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MECHANICAL PROPERTIES OF TANK CAR STEELS RETIRED FROM THE FLEET

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ABSTRACT

As a consequence of recent accidents involving the release of hazardous materials (hazmat), the structural integrity and crashworthiness of railroad tank cars have come under scrutiny. Particular attention has been given to the older portion of the fleet that was built prior to steel normalization requirements instituted in 1989.

This paper describes a laboratory testing program to examine the mechanical properties of steel samples obtained from tank cars that were retired from the fleet. The test program consisted of two parts: (1) material characterization comprised of chemical, tensile and Charpy V-notch (CVN) impact energy and (2) high-rate fracture toughness testing.

In total, steel samples from 34 tank cars were received and tested. These 34 tank cars yielded 61 different pre-1989 TC128-B conditions (40 shell and 21 head samples), three tank cars yielded seven different post-1989 TC128-B conditions (four shell and three head samples), and six tank cars yielded other material (A212, A515, and A285 steel) conditions (six shell and five head samples).

The vast majority of the TC128-B samples extracted from retired tank cars met current TC128-B material specifications. Elemental composition requirements were satisfied in 97 percent of the population whereas the required tensile properties were satisfied in 82 percent of the population. Interpretation of the high-rate fracture toughness tests required dividing the pre-1989 fleet into quartiles that depended on year of manufacture or age, and testing three tank cars per quartile. Considering the high-rate fracture toughness results at 0ºF for the pre-1989 fleet, 100 percent of the oldest two quartiles, 58 percent of the second youngest quartile, and 83 percent of the youngest quartile exhibited adequate or better fracture toughness (defined as toughness greater than 50 ksi$\sqrt{in}$). High-rate fracture toughness at –50ºF was adequate for 83 percent of two quartiles (the youngest and second oldest), but the other two quartiles exhibited lower toughness with only 33 (2nd youngest) to 50 percent (oldest) exhibiting adequate properties.

INTRODUCTION

The safe transport of hazardous materials (hazmat) by railroad tank cars is a concern to Government regulatory agencies and industry stakeholders. Both Government and industry have sponsored research over the past several decades to maintain the structural integrity of railroad tank cars under a broad range of loading conditions that vary from the normal operating environment to rare events such as accidents.

In the late 1980s, the Association of American Railroads recommended practices were changed to require all subsequent pressure cars to be fabricated from normalized TC128-B steel. Prior to 1989, non-normalized steel was predominantly used. Non-normalized steel has a higher transition temperature and potentially lower fracture toughness when compared to normalized steel.

However, the structural integrity of railroad tank cars during accidents has recently come under greater scrutiny due to three particular accidents involving the release of hazmat: (1) a derailment that occurred near Minot, North Dakota on January 19, 2002 [1], (2) a train collision that occurred in Macdona, Texas on June 28, 2004 [2], and (3) a train collision that occurred in Graniteville, South Carolina on January 6, 2005 [3]. Each of these accidents resulted in a release of hazmat and subsequent fatalities. Based on findings from investigations of these accidents, the National Transportation Safety Board (NTSB) made a series of safety recommendations to the Federal Railroad Administration (FRA). In particular, the following recommendation was issued following the Minot accident, and reiterated following the Macdona accident:

"Conduct a comprehensive analysis to determine the impact resistance of the steels in the shells of pressure cars constructed before 1989. At a minimum, the safety analysis should include results from dynamic fracture toughness tests and/or the results of nondestructive testing techniques that provide information on material ductility and fracture toughness. The data should come from a statistically representative sampling of the shells of the pre-1989 pressure tank car fleet."

In its role to provide technical support to the FRA, the Volpe National Transportation Systems Center (Volpe Center) enlisted experimental expertise to carry out a laboratory testing program to address the NTSB recommendation. This paper briefly summarizes the major results from this testing program.

The laboratory testing program was focused on quantifying overall material performance. In particular, it determined the basic material characterization (analysis of chemical or elemental composition, tensile properties and Charpy v-notch impact energy) parameters as well as the high-rate fracture toughness at rates consistent with what might be experienced during accidents such as derailments and train collisions.

