresses near the dent will increase, but the dent width W will not increase much because of this stress redistribution. The section A-A will see loading conditions approaching fixed-displacement conditions. On the other hand, if L is large, the stress redistribution caused by the dent will induce significant opening of the dent width at the dent longitudinal mid-position (Figure 2c). Then section A-A will see loading conditions approaching fixed-load conditions. This distinction is important with respect to the nucleation of a crack at section A-A, delayed crack growth, and the stability of a nucleated crack. Clearly, a long, deep, rail burn is most detrimental for both crack nucleation and instability.

Pellini recognized these aspects in References 2 and 6, albeit in a somewhat qualitative manner. However, his interpretation of the delayed fracture of tank cars with rail burns is not completely satisfactory because it does not provide an analysis of fully plastic, stable, crack growth and instability, and does not consider low (near room) temperature creep phenomena that occur in fully plastic, low-carbon, steel specimens. Pellini also states that "...it is not realistic to expect that the judgements can be made as to the possibility of delayed fracture initiation, for a tank car that has been involved in an accident that results in straight-line burn dents."[2] It is our belief that the potential for delayed fractures is a major risk of damaged tank cars. It should, therefore, be thoroughly understood and mitigated. Advances in fracture mechanics, as well as improved monitoring of damaged tank cars, can serve to achieve these goals.

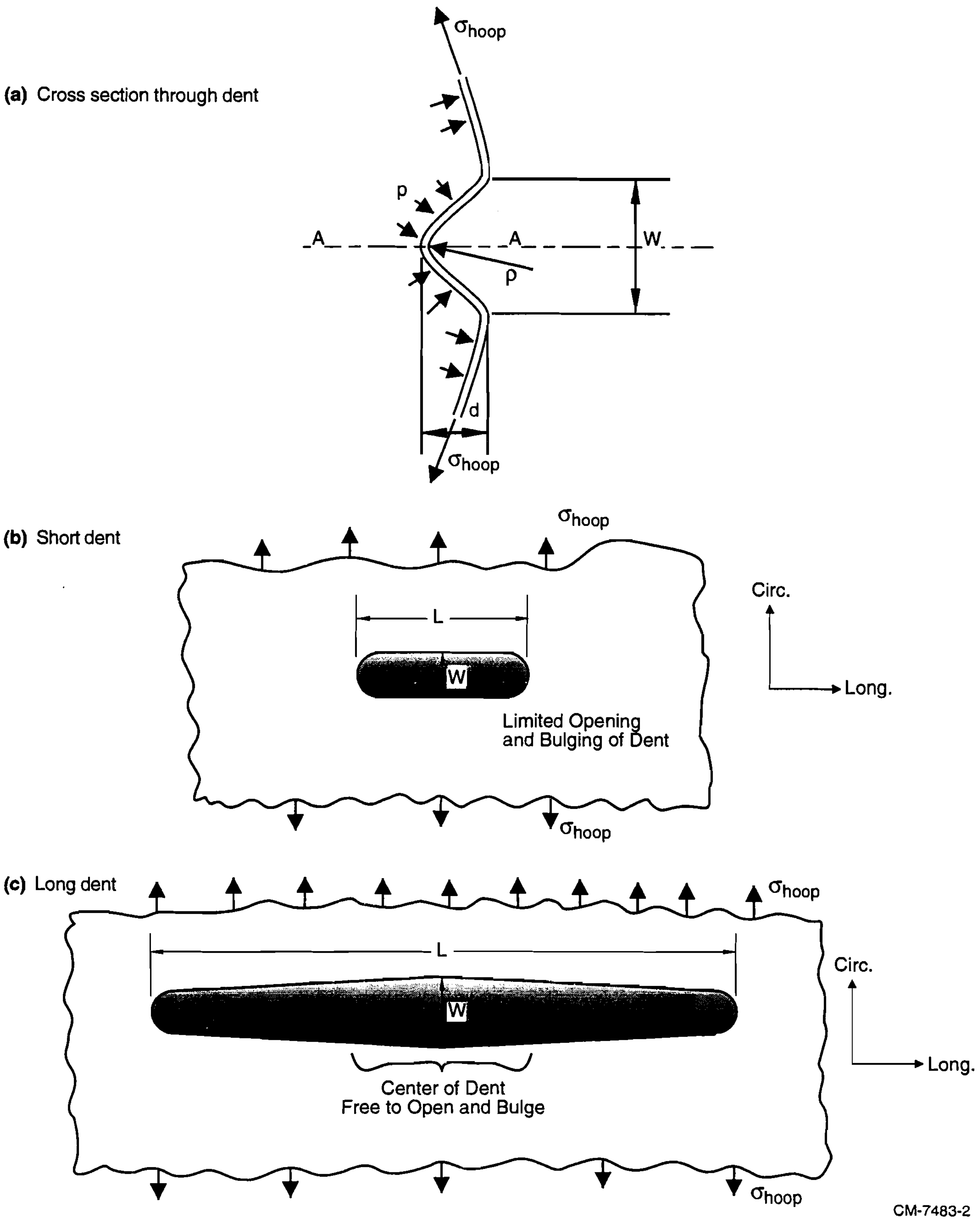


Figure 2. Schematic of dent in a tank car.

The guidelines incorporate some of the knowledge drawn from Pellini's analysis discussed above by specifying unloading of dented tank cars with a dent radius of curvature below a certain value, or with a weld, a crack, a score, or a gouge in the dented region. However, the guidelines **do not discriminate between long and short dents or deep and shallow dents**, although these dent characteristics also critically affect the influence of the dent on the structural integrity of the tank car. Also, they do not account for strain history effects (in particular, reversal of the bending moment when the denting loads are removed).

4.1.3.4 Scores, Gouges, and Wheel Burns

SRI obtained little information from the literature review concerning scores, gouges, and wheel burns. As discussed previously, Pellini comments in Appendix B of Reference 2 on the relative severity of rail burns on the one hand and scores, gouges, and wheel burns on the other hand (in the light of definitions given in the AAR *Manual of Standards and Recommended Practices*, Section C-Part III, Appendix R, Section R 13.00, "Repair of Deformation and Scoring"[21]). Pellini indicates that scores and gouges caused by sliding on a smooth rail are restricted to the crown of girth welds and do not normally result in cracks large enough to initiate delayed fracture. Wheel burns (defined by Section R 13.00 as circular cuttings into the shell surface by the wheel flange) are usually short and not associated with a deep dent.

SRI found geometric and metallurgical information regarding scores, gouges, and wheel burns only in Reference 29. In a recent derailment in Bonfield, Ontario, a tank car sustained (1) a 143 cm (56 in.) long, 4 to 7.3 cm (1.6 to 2.9 in.) wide, and at most 2.5 mm (0.1 in.) deep wheel gouge (sic), and (2) a shorter, 13 cm (5 in.) long, 3 mm (0.12 in.) deep gouge of unknown origin with sharp edges. Both gouges intersected a girth weld. From metallographic cross-sections, SRI estimated that the heat-affected zone and the deformed zone associated with the wheel gouge were approximately 25 to 100 μm (1 to 4 mil) and 100 μm (4 mil), respectively. Hardnesses as high as 62 HRC were measured in the untempered martensite layer of the heat-affected zone, whereas the hardness dropped to 42 HRC in the deformed layer. The martensite layer was cracked, but the cracks were arrested at the interface with the deformed layer. Longer cracks (0.6 mm or 24 mil) were found in the region where the smaller gouge intersected the girth weld. This information indicates that rather superficial damage is associated with wheel burns and gouges, suggesting that the cold work and metallurgical changes may not be significant. These points should, however, be validated by analysis and experiments.

The guidelines consider scores and gouges to be dangerous, in as much as they constitute a notch or affect the heat-affected zone of a weld. In the first instance, recommendations for unloading the car are given in terms of damage depth and internal tank pressure. If the maximum wheel burn depth exceeds 1/8 in. (3.2 mm), the guidelines mandate unloading of the damaged car.

4.1.4 Stress Analysis of Tank Cars and Re-Railing Loads

Our review provided pressure-temperature curves for various loadings from which the membrane hoop and axial stresses in the tank can be estimated. Appendix A-5 (Figures A-1 and A-2) of Reference 6 gives the pressure temperature curves, respectively, for carbon dioxide, hydrogen chloride, hydrogen sulfide, propane, ammonia, chlorine, vinyl chloride, and sulfur dioxide. The hoop stress-temperature curves can then be calculated for various types of tank cars (and hence wall thicknesses) using the pressure-temperature curves. As an example, Figure A-2 of Reference 6 shows the resulting stress-temperature curve for the minimum wall thickness of an A-340W tank car made of TC-128B steel. For the ladings suitable for transport with A-340 tank cars, the stress level is below 20 percent of the yield stress.

Lupkner treated analytically and experimentally the denting and perforation of tank car heads and the collapse of the underframe.[90] He also analyzed collision accident scenarios. Wierzbicki and Suh modeled the indentation of cylinders using rigid-plastic analysis.[106] This type of analysis may provide estimates of the strains associated with specific dent dimensions and help assess the severity of the damage associated with the dent.

Reference 38 reports on a stress analysis of the stub sill region and the effect of redesigns on fatigue cracking.

A decade before Pellini's report, Eiber et al. used LEFM to analyze tank car accidents predating 1972.[2] Using the model of References 87 and 88, they modified LEFM to account for the effect of plasticity and bulging. Eiber et al. also used their experience with the fracture of pressurized gas transmission lines to discuss dynamic aspects of pressurized tank fractures.[16] They showed the importance of the ratio of gas volume over liquid volume in the tank in the process of changing the (dynamic) propagation direction of a crack from axial to circumferential. There is no evidence that the work of Reference 16 influenced the drafting of the guidelines.

Additional applications of LEFM to tank car safety analysis are provided in References 28, 34, and 37. These analyses consider semi-elliptical surface flaws and estimate critical flaw sizes. They are essentially the same as the analysis used by Pellini in the SGFAS.

Reference 81 presents the results of finite element simulations of tank cars supported at various locations along their axis. It shows how the stress distribution varies with the position of the support brackets. This information could prove useful in establishing guidelines on where to apply hoisting cables to lift damaged tank cars. In this context, Reference 34 lists procedures and recommendations for lifting and moving cars.

Beyond the literature quoted here, SRI found little stress analysis relevant to damaged tank cars.* Reference 77 discusses methods to calculate membrane and bending stresses in three-dimensional configurations for use with the design rules of the ASME Pressure Vessel Code. References 78 and 79 report on other applications of LEFM to analyze the structural integrity of gas tanks. Reference 80 is a recent application of Pellini's SGFAS.

As is emphasized below, more extensive stress analysis is needed to support and augment the guidelines and their application.

*Just as this report was being completed, SRI became aware of a recent analysis of tank cars with circumferential throughwall cracks by Dr. Akram Zahoor, Zenith Corporation. The analysis uses the elasto-plastic fracture mechanics methodology discussed in the next section and is part of an investigation sponsored by DOT through NIST in 1992. The report on this work is at present not publicly available.

4.1.5 Characterization of Tank Car Steels

The literature search produced an extensive list of reports dealing with the characterization of tank car steels.[4,5,7,11,12,21,43-54] Many characterizations were associated with the analysis of tank cars that failed in accidents, and included tensile tests, Charpy impact tests, and microstructural data.[43-54] SRI did not review these references in detail.

The degradation in fracture properties caused by prior straining of the steel is an important aspect of damage assessment in tank cars and is addressed in References 4 and 37. For example, the -50°F (-46°C) Charpy V-notch energy of a TC-135A steel (proposed specification steel that was never approved) is reduced by 73 percent from 156 to 42 foot-pounds (6.8 to 1.8 kJ) by a 5-percent deformation [followed by a 1 hr stress relief treatment at 1150°F (621°C), see Exhibit 12B, page 31 of Reference 4]. Similarly, prestraining ASTM A515 steel to a strain of 12 percent can induce a 25 percent reduction in the static fracture toughness and a 65 percent reduction in the so-called tearing modulus* (see Reference 37, Figure 13, and Table 2 on page 32).

Reference 83 proposes a new correlation between Charpy energy and fracture toughness K_{Ic} transition curves for pressure vessel steels. Review of this correlation could provide additional support for the definition of Pellini's arrest curve.

4.1.6 Fractographic and Metallographic Information

References discussing tank car steels and the analysis of tank car accidents present little fractographic information. In particular, no fractographic or metallographic results were found for the accidents involving delayed fracture. Such information is essential to establish the mechanisms responsible for delayed fractures. Further, except for the data on gouges that was discussed above, SRI found little useful information about the extent of the zone affected thermally or by deformation at scores or gouges, and about the geometry of these types of damage.[29]

*The tearing modulus is discussed in the next section.

4.2 DEVELOPMENTS IN FRACTURE MECHANICS RELEVANT TO TANK CAR DAMAGE ASSESSMENT

SRI's review of the literature suggests that fracture analysis of tank cars is primarily based on LEFM and on engineering fracture assessment methods that use fracture transition temperature and crack arrest curve concepts.* However, over the last 20 years, many significant advances were made in the field of fracture mechanics. It is now feasible, with the **J-based elastic-plastic fracture mechanics approach (EPFM)**, to evaluate the conditions required to initiate and propagate a pre-existing crack in a **partially yielded or fully plastic** structure. It is also possible using **damage mechanics** or so called **local fracture methods**, to predict crack nucleation at blunt stress concentrations (such as gouges or scores) or in prestrained material.

These new approaches apply to both the problem of the onset of cleavage fracture under conditions of extensive yielding (which is a situation often encountered in practice) and the problem of ductile tearing, that is, the initiation of a stable fracture by microvoid coalescence, followed by stable growth of the crack, and finally unstable propagation.

The following section gives a brief review of these developments along with a discussion on how they can be applied to formulate more reliable and better documented guidelines for the assessment of damaged tank cars. For a more detailed treatment of these developments, refer to References 92 to 102.

4.2.1 J-Based, Elastic-Plastic, Fracture Mechanics

It has been shown that, if certain specific conditions are met,** the stress and strain fields in the neighborhood of a stationary crack in elastic-plastic or fully plastic material can be described in a form similar to the linear elastic solution, that is

$$\sigma \approx (J)^{\left(\frac{1}{n+1}\right)}\ r^{-\left(\frac{1}{n+1}\right)}\ \Sigma(\theta) \quad \varepsilon \approx (J)^{\left(\frac{n}{n+1}\right)}\ r^{-\left(\frac{n}{n+1}\right)}\ E(\theta) \quad (2)$$

*The only known exception is the recent unpublished elasto-plastic fracture analysis by Zahoor mentioned earlier.
**Among others: assumed small strain, small plastic deformation, and proportional loading.

where r and θ are polar coordinates centered at the crack tip, n is the strain hardening exponent, and $\Sigma(\theta)$ and $E(\theta)$ are nondimensional functions. In Equation (2), J is the so-called J-integral, which controls the amplitude of stresses and strains at the crack tip. By analogy with the elastic stress intensity factor K of LEFM, J can be viewed as a plastic stress intensity factor, which represents the influence of remote loading on the crack tip fields. It has been further shown that J can be estimated from remotely applied boundary conditions and that, in the limit of pure elasticity and for plane strain conditions, it is related to K in the following way:

$$J = \frac{K^2 (1 - \nu^2)}{E} \tag{3}$$

where ν is Poisson's ratio and E is Young's modulus.

It is argued that because the "plastic" crack tip stress and strain fields are controlled by the parameter J, it can be used to predict crack initiation under conditions of extensive plastic deformation. The criterion for initiation of a pre-existing sharp crack is then

$$J_{appl} \geqq J_{Ic} \tag{4}$$

where J_{appl} represents the loading applied to the crack tip and J_{Ic} is the material resistance to fracture (i.e., its fracture toughness), which can be measured in laboratory experiments. Procedures and size and geometric requirements for the determination of the material toughness J_{Ic} are given by ASTM-Standard E-813 (Reference 108).

For ductile materials, the initiation of a tearing crack is often followed by a phase of stable crack growth in which an increase in J_{appl} (and the applied loading) is required to overcome an apparent increased resistance of the material to tearing and to propagate the crack by an amount Δa. The curve J_{appl} versus Δa (the so-called J-resistance curve) can be measured in laboratory experiments (Reference 109), and is then considered a material property [J_{mat} (Δa)]. The resistance curve serves to predict the amount of crack growth using the relation

$$J_{appl} (\Delta a) = J_{mat} (\Delta a) \tag{5}$$

which states that, at any point Δa during the crack growth phase, the J_{appl} (Δa) applied by the external forces must be in equilibrium with the ability of the material to resist tearing J_{mat} (Δa). A comparison of the rate at which J_{appl} and J_{mat} increase with Δa determines whether the new increment of crack growth is stable or not, that is

$$\left(\frac{\partial J_{appl}}{\partial a}\right)_{fbc} < \left(\frac{\partial J_{mat}}{\partial a}\right) \Rightarrow \text{stable crack growth} \tag{6a}$$

$$\left(\frac{\partial J_{appl}}{\partial a}\right)_{fbc} > \left(\frac{\partial J_{mat}}{\partial a}\right) \Rightarrow \text{unstable crack growth} \tag{6b}$$

In Equations 6a and 6b, the subscript "fbc" indicates that the rate of change of J_{appl} is estimated holding the boundary conditions fixed (for example, fixed load level for a load-controlled situation or fixed displacement for a displacement-controlled situation). Therefore, the instability condition depends on the loading configuration and more specifically on the compliance of the loading system. A compliant (soft) loading system promotes early instability, whereas a stiff system retards or precludes instability. This point is important in considering the safety of pressurized tank cars, because the proportion of liquid to gas phase in the tank will affect the compliance of the system and hence the onset of instability.

The parameter $\frac{\partial J_{mat}}{\partial a}$ represents the slope of the experimental resistance curve. The derived parameter

$$\frac{\partial J_{mat}}{\partial a} \frac{E}{\sigma_{flow^2}}$$

(where σ_{flow} is the flow stress defined as the average of the yield and ultimate strengths) is called the tearing modulus and is often used to characterize the resistance of a material to tearing instability.

Figure 3 shows how this method is applied to the fracture of a 4T, compact tension specimen of A533B pressure vessel steel loaded by testing systems of different compliances C_M (fixed grip, $C_M = 0$; soft loading system, $C_M \times E = 1000$; dead load, $C_M = \infty$). For each case, the figure shows families of J_{appl} versus crack length loading curves, over which the material resistance curve has been superimposed. The point where loading and resistance curves are tangent represents the point of instability. The figure indicates that for $C_M = 0$, crack growth is always stable, whereas for $C_M = \infty$, instability sets in after only a limited amount of crack growth. However, the point of crack initiation is independent of the compliance of the loading system.

The elastic-plastic analysis method discussed here has been validated for several applications and its limitations have been established. One of the main limitations is that the material resistance curve is not really a material property. Rather it is a structural property that depends on specimen geometry and dimensions. Therefore, the resistance curve must often be measured with specimens simulating the specific application. Nevertheless, the method is now well accepted in the community and is used to characterize ductile materials as well as to make structural integrity evaluations, particularly in the nuclear industry. A handbook of solutions for J_{appl} has been published.[93] The Failure Assessment Diagram, discussed in Reference 79, is a convenient extension of the method for engineering applications.

An elasto-plastic fracture analysis method based on the concept of crack-tip opening displacement (CTOD) has also been developed, mainly in Europe, and applied successfully to ductile engineering structures. One can show that the J-based elastic-plastic fracture analysis and the CTOD-based theory are essentially equivalent (see Reference 97 for a review).