Material for the testing program was obtained from tank cars that were retired from the fleet. A more comprehensive and detailed description of the entire testing program can be found in the final technical report [4] that is currently available on the Volpe website (*http://www.volpe.dot.gov/sdd/pubs-tank.html*).

PRESSURE TANK CAR FLEET CHARACTERIZATION

Data were obtained from the Universal Machine Language Equipment Register (UMLER), which is maintained by the Association of American Railroads, in order to examine the make-up of the pressure tank car fleet in terms of material distribution and age. The data shown in Figure 1 represent a snapshot of the fleet at the time when the laboratory test program was initiated (April 2005). Over 93 percent of the fleet is fabricated from TC128-B with four percent made from A212-B. The remaining three percent of the pressure tank car fleet is fabricated from other materials, which include A515, A516 and A285-C as the most numerous choices in this small percentage of the fleet.

An overlay of two plots is indicated in Figure 2 providing a sense of the material obtained and the fleet make-up. The bottom plot shows the cumulative number of pressure cars as a function of year of manufacture for (a) the whole fleet (represented by the triangles) and (b) the pre-1989 fleet (represented by the squares). Approximately 75 percent of the pressure car fleet was built prior to 1998. Moreover, one-quarter of the fleet was produced before 1976 and one-half before 1990. The top plot shows the makeup of the cars from which the material for the test program was obtained. Material from these retired cars were donated from owners and operators of the pressure car fleet.

MATERIAL CHARACTERIZATION

Basic material characterization was conducted in accordance with standard test methods that are developed and published by the American Society for Testing and Materials (ASTM), as listed in Table 1. Although all materials (Figure 1) were examined, the focus of the results presented herein will be on TC128-B material, the most prevalent material found in the pressure car fleet.

Table 1: Standard Material Characterization Tests

Type of Characterization	*ASTM Standard*
Chemical (elemental) analysis	ASTM E415 [5]
Tensile properties	ASTM A370 [6]
CVN impact energy	ASTM A23 [7]

Chemical Composition

In the chemical analysis, sixteen elements were measured and reported, even though the TC128-B composition specification calls for controlling only nine distinct elements. In summary, 59 of 61 TC128-B samples (97 percent) met composition requirements. One of the deviations was due to a slightly higher carbon content than allowable (0.32 wt % as opposed to the criteria of <0.29 wt %). The second deviation was due to higher (0.05 wt %) than allowable (< 0.04 wt %) sulfur content. No other disparities with regard to chemical content were noted during testing. However a cautionary point should be noted; the applicability of modern AAR material specification to vintage material (some of it 30 years old) is not clear.