4.2.2 Fracture Predictions Using Damage Mechanics/ Local Fracture

As pointed out in the preceding section, the J-based EPFM approach has limitations and cannot be used to predict fracture in the absence of pre-existing cracks. Therefore, it cannot be used for the analysis of scores, gouges, or dents in tank cars.

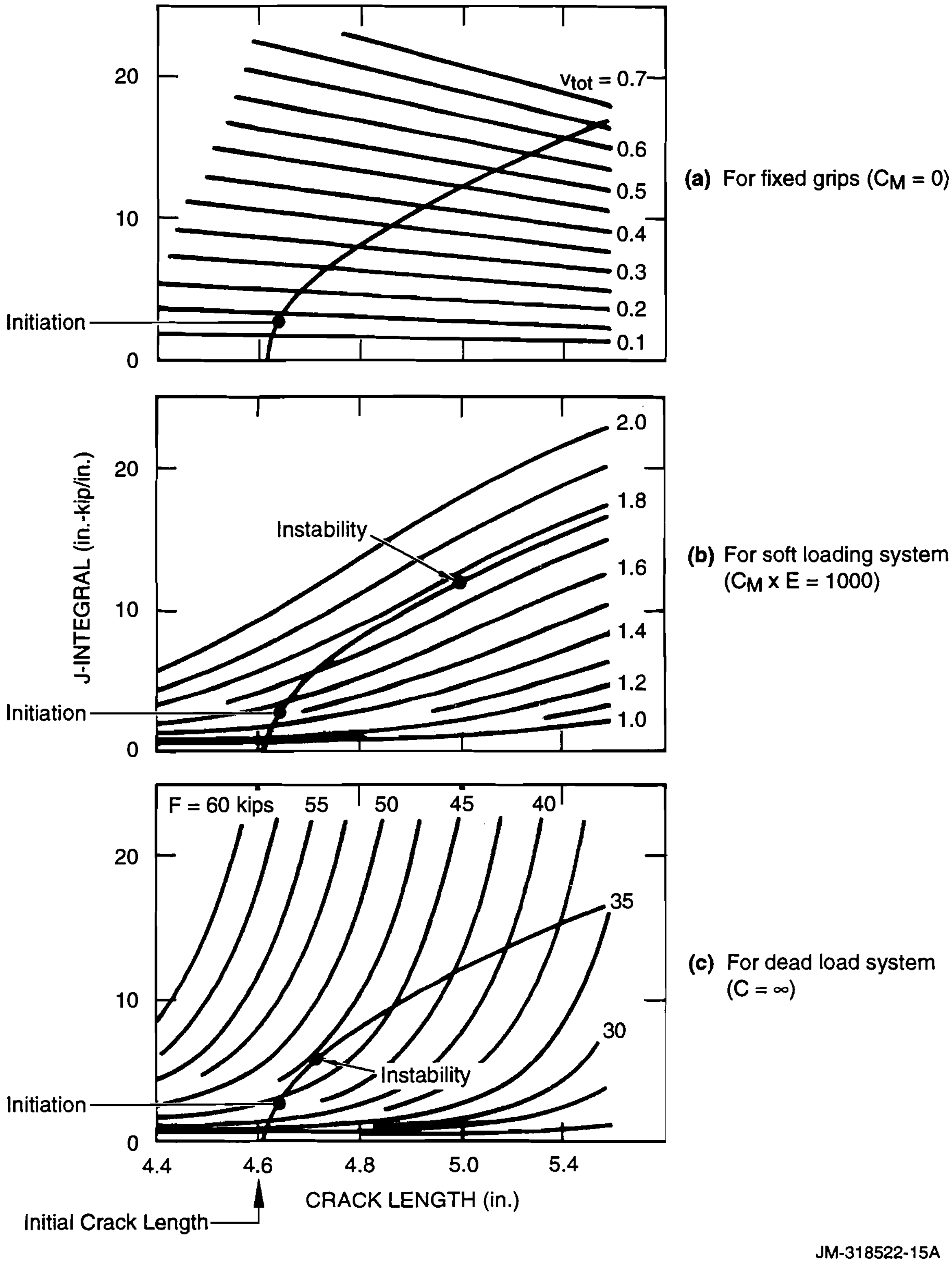


Figure 3. J_{appl} versus crack length for a 4T A533B steel compact tension specimen compared to a material resistance curve. (Ref. 96)

To overcome the limitations of classical fracture mechanics approaches, new methods have been developed that use continuum mechanics and focus on modeling the microstructural damage (such as cleavage or ductile void growth) induced in small volumes of structural materials. These models, although somewhat more complex in their use, present many advantages. They can handle more general fracture problems (multiaxial loading, no pre-existing cracks, microstructural gradients, large amounts of crack extension) and they can be calibrated using small notched and cracked tensile specimens, which are easy to fabricate, test, and analyze.

An exhaustive review of developments in damage/local fracture mechanics is beyond the scope of this report, therefore the reader is directed to References 98 to 102 for more details. Nevertheless, to illustrate the capabilities of these new approaches, SRI will discuss a ductile fracture model proposed by MacKenzie et al. (Reference 103), that they have implemented in a finite element code and used in their own work on the fracture of weldments (References 104 to105).

The local ductile fracture model (References 98 and 103) assumes that failure of a material location occurs when the damage within a surrounding characteristic volume V_{MIC} exceeds a critical value that is

$$D = \int \frac{d\varepsilon_{eq}^{p}}{\varepsilon_{c}(\sigma^{*})} = 1 \qquad \text{over } V_{MIC} \approx (R_{MIC})^{3} \tag{7}$$

where D is the normalized damage parameter, $d\varepsilon_{eq}^{p}$ is an increment in plastic strain, and $\varepsilon_c(\sigma^*)$ is the critical failure strain as a function of the stress triaxiality σ^*, defined as the ratio of the mean stress to the equivalent stress. This critical strain function can be determined by a series of notched tensile tests with specimens of varying notch radii. V_{MIC} and R_{MIC} are the volume and radius of the process zone. These constant microstructural parameters introduce nongeometric scaling effects. The fracture model is implemented in a version of the explicit finite element code DYNA3D, which contains a node release feature allowing the simulation of propagating cracks.

The model of Equation (7) is equivalent to other local ductile fracture models based on the attainment of a critical void size or volume fraction (References 98 to 102). SRI has used this model to successfully predict the dynamic fracture behavior of welded joints in HY-130 steel. Figure 4 compares the results of experiments and computations for a stiffened plate loaded impulsively by sheet explosive. The input to the calculation was the initial velocity imparted to the plate. The simulation models the deformation of the broken plate quite well. More importantly, the crack path through the plate, which was not prescribed a priori, resembles quite well the crack path through the metallurgical cross section of the weld.

SRI believes that a local fracture model such as the one discussed here can be used in conjunction with laboratory experiments on notched plates and round bars to analyze the effect of scores and gouges, and the effect of various amounts of cold work on the structural integrity of tank cars. SRI will discuss this approach further in this report.

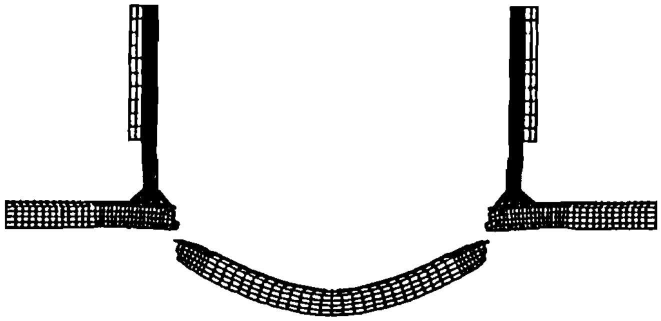
4.3 ASSESSMENT OF GUIDELINES AND THEIR DEGREE OF VALIDATION

Reading the guidelines brought to light several omissions, inconsistencies, or errors, which can in most cases be easily corrected. These are discussed below.

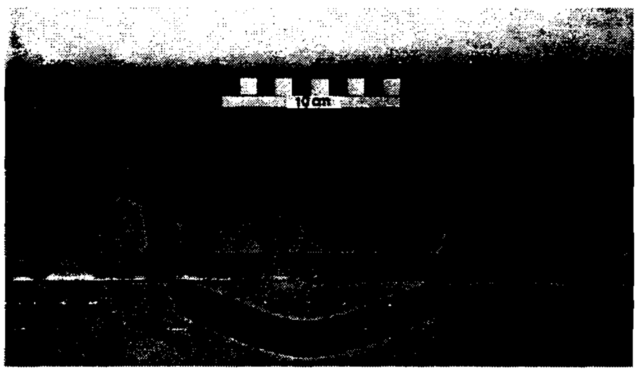
Page numbers referenced in this section are in relation to Section G of AAR/TTC's Tank Car Safety Course Manual (Reference 110).

Section 1 (page 2) of the guidelines discusses the four conditions affecting the ductility of tank car steels as

- The specification of the steel
- Its service temperature
- The amount of cold work it has received
- The presence of heat-affected zones

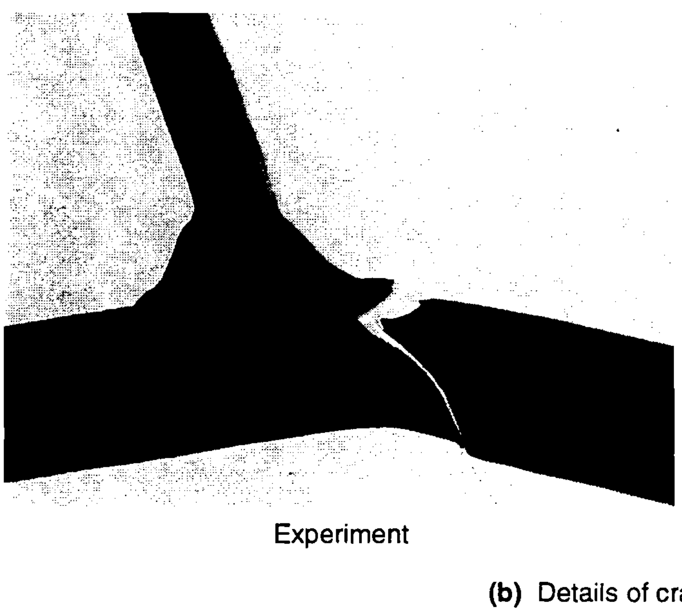


Calculation

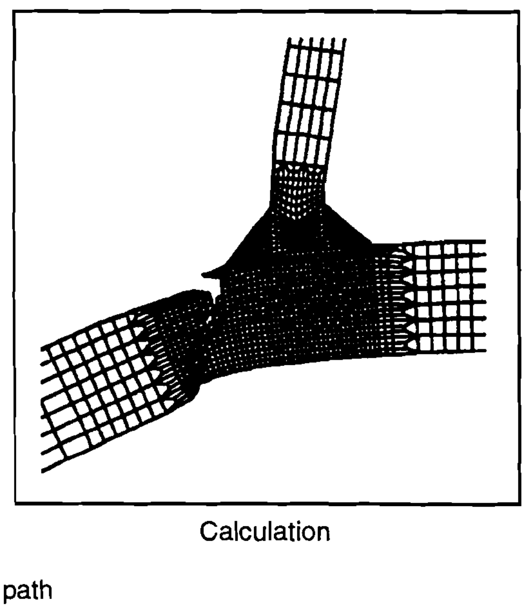


Experiment

(a) Final deformation



Experiment



Calculation

(b) Details of crack path

CPM-3493-1A

Figure 4. Deformation and fracture behavior of explosively loaded welded HY-130 steel T-joints.

This list omits a fifth very important factor, namely the loading rate, which in steels can significantly reduce both ductility and fracture toughness, and even induce a change in the microscopic mode of fracture from ductile void growth to brittle cleavage at a given temperature.

On page 2, the discussion of the effect of pressure-induced stress on the stability of cracks does not recognize the possibility for slow, stable, ductile growth of a crack under conditions of gradually rising temperatures and pressures. Stable crack growth may play an important role in delayed fracture of damaged tank cars, as will be discussed below.

The discussion of scores and gouges (page 4) should mention that, in addition to reducing the tank metal thickness, these damage types induce a geometric stress concentration, locally work-harden the steel, and possibly change its microstructure because of thermal effects. All these factors help make the tank car wall weaker at the damage location. These remarks also apply to wheel burns (page 5).

The terminology used for the damage induced by the contact of the tank car wall with a rail is ambiguous and should be clarified. If the tank car simply impacts the rail (for instance, because it overturned) without relative sliding motion between the rail and the wall, then the resulting damage is a relatively long and narrow dent. This type of damage is referred to as a rail dent in the AAR *Manual of Standards and Recommended Practices* (Reference 21). If the rail slides relative to the wall while in contact with it, it may leave a region of reduced wall thickness with a surface microstructure affected by plastic deformation and frictional heating. This second type of rail damage is similar to a wheel burn and should be appropriately named rail burn. It is, of course, possible that a rail induces both a dent and a burn in the tank wall.

The criteria for assessing the limiting score depth for 340W and 400W tanks are not clear. On page 8, the text mentions "Tanks having scores or gouges should be unloaded in place when the internal pressure exceeds half of the allowable internal pressures listed in the tables below." In the referenced tables, pressures associated with various score depths are listed under the heading "Maximum Safe Internal Pressure." Should the tank car be emptied when the pressure reaches the full pressure or only half the pressure in the table? This ambiguity must be resolved. Similarly, SRI identified an inconsistency in the criterion for unloading a tank car containing a wheel burn. The guideline text on page 9, left column, requires that a tank containing a wheel burn deeper than 1/8 in. (3.2 mm) be unloaded as soon as possible. On the other hand, Figure 10 on page 10 shows a major wheel burn requiring immediate unloading as one with a depth of 1/4 in. (6.3 mm) or more, whereas cars with burns less than 1/8 in. (3.2 mm) can be transported. The text does not refer to Figure 10.

On page 9, paragraph heading "Dents, Rail Burns" should be introduced before the second bulleted paragraph. In addition, SRI believes that it should be more clearly stated that if any one of the conditions listed at the bottom of the left column of page 9 is fulfilled, the tank car should be unloaded without moving it. Also, the last condition for tank cars built since 1967 requires unloading if the dent "shows evidence of cold work." By its very nature, a dent will always be associated with plastic deformation and hence cold work. Therefore, this requirement must be more specific.

Finally, as indicated by Pellini and discussed earlier, a dent should be characterized not only by its radius of curvature but also its length and depth. Below, SRI suggests that more precise safety criteria involving these dent parameters should be formulated.

4.3.1 Validation and Limitations of the Guidelines

In discussing the degree of validation and the limitations of the guidelines, SRI focused primarily on Section 5, "Interpreting Tank Damage to Pressure Tank Cars," because it is the only part of the guidelines containing quantitative rules for assessing damage severity.

First, given the available evidence, it was found that the guidelines reflect good, overall, physical understanding of potentially dangerous damage to tank cars. However, recommendations are sometimes formulated in an ambiguous and qualitative way that could lead to misinterpretations.

Second, the validation for the guidelines appears to be service experience and, possibly, analyses based on Pellini's SGFAS, taking only pressure loads into consideration. This degree of validation is not sufficient to guarantee safe handling of damaged tank cars. New experimental and analytical tools available today provide a means to refine and more thoroughly validate the guidelines.

Third, to guarantee the safe handling of damaged tank cars, the effect of rerailing loads on pre-existing damage, particularly dents, and structural integrity must also be considered more explicitly. The damage severity criteria included in the guidelines should take into account these loads. Specific lifting practices and load application locations should be provided, and the damage assessment guidelines should be validated for these conditions.

Fourth, the safety-critical issue of delayed fracture has not been fully and satisfactorily explained by available analysis and should be reconsidered in the light of more recent understanding of ductile and ductile-brittle transition fracture processes.

Finally, the qualitative character of the guidelines may contribute to very conservative assessments of damage in some cases and much less conservative assessments in others. The degree of conservatism may have been assessed at the time the guidelines were drafted (as indicated by the footnotes in Tables 1 and 2), but no records exist of the method used to estimate it and no underlying experimental or analytical results are available at the date of this report. Therefore, any proposed work on improving the guidelines should result in clear bounds on the safety margins associated with each recommendation, backed by a description of the method used to arrive at the estimates of the margins. The outcome will most likely show that, in some cases, the current guidelines are too conservative and in other cases not conservative enough. In the following paragraphs, the conclusions will be discussed in more detail.

The guidelines express the criticality of sharp dents, scores, and gouges in terms of dimensional and geometric features (radius of curvature of dents, depth of scores) and the type of material they affect (base metal of the tank shell, weld metal, or the heat-affected zone). The guidelines also consider interactions between several types of defects. The rationale behind using score depth and radius of curvature of dents is that these parameters relate respectively to a reduction in wall thickness and an associated increase in stress, and to a certain level of plastic straining. Both stress and strain play a critical role in damaging the material and inducing fracture. In that respect, depth and curvature are good parameters to estimate the criticality of tank car damage, provided that a reliable correlation has been established (1) between them and the stress and strain distribution in the vicinity of the damage, and (2) between stress and strain states and fracture. These correlations can best be established by an analysis and some laboratory experiments. The analysis provides accurate values of stresses and strains in the damaged region, whereas experiments serve to establish the critical conditions for fracture and to validate the overall predictive approach. The power of such an approach is to allow analytical treatment of many situations without having to perform an excessive number of laboratory experiments.

SRI suggests that the score depth-safe pressure specification in the guidelines was based on a requirement that net section stress at the score not exceed a fraction of the ultimate stress. Expressed in terms of pressures, this requirement is of the form

$$P_{safe} = \frac{(t - d_{score})\, P_{burst}}{t\, \alpha\, K_t} \qquad\qquad P_{burst} = \frac{\sigma_u\, t}{r} \tag{8}$$

wher[illegible] and t are the shell radius and thickness, respectively, d_{score} the score depth, P_{burst} the bu[illegible]essure (850 psi and 1000 psi (5.8 and 6.9 MPa) respectively for 340W and 400W tank cars), P_{safe} the safe pressure cited in Tables 1 and 2 of the guidelines, α a safety factor, and K_t a stress concentration factor accounting for the score geometry. The data of Tables 1 and 2 indeed follow this linear relationship (see also Figure 3-3 on page 3-25 of Reference 34) and indicate values of the product $\alpha\, K_t$ of around 4. Assuming that the required factor of safety is the same as for the undamaged tank car (2.5), then K_t is about 1.6. Dropping the value of α to 2 yields a value of K_t of 2, which is the value quoted in Reference 34. Validation for the depth specifications may have been obtained by testing small flat plates with simulated score damage and calculating from the load at failure the fracture stress and the corresponding tank pressure. No explicit provision is made in this analysis for changes in material properties due to heating or work-hardening caused by the gouging or scoring process.

SRI further suggests, as also discussed in Reference 34, that the specification for the radius of curvature of dents is based on a comparison of the maximum strain ε_{dent} associate with a certain dent radius ρ and the elongation or strain at failure $\varepsilon_{failure}$ of typical tank materials, i.e.

$$\varepsilon_{dent} = \frac{t}{2\rho} < \frac{\varepsilon_{failure}}{\beta} \tag{9}$$

where β is again a safety factor. For $\rho = 2$ in. (5 cm) and 4 in. (10 cm), the corresponding maximum strains are roughly 15 percent to 18 percent and 7 percent to 9 percent respectively, depending on the thickness. For comparison, the room temperature failure elongations (2 in. or 5 cm gage length) for TC128 and TC135 steels must be at least 22 percent to 23 percent (from exhibit 6, Reference 4; see also Reference 7). Equivalent plastic strains at failure calculated from available reduction of area values exceed 50 percent. This comparison shows that the value of the safety factor underlying the recommendations depends on what experimental failure strain is used in conjunction with Equation 8. Using an (to our knowledge) undocumented correlation between failure strain in pure bending and reduction in area in the tensile test, and a value of the reduction of area of 19 percent, Reference 34 estimates that the guidelines ensure a safety factor of 3. The recommendations of the guidelines may have also been based on, or validated by, laboratory bend tests with shell base metal.