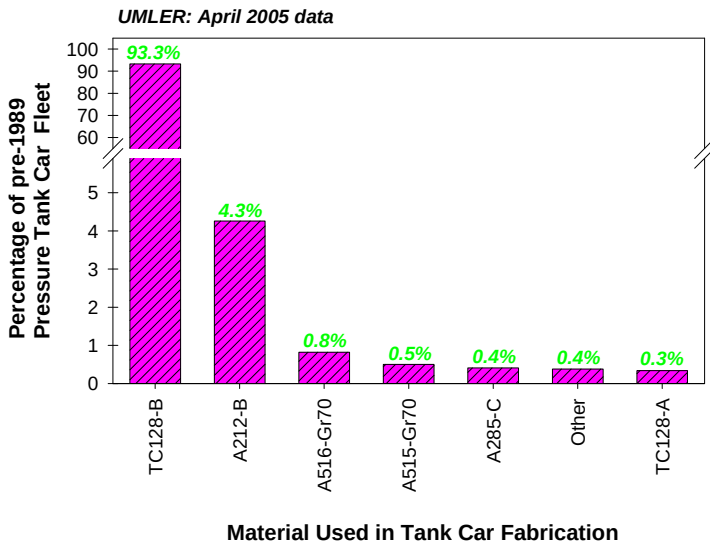


Figure 1: Steel Types in Pre-1989 Pressure Tank Car Fleet

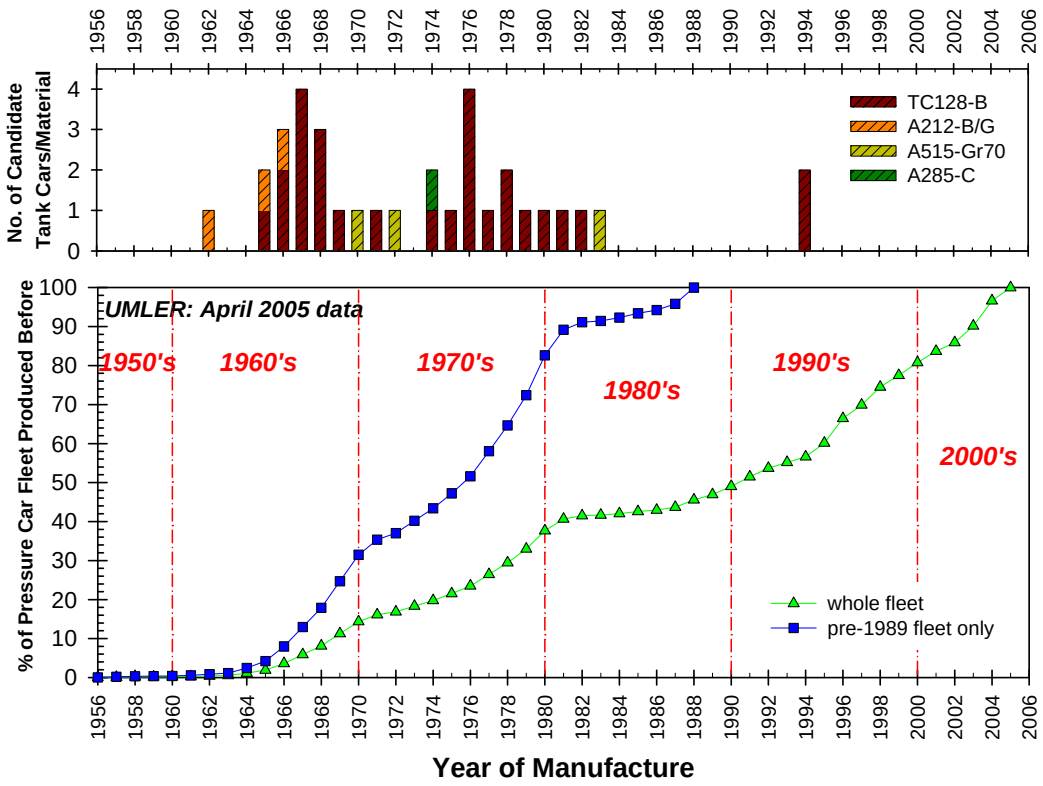


Figure 2: Cumulative Distribution of Pressure Tank Car Fleet and Tank Cars Used for Testing

Tensile Properties

Measurements of tensile properties included: yield strength, ultimate strength, and ductility in terms of percent elongation and percent reduction in area. The customary gage length specimen utilized was a 2-inch gage length, although material limitations sometimes required testing subsize (1-inch or 1.4-inch) gage length specimens. All specimens were oriented transverse to the primary plate axis for the shell specimens although in the case of the head specimens the orientation was arbitrary.

Table 2: Tensile Property Specifications for TC128-B

Property	*Allowable**
Ultimate Tensile Strength	81 to 101 ksi
Yield Strength	Greater than 50 ksi
Elongation	Greater than 22%

*AAR Manual of Standards and Recommended Practices and Specifications for Tank Cars, M-1002, Appendix M.

Charpy Impact Energies

Charpy tests were conducted at three different temperatures: ±50ºF and 0ºF. CVN specimens from the shell material were oriented with the primary axis of the specimen in the transverse plate direction and the crack direction orthogonal and in the plane of the plate.

Tensile and Impact Property Summary

A summary of the average tensile properties and CVN impact data is shown in Table 3. The data trend as a function of time, with the tank car fleet divided up into quartiles, is depicted in Figures 3-5. A total of 61 TC128-B conditions were examined: 40 shell and 21 head conditions.