The recommended curvature values may be less conservative than indicated above. The process of forming a rail dent involves pushing the shell wall inward to form the dent. If the dent is deep, once the rail load is removed, the dent will possibly be pushed and bent outward again under the action of the internal pressure and the associated membrane stresses (see earlier discussion). This process will tend to reduce the curvature. Thus, a dent may have accumulated more plastic strain (in a sense be more damaged by the deformation cycle) than simply indicated by its curvature. This point illustrates another deficiency of the guidelines. Although the guidelines acknowledge, in some cases, the possibility for deformation history effects (e.g., conditions on the presence of cold work in the dent), they do not indicate whether or how they account for these effects in specifying safe/unsafe conditions. In view of the important effect that prestraining can have on the fracture properties (see earlier discussion of References 4 and 37), a validation of the guidelines requires an assessment of deformation history effects.

As was discussed earlier, the criticality of a rail dent should also depend on its length and depth. Long deep dents are more dangerous than short ones in terms of delayed fracture and catastrophic failure after the accident. Therefore, the guidelines should specify limit values of these parameters on the basis of a structural and fracture mechanics analysis.

The literature reviewed did not provide a satisfactory explanation of the phenomenon of delayed fracture of tank cars with large rail dents. The guidelines do not address this important safety issue; therefore, this phenomenon should be revisited, using developments in experimental and analytical elastic-plastic fracture made over the last 20 years. SRI believes that two mechanisms of slow-crack growth are possible for delayed fracture under either monotonically increasing loads or constant load in a creeping material.

Slow, stable, ductile growth of a small thumbnail crack can occur if the tank car pressure increases, because of slowly increasing external temperatures. The growing crack then becomes unstable either because the applied (compliant) pressure loading overcomes the tearing resistance of the material (tearing instability) or because the stress state and the microstructural conditions at the tip of the growing crack are such that low-energy cleavage is induced (cleavage instability).

Low temperature creep deformation in carbon steels subjected to a constant, fully plastic load is a well-documented phenomenon. This type of fully plastic, dead weight, loading condition may prevail in the middle of a long-rail dent, so that if a crack is present, it can blunt and grow, driven by creep plasticity. The instability phase is then similar to that of a crack growing under monotonically increasing load. In the future, attention should be given to these possible delayed fracture scenarios, and to explaining unequivocably the conditions governing this dangerous failure mode of tank cars.

Another area in which SRI believes the guidelines need improvement is in identifying recommended procedures for moving and lifting tank cars. By limiting these procedures to a few well-defined load application configurations (as suggested in references 34 and 35), the effect of rerailing loads on damaged regions of the tank car can be evaluated quantitatively. Only by truely taking into account the effect of these loads, will it be possible to validate reliably the damage severity criteria now proposed by the guidelines.

Although this topic falls outside the scope of this project, recommendations for using nondestructive techniques to evaluate damaged tank cars should be seriously considered. The field of NDE has evolved rapidly since publication of References 36 and 37, and an update on NDE technologies that may be suitable to assess damaged tank cars should be obtained.

4.4 EXPERT REVIEW

The report prepared by SRI was sent to a number of individuals for review and comment. The individuals were selected because of their knowledge in the fields of tank car construction, metallurgy, fracture mechanics, and finite element analysis. The individuals identified below participated in the review of the report and with few exceptions they agreed that the report was sound. In general, the reviewers indicated that the report provided a good assessment of the literature and that the recommended approach for validation of the guidelines appeared to be reasonable. Appendix B lists the following reviewers specific comments.

- J. Robert Sims, Exxon Research and Engineering, Chairman ASME Post Construction Committee
- Dr. William J. Koves, UOP, Chairman ASME Flaw Analysis Subcommittee
- Stephen Wong, Procor Limited
- Paul Kinnecom, Association of American Railroads
- Diane Rocheleau, Transportation Safety Board of Canada
- Edgar Ladouceur, Transport Canada

5.0 CONCLUSIONS AND RECOMMENDATIONS

Based upon the review of over 100 references, the subcontractor has identified the analytical and experimental work necessary to evaluate the criticality of the damage (cracks, scores, gouges, dents, and wheel burns). They have found that the guidelines reflect a good, overall physical understanding of potentially dangerous damage to tank cars. Quantitative specifications are generally expressed in terms of convenient parameters that can be related to the degree of structural and material weakening caused by the damage. The additional conclusions drawn by SRI regarding the relevance and validity of the guidelines are presented as follows.

- The guidelines are often only qualitative and somewhat vague in their requirements.
- There is no record of analytical or experimental work to directly support and validate the guidelines. The subcontractor was able to reconstruct some of the reasoning that must have led to the guidelines. It appears that the guidelines rely on 20-year or older analysis methods and do not reflect recent advances in computational and fracture mechanics.
- The effect on damage of loads applied to move or lift the derailed tank car is not explicitly accounted for in the guidelines even though these loads could be important in causing damaged areas to rupture.
- The phenomenon of delayed fracture is not appropriately documented and understood. The guidelines do not adequately address this important safety issue.
- The margins of safety associated with the current guidelines are not known.
- The guidelines do not consider advanced non-destructive evaluation (NDE) methods available to identify tank car damage and to monitor the damage during tank car handling at the accident scene.

To alleviate these shortcomings and improve the reliability and usefulness of the guidelines, SRI and AAR recommend that the following research be initiated:

- Identify typical rerailing load scenarios and calculate by finite element analysis methods the stress and strain fields they induce in pressurized tank cars. Use these results as loading conditions to assess the criticality of various types of damage in tanks cars.
- Assess the residual resistance of tank cars with large dents to buckling and plastic collapse when subjected to rerailing loads.
- Refine and validate the severity criteria for scores, gouges, and wheel burns using recent advances in analytical and experimental fracture mechanics.
- Assess the possibility for stable crack growth in fully plastic tank car steels and the implications for delayed fracture.
- Evaluate the applicability of current NDE equipment and recommend use of suitable NDE techniques in the guidelines.

- Monitor and participate in the activities of the committee on "Post-Construction Standards" of the Pressure Vessel and Piping Division of the American Society of Mechanical Engineers.

SRI recommends that the structural and fracture mechanics analysis aspects of the proposed research be accomplished by combining nonlinear finite element simulations with advanced elasto-plastic fracture and local fracture theories to quantify the severity of various types of tank car damage. This analytical effort should be performed in conjunction with an experimental effort using small laboratory specimens that will provide material properties data as well as validation for the analyses.

The results of this research should be used to reformulate the guidelines in more precise and quantitative terms so that their use will contribute to increased safety at derailment sites.

6.0 GLOSSARY

Below are definitions of key terms used in this document:[110]

tank: "Tank" in this document refers to the actual tank car tank.

jacket: The jacket is the first thin steel outer shell that holds the insulation or thermal protection in place and protects the tank from the elements. The jacket is not designed to hold the leaking contents of the car.

cold work: Cold work is deformation of steel when it is bent at ambient temperatures without benefit of heat treatment or suffers an impact or static load (i.e., a tank sliding over a solid object with a rounded point.)

heat affected zone: The heat affected zone is an area in the undisturbed tank metal next to the actual weld material. This zone is less ductile than either the weld or the plate due to the effect of the heat on the welding process.

internal pressure: Internal pressure is the force against the internal surfaces of the tank caused by the vapor pressure of the contents.

crack: A crack is a narrow split or break in the tank metal which may penetrate through the tank metal.

score:	A score is a relocation of tank or weld metal so that the metal is pushed aside along the line of contact with another object. This causes a reduction in tank metal thickness.
gouge:	A gouge is removal of the tank or weld metal along the line of contact with another object. This causes a reduction in tank metal thickness.
wheel burn:	A wheel burn is similar to a gouge but is caused by prolonged wheel contact with the tank.
dent:	A dent is a deformation that changes the tank contour from that of original manufacture as a result of impact with a relatively blunt object (coupler or end of an adjacent car).
rail burn:	A rail burn is a long dent, usually parallel to the length of the tank which crosses a weld and causes cold work. It may be caused by the tank passing over a section of rail.
radius of curvature:	Radius of curvature is used to describe the sharpness of a curve (dent). A small radius of curvature indicates a small circle and a sharp bend, whereas a larger radius of curvature indicates a larger circle and a more gentle bend.
transition temperature:	Transition temperature is the point where the properties of steel change from ductile to brittle.

APPENDIX A

Bibliography

1. Tetelman, A. S. and D. H. Stone, "An Introduction to the Fracture Mechanics of Railroad Materials," Association of American Railroads, Report No. R-157, Chicago, Illinois (May 1974).

2. Pellini, W. S. "Analysis of Tank Car Failures Related to Rail Burn Dents," Association of American Railroads, Report No. R-551, Chicago, Illinois (June 1983).

3. Phillips, E. A. and H. Role, "Analysis of Tank Cars Damaged in Accidents, 1965 through 1986, Documentation Report," Association of American Railroads, Report No. RA-02-6-55 (AAR R-709), Chicago, Illinois (January 30, 1989).

4. Phillips, E. A. "Evaluation of New Steels for Tank Cars, Phase II," Association of American Railroads, Report No. RA-03-9-59 (AAR R-773), Chicago, Illinois (May 2, 1991).

5. Pellini, W. S. "Feasibility Analysis for Tank Car Applications of New Microalloyed and Controlled Rolled Steels—Description of Fracture Properties and Comparisons with Steels in Present Use," Association of American Railroads, Report No. R-543, Chicago, Illinois (April 1983).