In summary, two material conditions exhibited slightly lower than allowable yield strength (45 and 48 ksi versus the minimum 50 ksi). Three material conditions exhibited ductilities slightly lower (in the range of 19-21%) than allowed (percent elongation in excess of 22%). The allowable UTS range (81-101 ksi) was exceeded in nine samples (two with higher and seven with lower values). In only one case was the measured strength level in excess of 5 ksi lower than the allowable (approximately 7 ksi low). Given requirements on ductility, ultimate and yield strengths, all except eleven tank car material conditions (82% of the total) were within the required TC128-B specifications.

There is no current applicable TC128-B CVN energy level required. As noted in Table 3 and Figure 5, considerable scatter was evident in the highest temperature CVN value. The lowest observed impact energies were in the shell at the lowest -50° F test condition where single digit energies were observed. Contrast this with the highest energies observed for the normalized material (head or post 1989) where energies in excess of 25 ft-lbs were commonly observed.

Table 3: Statistical analysis (averages and standard deviations) of TC128-B material characterization testing.

Subset A:	1969 and before build date,	25% of the pre-1989 pressure car fleet
Subset B:	1970 to 1976 build date,	25-52% (27% total) of the pre-1989 pressure car fleet
Subset C:	1977 to 1979 build date,	52-72% (20% total) of the pre-1989 pressure car fleet
Subset D:	1980 and later build date,	28% of the pre-1989 pressure car fleet

Data	Tank	# Cars	UTS, ksi			YS, ksi			Elong, percent			RA, percent			CVN at +50°F			CVN at 0°F			CVN at -50°F		
Set	**Posn**	**(conds)**	**N**	**avg**	**2SD**	**N**	**avg**	**2SD**	**N**	**avg**	**2SD**	**N**	**avg**	**2SD**	**N**	**avg**	**2SD**	**N**	**avg**	**2SD**	**N**	**avg**	**2SD**
all	H&S	25 (61)	122	88.8	13.45	122	61.1	13.33	122	26.3	7.15	122	54.3	14.78	110	31.9	49.07	141	19.9	33.60	110	9.8	17.58
	S-only	25 (40)	80	89.3	14.72	80	60.5	15.31	80	24.8	5.90	80	50.2	9.81	74	21.0	18.77	96	12.5	13.55	74	6.3	9.18
	H-only	19 (21)	42	87.7	10.45	42	62.3	8.01	42	29.2	5.52	42	62.1	8.69	36	54.4	60.69	45	35.5	41.43	36	16.9	21.83
A	H&S	11 (28)	56	87.6	12.56	56	60.0	10.87	56	26.6	6.93	56	55.1	14.56	52	32.7	40.94	59	19.6	31.84	52	9.2	14.52
	S-only	11(16)	32	87.6	13.75	32	58.9	13.49	32	24.9	5.95	32	50.0	9.66	30	20.9	13.93	34	12.6	13.93	30	5.7	7.94
	H-only	11 (12)	24	87.6	11.06	24	61.6	4.50	24	28.9	5.37	24	62.0	5.69	22	48.8	43.82	25	29.1	39.06	22	14.0	15.98
B	H&S	7 (17)	34	90.0	13.37	34	60.8	15.39	34	26.0	7.39	34	52.8	12.07	26	23.1	21.56	47	17.4	26.92	26	6.9	8.76
	S-only	7 (13)	26	90.9	13.58	26	59.9	16.34	26	24.6	6.00	26	50.3	6.67	22	20.1	14.16	37	11.1	9.08	22	5.5	3.94
	H-only	3 (4)	8	87.0	11.37	8	63.5	10.89	8	30.3	3.96	8	60.9	11.68	4	39.3	28.58	10	40.7	17.51	4	15.0	10.95
C	H&S	4 (8)	16	89.7	11.98	16	62.9	12.40	16	25.3	5.78	16	53.4	13.14	16	33.4	67.27	19	18.5	21.00	16	12.6	23.45
	S-only	4 (6)	12	89.4	13.88	12	62.5	14.01	12	24.8	5.49	12	51.6	11.96	12	22.8	27.72	15	16.9	18.71	12	10.3	14.77
	H-only	2 (2)	4	90.8	1.87	4	64.2	6.23	4	26.8	6.45	4	58.7	11.73	4	65.0	112.68	4	24.5	27.74	4	19.5	40.08
D	H&S	3 (8)	16	89.4	17.43	16	63.8	16.16	16	26.9	8.63	16	55.3	21.27	16	42.6	73.86	16	29.6	58.10	16	13.6	26.36
	S-only	3 (5)	10	90.7	20.55	10	64.8	17.48	10	24.7	6.80	10	48.8	14.28	10	21.3	28.27	10	10.8	13.28	10	5.6	8.94
	H-only	3 (3)	6	87.2	10.72	6	62.2	14.60	6	30.7	5.61	6	66.3	8.12	6	78.0	72.67	6	61.0	47.28	6	27.0	23.66
normalized		3 (7)	13	81.7	5.71	13	55.4	5.14	13	31.2	7.47	13	62.0	16.62	12	77.3	94.95	15	52.2	63.22	12	26.4	38.33