6. Pellini, W. S. "Guidelines for Fracture Mechanics Analysis of Pressure Tank Car Structural Integrity Factors," Association of American Railroads, Report No. R-586, Chicago, Illinois (June 1985).

7. Phillips, E. A., R. J. Eiber, S. A. Coughlin, P. B. Heideman, and M. C. Fec, "Evaluation of New Steels for Tank Cars," Association of American Railroads, Report No. RA-03-7-53 (AAR R-643), Chicago, Illinois (April 29, 1987).

8. Phillips, E. A. and W. B. Krauskopf, "Phase 01 Report on Summary of Ruptured Tank Cars Involved in Past Accidents," Addendum-Report of Association of American Railroads, Report No. RA-01-2-7 (AAR R-130), Chicago, Illinois (May 1, 1973).

9. Phillips, E. A. and L. L. Olson, "Phase 03 Report on Metallographic Examination of Specimens Removed from Sections of Tank Cars in Crescent City Derailment," Association of American Railroads, Report No. RA-03-1-2 (AAR R-125), Chicago, Illinois (October 15, 1970).

10. Phillips, E. A. and L. L. Olson, "Phase 03 Report on Metallographic Examination of Specimens Removed from a Section of Tank Car in South Byron, New York Derailment," Association of American Railroads, Report No. RA-03-2-4 (AAR R-127), Chicago, Illinois (March 10, 1971).

11. Phillips, E. A. and L. L. Olson, "Phase 03 Report on Fracture Properties of Tank Car Steels—Characterization and Analysis," Association of American Railroads, Report No. RA-03-4-32 (AAR R-192), Chicago, Illinois (August 20, 1975).

12. Eiber, R. J. and L. L. Olson, "Final Phase 03 Report on Material Study on Steels Used in Current and Former Tank Car Construction and from Cars Involved in Accidents," Association of American Railroads, Report No. RA-03-5-33 (AAR R-193), Chicago, Illinois (August 21, 1975).

13. Phillips, E. A. and W. S. Pellini, "Phase 03 Report on Behavior of Pressure Tank Car Steels in Accidents," Association of American Railroads, Report No. RA-03-6-48 (AAR R-553), Chicago, Illinois (June 20, 1983).

14. Phillips, E. A. and H. Role, "A Review of Pressure Car Shell Puncture Vulnerability," Association of American Railroads, Report No. RA-09-6-52 (AAR R-628), Chicago, Illinois (January 23, 1987).

15. Reedy, C. E. and E. A. Phillips, "Phase 12 Report on Tank Car Accident Investigation Guide," Association of American Railroads, Report No. RA-12-1-6, Chicago, Illinois (revised April 26, 1973).

16. Eiber, R. J., W. A. Maxey, and A. R. Duffey, "Analysis of Fracture Behavior of Tank Cars in Accidents," Association of American Railroads, Report No. RA-12-2-20 (R-143), Chicago, Illinois (September 1972).

17. Pellini, W. S. "Slide Graph Fracture Analysis System," Association of American Railroads, Report No. R-552, Chicago, Illinois (June 1983).

18. Pellini, W. S. "Guidelines for Fracture-Safe Design of Steel Structures," Association of American Railroads, Report No. R-455, Chicago, Illinois (November 1980).

19. Pellini, W. S. "Guidelines for Fatigue-Reliable Design of Steel Structures," Association of American Railroads, Report No. R-490, Chicago, Illinois (September 1981).

20. Association of American Railroads. "Phase 18 Study: Integrity of Damaged Tank Cars," Chicago, Illinois (pub. date unknown).

21. Association of American Railroads, *Manual of Standards and Recommended Practices*, Sec. C - Part III, "Specifications for Tank Cars," Specification M-1002.

22. Tank Car Fatigue Crack Growth Test, DOT/FRA/ORD - 93/10.

23. National Transportation Safety Board, "Derailment of Burlington Northern Freight Train No. 01-142-30 and Release of Hazardous Materials in the Town of Superior,"

Hazardous Materials Accident Report NTSB/HZM-94/01, Notation 5842B, Washington, DC (March 1994).

24. Phillips, E. A. and W. A. Pellini, "Phase 03 Report on Behavior of Pressure Tank Car Steels in Accidents," Association of American Railroads, Report No. RA-03-6-48 (June 20, 1983).

25. National Transportation Safety Board, "Derailment of Louisville and Nashville Railroad Company's Train No. 584 and Subsequent Rupture of Tank Car Containing Liquefied Petroleum Gas Waverly," Railroad Accident Report No. NTSB-RAR-79-1, Notation 2313B, Washington, DC (February 22, 1978).

26. National Transportation Safety Board, "Tank Car Structural Integrity After Derailment," Special Investigation Report No. NTSB-SIR-80-1, Notation 3062, Washington, DC (October 16, 1980).

27. Phillips, E. A. and H. Role, "Effectiveness of Shelf Couplers, Head Shields and Thermal Shields on DOT 112 (114) and 105 Tank Cars," Association of American Railroads, Report No. RA-02-5-51 (AAR R-610), Chicago, Illinois (June 13, 1985).

28. Wright, W. P. "Tank Car Damage Assessment Procedure Study," Ballistic Research Laboratory Final Report, Aberdeen Proving Ground, Maryland, to Federal Railroad Administration of the Department of Transportation, Washington, DC, Contract No. DTFR53-82-X-00275 (May 1984).

29. Bryson, W. "Tank Car Wheel Gouge, PROX 80665, Bonfield Derailment," Report of the Transportation Safety Board of Canada, Gloucester, Ontario, to the Association of American Railroads, Pueblo, Colorado, Contract No. 580-3 R95H0003 (February 1995).

30. Pellini, W. S. "Guidelines for Fracture-Safe and Fatigue-Reliable Design of Steel Structures—Applications of Fracture Mechanics and Structural Integrity Technology," Welding Institute, Abington, Cambridge, England (1983).

31. Phillips, E. A., H. Role, and L. L. Olson, "Phase 02 Report on Analysis of Non-Pressure Tank Car Behavior in Accidents," Association of American Railroads, Report No. RA-02-4-47 (AAR R-541), Chicago, Illinois (March 24, 1983).

32. Johnson, M. R. and E. A. Phillips, "Study of Railroad Tank Car Thickness Minimums," Association of American Railroads, Report No. RA-12-3-56 (AAR R-726), Chicago, Illinois (May 5, 1989).

33. Conlon, P. C. L. "Exhaust Emission Testing of In-Service Diesel-Electric Locomotives 1981 to 1983," Association of American Railroads, Publication No. R-688, Washington, DC (March 1988).

34. Shaver, D. K. and R. L. Berkowitz, "Guideline Manual, Post Accident Procedures for Chemicals and Propellants," Air Force Rocket Propellant Laboratory Report AFRPL TR-82-077 (January 1983).

35. Shaver, D. K., R. L. Berkowitz, and P. V. Washburne, "Accident Management Orientation Guide," Air Force Rocket Propellant Laboratory Report AFRPL TR-82-0075 (October 1983).

36. Beller, L. S., J. D. Mudlin, W. G. Reuter, and M. A. Tupper, "Survey of Nondestructive Methods for Evaluating Derailed Tank Cars," US Army Ballistic Research Laboratory Contract Report BRL-CR-539 (November 1984).

37. Reuter, W. G., J. D. Mudlin, R. L. Harris, F. M. Haggag, W. L. Server, and J. S. Epstein, "Evaluation of Damaged Tank Car Structural Integrity," Department of Transportation, Federal Railroad Administration, Office of Research and Development Report DOT/FRA/ORD-88/02 (January 1988).

38. Walsh, W. J. R. C. Rice, and D. R. Ahlbeck, "Stub Sills on Tank Cars," Battelle Memorial Institute, Report No. FRA/ORD-89/01, NTIS Report No. PB90-161456/WTS (March 1989).

39. Phillips, E. A. "Designing for Damage Prevention in the Railroad Tank Car Industry," *Proceedings of the 34th Meeting of the Mechanical Failures Prevention Group* (National Bureau of Standards, Special Publication 652, Washington, DC, 1983), pp. 181-212.

40. Pellini, W. S., D. H. Stone, and W. J. Harris, Jr., "Applications of Structural Integrity Technology in the Railroad Industry," *Structural Integrity Technology*, American Society of Mechanical Engineers, 125-143 (1979).

41. Phillips, E. A., R. L. Wenk, R. R. Fessler, and R. J. Eiber, "Analysis of Fracture Behavior of Tank Cars, Phase 12 Report," Association of American Railroads, Report No. RA-12-2-20 (AAR R-143), Chicago, Illinois (1972).

42. Phillips, E. A. "Report on Analysis of Tank Car Tub Rocketing in Accidents," Association of American Railroads, Report No. RA-12-2-23 (AAR R-146), Chicago, Illinois (1972).

43. Early, J. G., C. G. Interrante, S. R. Low, and B. A. Fields, "Dynamic Mechanical Properties of Two AAR M128 and One ASTM A212-B Steel Tank Car Head Plates," National Institute of Standards and Technology, Report No. NBSIR-88/3690 (June 1988).

44. Early, J. G. and C. G. Interrante, "A Metallurgical Evaluation of Two AAR M128 Steel Tank Car Head Plates Used in Switchyard Impact Tests," National Bureau of Standards, Federal Railroad Administration, Office of Research and Development, Report No. FRA/ORD-81/33 (NBSIR 80-2039) (April 1981).

45. Early, J. G. "Elevated-Temperature Mechanical Behavior of a Carbon-Manganese Pressure Vessel Steel," *J. Eng. Mater. Technol.*, **99**(4), 359-365 (October 1977).

46. Early, J. G. "Mechanical Properties of AAR M128-69-B Steel Plate Samples Taken from Insulated Fire Tested Tank Car RAX 202," National Bureau of Standards, Report No. FRA/ORD-76-74, Contract No. DOT-AR-40008 (NBSIR 75725), Washington, DC (1976).