 # Cars = No. of unique tank cars, **conds** = unique material conditions, **H** = head, **S** = shell, **avg** = average, **2SD** = 2 std. deviations

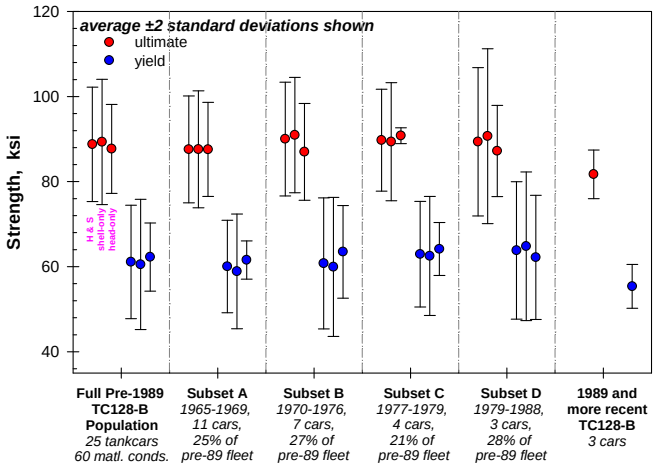


Figure 3: Strength properties of the tank car fleet.

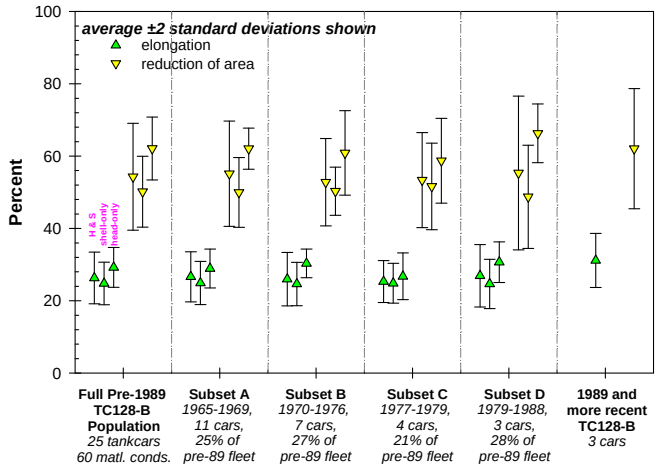


Figure 4: Ductility properties of the tank car fleet.