47. Interrante, C. G. "Impact Properties of Steels Taken from Four Failed Tank Cars," National Bureau of Standards, Report No. FRA/ORD-75-51 (NBSIR 75656), Washington, DC (1976).

48. Hicho, G. E. and C. H. Brady, "Hazardous Materials Tank Cars—Evaluation of Tank Car Shell," National Bureau of Standards, Report No. FRA/ORD-75-46, Washington, DC (1975).

49. Interrante, C. G., G. E. Hicho, and D. E. Harne, "A Metallurgical Analysis of Eleven Steel Plates Taken from a Tank Car Accident Near Callao, Missouri," National Bureau of Standards, Report No. NBS/312.01/51; FRA/ORD-75-49, Washington, DC (1972).

50. Lyle, F. J. "A Study of Stress Corrosion Phenomena Resulting From Transportation of Anhydrous Ammonia in Quenched-and-Tempered Steel Cargo Tanks," Southwest Research Institute, Report No. SWRI-01-4101-001; DOT-FHBMCS-11-8568, San Antonio, TX (1976).

51. Interrante, C. G. and G. E. Hicho, "Metallurgical Analysis of a Steel Shell Plate Taken from a Tank Car Accident Near South Byron, New York," National Bureau of Standards, Report No. NBX-312.01/35; FRA/ORD-75/47, Washington, DC (1971).

52. Early, J.G. and C. G. Interrante, "A Metallurgical Investigation of a Full-Scale Insulated Rail Tank Car Filled with LPG Subjected to a Fire Environment," National Bureau of Standards, Report No. FRA/ORD-75-52 (NBSIR 75657), Washington, DC (1975).

53. Olson, L.L. "Data Display Report on Results of Tests on Mill Plate Samples and Samples Removed from Tank Cars Involved in Accidents, Phase 03 Report," Association of American Railroads, Report No. RA-03-3-13 (AAR R-136), Chicago, Illinois (1972).

54. Wisnowski, M. J. "Coupler Steel Study," Association of American Railroads, Report No. 70R-61 (AAR R-107), Chicago, Illinois (1970).

55. Brown, S. J. and T. J. Brown, "Explosion Failure of a Pressurized Railroad Tank Car Initiated at a Nozzle: Forensic Investigation," *Proceedings of the 1994 Pressure Vessels and Piping Conference*, Part 13, New York, **282**, 137-156 (1994).

56. National Transportation Safety Board, "Railroad Accident Report: Louisville and Nashville Railroad Company Freight Train Derailment and Puncture of Hazardous Materials Tank

Cars," Bureau of Accident Investigation, Report No. NTSB-RAR-79-11, Washington, DC (1979).

57. Rice, J. "3 LPG Blasts Follow Derailment of Tankers, Evaluation of Area," *Fire Engineering Journal*, **132**(3), 24-26, 1979.

58. National Transportation Safety Board, "Railroad Accident Report: Derailment of a Burlington Northern Freight Train at Belt, Montana, November 26, 1976," Bureau of Accident Investigation, Report No. NTSB-RAR-77-7, Washington, DC (1977).

59. National Transportation Safety Board, "Railroad Accident Report: Derailment of Tank Cars with Subsequent Fire and Explosion on Chicago, Rock Island, and Pacific Railroad Company, Near Des Moines, Iowa, September 1, 1975," Bureau of Surface Transportation Safety, Report No. NTSB-RAR-76-8, Washington, DC (1976).

60. National Transportation Safety Board, "Railroad Accident Report: Hazardous Materials Accident at the Southern Pacific Transportation Company's Englewood Yard in Houston, Texas, September 21, 1974," Bureau of Surface Transportation Safety, Report No. NTSB-RAR-75-7, Washington, DC (1975).

61. National Transportation Safety Board, "Railroad Accident Report: Hazardous Materials Accident in the Railroad Yard of the Norfolk and Western Railway at Decatur, Illinois, July 19, 1974," Bureau of Surface Transportation Safety, Report No. NTSB-RAR-75-4, Washington, DC (1975).

62. Weston, R.A. "Report on Accident Review, Phase 01 Report," Association of American Railroads, Report No. RA-01-4-16 (R-139), Chicago, Illinois (1972).

63. Phillips, E. A. "Overall Project Summary Report," Association of American Railroads, Report No. RA-00-1-22 (R-145), Chicago, Illinois (1972).

64. Reedy, C.R., L. L. Olson, and R. A. Weston, "Sequence of Events Following Crescent City Derailment," Association of American Railroads, Report No. RA-01-1-1 (R-124), Chicago, Illinois (1970).

65. National Transportation Safety Board, "Railroad Accident Report: Southern Railway Company Train 154 Derailment with Fire and Explosion Laurel, Mississippi, January 25, 1969," Department of Transportation, Washington, DC (1969).

66. National Transportation Safety Board, "Railroad Accident Report: Derailment and Subsequent Burning of Delaware and Hudson Railway Freight Train at Oneonta, New York, February 12, 1974," Report No. NTSB-RAR-74-4, Washington, DC (1974).

67. National Transportation Safety Board, "Railroad Accident Report: Pennsylvania Railroad Train PR-11A, Extra 2210 West and Train SW-6, Extra 2217 East Derailment and

Collision, Dunreith, Indiana, January 1, 1968," Report No. SS-R-2, Washington, DC (1968).

68. National Transportation Safety Board, "Railroad Accident Report: Illinois Central Railroad Company Train Second 76 Derailment at Glendora, Mississippi, September 11, 1969," Report No. NTSB-RAR-70-2, Washington, DC (1970).

69. National Transportation Safety Board, "Railroad Accident Report: Chicago, Burlington, and Quincy Railroad Company Train 64 and Train 824 Derailment and Collision with Tank Car Explosion Crete, Nebraska, February 18, 1969," Report No. NTIS-RAR-71-2, Washington, DC (1971).

70. National Transportation Safety Board, "Railroad Accident Report Derailment of Toledo, Peoria, and Western Railroad Company's Train No. 20 with Resultant Fire and Tank Car Ruptures, Crescent City, Illinois, June 21, 1970," Report No. NTSB-RAR-72-2, Washington, DC (1972).

71. Venart, J. E. S. "Major Hazards in the Transport and Storage of Pressure Liquified Gasses," *Journal of Hazardous Materials*, **20**, 3-392 (1988).

72. "Tank-Car Retrofit: What? How many? When?," G. Welty, Ed., *Railway Age*, **179**(12), 31-33 (Simmons-Boardman Publishing Corporation, Bristol, CT, 1978).

73. Anderson, C. and E. B. Norris, "Fragmentation and Metallurgical Analysis of Tank Car Rax 201," Ballistic Research Laboratory, Aberdeen Proving Ground, Federal Railroad Administration, and Office of Research and Development, Final Report, Washington, DC (1974).

74. Skogsberg, A.M. "Report on Literature and Related Experience, Phase 04 Report," Association of American Railroad, Report No. RA-04-1-8 (R-131), Chicago, Illinois (1971).

75. Dancer, D.M. "Rail Tank Car Impacts," National Bureau of Standards, Special Publication 652, Washington, DC, 165-171 (1983).

76. Interrante, C.G. "Fracture of Steel Plate Materials Under Abusive Service Conditions in Railroad Tank Cars," National Bureau of Standards, Special Publication 621, Washington, DC, 18-29 (1982).

77. Hechmer, J.L. and G. L. Hollinger, "The ASME Code and 3D Stress Evaluation," *Journal of Pressure Vessel Technology*, **113**, 481-487 (November 1991).

78. Rahka, K. "The Anatomy of a Break Before Leak Case," ASME PVP-Vol. 281, *High Pressure Technology*, ASME, 49-54 (1994).

79. Underwood, J. H., R. A. Farrara, and M. J. Audino, "Yield-Before-Break Fracture Mechanics Analysis of High-Strength Steel Pressure Vessels," *Journal of Pressure Vessel Technology*, **117**, 79-84 (February 1995).

80. Rana, M. D. "Structural Integrity Assessment of Carbon and Low-Alloy Steel Pressure Vessels Using a Simplified Fracture Mechanics Procedure," *Journal of Pressure Vessel Technology*, **116**, 324-330 (August 1994).

81. Widera, G. E. O., Z. F. Sang, and R. Natarajan, "On the Design of Horizontal Pressure Vessels," *Journal of Pressure Vessel Technology*, **110**, 393-401 (November 1988).

82. Bloom, J. M. "Extensions of the Failure Assessment Diagram Approach Semi-Elliptical Flaw in Pressurized Cylinders—Part II," *Journal of Pressure Vessel Technology*, **108**, 485-489 (November 1986).

83. Iwadate, T, Y. Tanaka, and H. Takemata, "Prediction of Fracture Toughness K_{IC} Transition Curves of Pressure Vessel Steels from Charpy V-Notch Impact Test Results," *Journal of Pressure Vessel Technology*, **116**, 353-358 (November 1994).

84. Sugie, E., Sugie M. Matsuoka, T. Akiyama, K. Tanaka, and Y. Kawaguchi, "Notch Ductility Requirements of Line Pipes for Arresting Propagating Shear Fracture," *Journal of Pressure Vessel Technology*, **109**, 428-434 (November 1987).

85. Baum, M. R. "Disruptive Failure of Pressure Vessels: Preliminary Design Guidelines for Fragment Velocity and the Extent of the Hazard Zone," *Journal of Pressure Vessel Technology*, **110**, 168-176 (May 1988).

86. Rosenberg, Z., J. Mironi, A. Cohen, and P. Levy, "On the Catastrophic Failure of High-Pressure Vessels by Projectile Impact," *Int. J. Impact Engng.*, **15**(6), 827-831 (1994).

87. Hahn, G. T., M. Sarrate, and A. R. Rosenfield, "Criteria for Crack Extension in Cylindrical Pressure Vessels," *Int. Journ. of Fracture Mech.*, **5**(3), 187-210 (September 1969). Printed in the Netherlands.