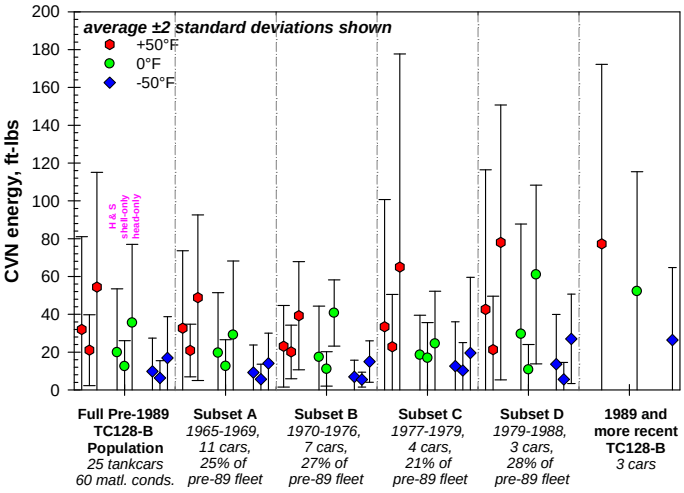


Figure 5: CVN impact energy of the tank car fleet.

Tensile/Impact Property Correlation with Composition

It is useful to examine if any correlations exist between key compositional quantities and the tensile/impact performance. One theory tested is a correlation between sulfur content and upper shelf impact energy [8]. This correlation, shown in Figure 6, clearly indicates no functional relationship between sulfur content and upper shelf CVN energy. This plot does provide an excellent indication of the low CVN energies associated with the shell material compared with the effectively normalized head material. However the highest energies and cleanest compositions are observed in the most recent, normalized (post-1989) condition although data are few.

Finally, the correlation between carbon content and yield strength is shown in Figure 7. As before with sulfur content, there does not appear to be any clear functional relationship between carbon and strength. Although in some cases the error bars are fairly broad, the amount of data is likely sufficient to conclude no functional link between these variables.

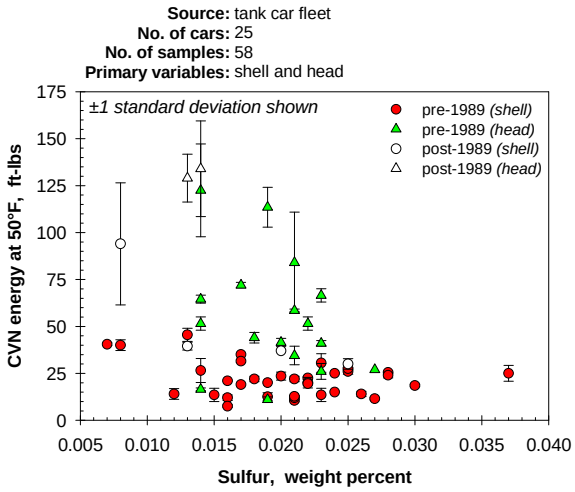


Figure 6: Poor correlation between impact energy and tensile properties for TC128-B steel.

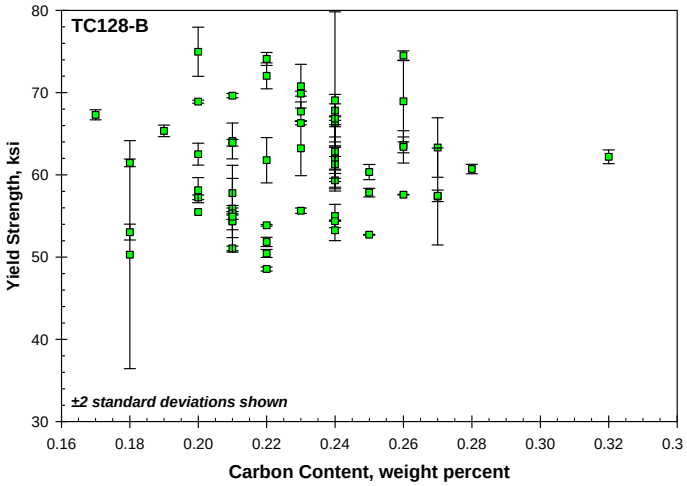


Figure 7: Poor correlation between carbon content and yield strength for TC128-B steel.

HIGH-RATE FRACTURE TOUGHNESS TESTING

Tests were conducted in accordance with ASTM E399 [9] and ASTM E 1820-01 [10] at two different temperatures: 0 ºF and –50ºF. Compact tension specimens with a width of 2-inch were utilized for testing. The thickness of the specimens depended upon the starting thickness of the shell/head product; the majority of specimens were 0.5-0.6 inch thick. These specimens were oriented in the T-L direction and configured with an eddy current displacement gage that provided sufficient responsiveness for the high rate testing. In addition, a displacement gage was also utilized on the front face of the specimens and strain gages on the back face of the specimens. Redundant load measurements were available with instrumented grips and a conventional, high response load cell. A slack adapter was utilized in the loading train to insure that the fastest strain rate was applied to the specimens.