88. Hahn, G. T., M. Sarrate, M. F. Kanninen, and A. R. Rosenfield, "A Model for Unstable Shear Crack Propagation in Pipes Containing Gas Pressure," *Int. Journ. of Fracture*, **9**(2), 209-222 (June 1973). Printed in the Netherlands.

89. Rana, M. D. "Experimental Verification of Fracture Toughness Requirement for Leak-Before-Break Performance for 155-175 ksi Strength Level Gas Cylinders," *Journal of Pressure Vessel Technology*, **109**, 435-439 (November 1987).

90. Lupkner, H. A. "LPG Rail Tank Cars Under Head-On Collisions," *International Journal of Impact Engineering.* **9**, 359-376 (1990).

91. Pieratt, S. AAR-TTC, *private communication.*

92. Anderson, T. L. *Fracture Mechanics: Fundamentals and Applications*, CRC Press, Boca Raton (1991).

93 Barsom, J. M. and S. T. Rolfe, *Fracture and Fatigue Control in Structures: Applications of Fracture Mechanics*, Second Edition, Prentice-Hall, Englewood Cliffs (1987).

94. Knott, J. F. *Fundamentals of Fracture Mechanics*, John Wiley & Sons, New York (1973).

95. Giovanola J. H. and I. Finnie, "A Review of the Use of the J-Integral as an Elastic-Plastic Fracture Parameter," *Solid Mechanics Archives*, **9**, 197 (1984).

96. *Ductile Fracture Handbook*, Volumes 1 and 2, Electric Power Research Institute, Palo Alto (1989).

97. Giovanola, J. H. and I. Finnie, "The Crack Opening Displacement (COD) as an Elastic-Plastic Fracture Parameter and a Comparative Assessment of the COD and J-Integral Concepts, " *Solid Mechanics Archives*, **9**, 227 (1984).

98. Mudry, F. "Methodology and Applications of Local Criteria for Prediction of Ductile Tearing," *Elastic-Plastic Fracture Mechanics,* L. H. Larson, ed., ECSC, EEC, EAEC, Brussels and Luxembourg, Belgium, 263-283 (1985).

99. Mudry, F., M. Di Fant, A. Fontaine, and C. Sainte Catherine, "Development of Local Criteria in Steels," in *Advances in Local Fracture/Damage Models for the Analysis of Engineering Problems,* AMD-Vol. 137 , J. H, Giovanola and A. J. Rosakis, eds., American Society of Mechanical Engineers, New York, 305-318 (1992).

100. Curran, D. R., L. Seaman, and D. A Shockey, "Dynamic Failure of Solids," *Physics Reports*, **147**, 253-388 (1987).

101. Tvergaard, V., "Material Failure by Void Growth to Coalescence," *Advances in Applied Mechanics,* **27**, Academic Press, New York, 83-151 (1990).

102. Pineau, A. "Global and Local Approaches of Fracture—Transferability of Laboratory Test Results to Components," in Topics in Fracture and Fatigue, A. S. Argon, Editor, Springer Verlag, New York, 197-234 (1990).

103. MacKenzie, A. C., J. W. Hancock, and D. K. Brown, "On the Influence of State of Stress on Ductile Failure Initiation in High-Strength Steels," *Engineering Fracture Mechanics*, **9**, 167-188 (1977).

104. Giovanola J. H. and S. W. Kirkpatrick, "Applying a Simple Ductile Fracture Model to Fracture of Welded T-Joints," in *Advances in Local Fracture/Damage Models for the*

Analysis of Engineering Problems, AMD-Vol. 137 (American Society of Mechanical Engineers, New York, 285-303 (1992).

105. Giovanola J. H. and S. W. Kirkpatrick, "Methodology for Evaluating Strength and Fracture Resistance of Weldments Using a Local Approach to Fracture," in *Pressure Vessel Integrity-1993*, PVP-Vol. 250, W. E. Pennel, S. Bhandari, G. Yagawa, eds., American Society of Mechanical Engineers, New York, 157-171 (1993).

106. Wierzbicki T. and M. S. Suh, "Indentation of Tubes under Combined Loading," *International Journal of Mechanical Sciences*, **30**, 229-248 (1988).

107. ASTM Standard E 208-91, "Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," Annual Book of ASTM Standards, Section 3, vol. 03.01, American Society for Testing and Materials, Philad elphia (1994).

108. ASTM Standard E 813-89, "Standard Test Method for J_{IC}, a Measure of Fracture Toughness," *Annual Book of ASTM Standards*, Section 3, Vol. 03.01, American Society for Testing and Materials, Philadelphia (1994).

109. ASTM Standard E 1152-87, "Standard Test Method for Determining *J-R* Curves," *Annual Book of ASTM Standards*, Section 3, Vol. 03.01, American Society for Testing and Materials, Philadelphia (1994).

110. Association of American Railroads, Transportation Test Center, Hazardous Material Training School, *Tank Car Safety Course Manual,* Pueblo, Colo.(1991).

APPENDIX B

Expert Review

Comments were received from several individuals after their review of the Draft Final Report titled, *Literature Search and Evaluation Pertaining to Damage Assessment of Tank Cars Involved in Accidents,* prepared by SRI. In the list below, the reviewers are identified along with the company and/or organization they represent and their comments. Several of the comments were not received prior to the SRI report being finalized and were not incorporated. Those comments will be taken into consideration when Phase II modeling and validation efforts are planned and during the drafting of the handbook.

- J. Robert Sims, Exxon Research and Engineering, P.O. Box 101 Florham Park, NJ 07932; ASME Pressure Vessel and Piping Division, Post Construction Committee Chairman.

  (1) "The document is an excellent summary of the problem, and gives good guidance for the future work which is needed."

  (2) "The discussion of dents and delayed fracture appears to be well reasoned. Slow, stable crack growth due to time dependent behavior of materials is a very real possibility and should be studied if additional work is undertaken in this area."

  (3) "The proposed work should be of interest for other applications such as pipelines and other pressure vessels."

- Dr. William J. Koves, UOP, Inc., 25 East Algonquin Road, Des Plaines, IL 60017-5017; ASME Pressure Vessel and Piping Division, Chairman of the Flaw Analysis Subcommittee to the Post Construction Committee.

  (1) "The procedures for evaluating dents is a simple, field expedient method and the radii of curvature appear somewhat arbitrary."

  (2) "Limiting the radius of curvature is a good practical method, since the influence of global damage, out of roundness, etc. on the stress at the local critical regions is not evaluated."

(3) "Loads other than internal pressure do not seem to be addressed. Support attachment stresses as well as those due to lifting the car should be evaluated. High local compressive stresses could cause buckling in low pressure applications."

(4) "Scores, gouges, and wheel burns could be evaluated as local thin areas, using some of the information already published.

(5) "The use of NDE should be considered in critical applications since cracks in a cold work region may behave in a brittle manner."

(6) "The effect of damage on material properties must also be considered. The effect of cold work or heat due to friction should be evaluated."

(7) "The ASME Subcommittee on Flaw Evaluation will be addressing some similar issues and would like to cooperate with the AAR in any way."

- Stephen Wong, Chief Engineer, Rail Car Division, Procor Limited, 2001 Speers Rd., Oakville, Ontario L6J 5E1.

(1) "We feel the report achieved its objective of gathering information relating to damaged tank cars and pressure vessels, and their residual structural integrity, thus providing a good assessment of the validity of the current AAR guidelines."

(2) The report revealed omissions, inconsistencies, and/or errors in the guidelines that should be resolved. The findings appear to be sound.

(3) The approach SRI recommends to validate the criteria and to improve the reliability and usefulness of the guidelines appears reasonable.

(4) Any revisions to the guidelines should maintain a significant factor of safety to allow its use under field conditions.

(5) "The existing guidelines are direct, simple, easy to understand and use. Any revisions should also be easy to understand and use."

- Paul Kinnecom," Assistant Director of Tank Cars, Customer Operations, Operations and Maintenance Department, Association of American Railroads, Washington Headquarters, 50 F Street, N.W., Washington DC 20001.

(1) Page 15 of the report make reference to a TC-135A steel specification. "TC-135A was a draft steel specification that was proposed, but never implemented for tank car construction. It is not representative of tank car steels, and conclusions based upon a study of TC-135A should be made with care."

(2) "On Page 13, reference is made to an "A-340" tank car and it is implied that such a car may transport carbon dioxide, hydrogen, chloride, or hydrogen sulfide with associated tank stresses (due to commodity pressure) of up to 60 percent of the tank material yield stress. The referenced commodities are required by DOT to be transported in -500, -600, and -800 lb. tanks, respectively. The logic of this paragraph needs to be revisited."

- Diane Rocheleau, Superintendent, Materials Engineering, Engineering Branch, Transportation Safety Board of Canada, 1901 Research Road, Gloucester, Ontario K1A 1K8.

  (1) "Page 23: rail burn vs. rail dent. I see a burn as resulting in metallurgical changes in the metal, for example the creation of an untempered martensitic layer. A dent would not have such a microstructural change. If a rail impacts the tank car, yes a rail dent, but if the tank car slides along the rail and the material is blued or if a significant gouge appears and localized heating of the microstructure took place, I would call this a rail burn."

  (2) "Page 28, I fully agree that NDE methods should be considered, since stresses can be measured using methods such as infrared thermography, acoustic emission, etc."

- Edgar Ladouceur, Chief of Response Operations, Transport Canada, Canada Building, 344 Slater Street, Ottawa, Ontario K1A ON5.

  (1) The report does a good job of providing background information regarding the origin of the guidelines as well as identifying the shortcomings of the guidelines.

  (2) "The recommendations put forth in the report regarding future research appear reasonable and appropriate."

  (3) "The only caution flag that I would raise is that it will be important to ensure that the final product be something useful at the field level. A small pocket guide would be helpful for responders in the field. The margins of safety associated with using the "rule of thumb" information contained in the pocket guide would also need to be well identified."