During high rate toughness testing, the integrity of the load-displacement behavior is often less than optimum (due primarily to dynamic effects). When this occurs, it is often difficult to apply a conventional offset analysis procedure to determine a K_{Ic} from the test data. Therefore, during this testing the reported toughness is a K_{max} toughness corresponding to the maximum applied stress intensity factor calculated using the initial crack length and the maximum load (assuming no crack advance or tearing). This approach yields conservative values where higher levels of plasticity are observed (non-brittle conditions) and also minimizes bias in the test results. To account for plasticity, a correction to the K_{max} value was applied to yield a K_{Jmax} value so as to accommodate the plasticity under the load-displacement curve consistent with methods presented in the ASTM elastic-plastic toughness test procedures.

A framework for interpreting fracture toughness values was developed previously by Anderson and McKeighan [11] based upon existing design codes for pressure vessels, bridges and other structure. Classifications for different values of

fracture toughness obtained from the K_{max} approach were defined as follows:

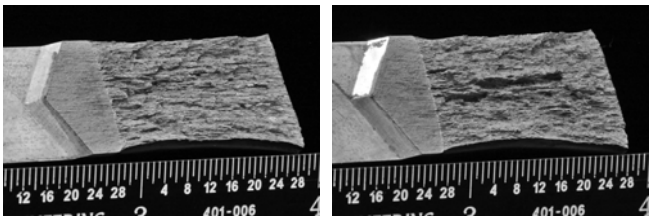
- Less than 50 ksi√in — Poor toughness
- 50 – 100 ksi√in — Adequate toughness
- 100 – 200 ksi√in — Good toughness
- Greater than 200 ksi√in — Excellent toughness

Typical Behavior and Overall Toughness Results

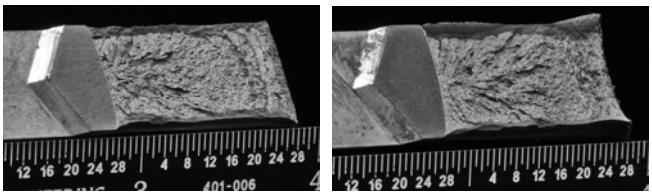
Example fracture surfaces that indicate the type of fractures observed are shown in Figure 8. The gross fracture morphology was rough and typically indicative of high energy fracture. Some texture was noted especially in the older product where lamellar layers, consistent with grain structure, were sometimes observed on the fracture surface.

Fracture toughness was measured at loading or strain rates that might be experienced during accidents such as derailments and collisions. An estimate of the strain rate during an accident was made based on collision dynamics analysis. Assuming that an impact speed of 40 miles per hour creates a dent depth of 20 inches, the corresponding strain rate is 35 inch per inch per second. The observed actuator rates were typically on the order of 50-65 inch/second. This rate translated into a strain rate, on the back face of the specimen, of 2-4 in/in/second. In terms of applied stress intensity factor, the high rate toughness tests were on the order of 50,000-100,000 ksi√in/second.

Some material behaved in a classic, linear-elastic mode such as that shown in Figure 9. The initial load-displacement behavior is highly linear until peak load occurs when the specimen fails. This is contrasted to the more ductile behavior noted in Figure 10 where higher levels of nonlinearity are evident in the initial slope and upon reaching peak load extensive plasticity (or crack advance) is apparent. Tests that exhibit extensive ductility like this are apparent with a K_{Jmax} toughness value that is nearly identical to the K_{max} value. This is contrasted to the case of ductile behavior where K_{Jmax} toughness is much greater than K_{max} toughness.



(a) Pre-1989 TC128-B material



(b) Post-1989 TC128-B material

Figure 8: Typical fracture surfaces observed.

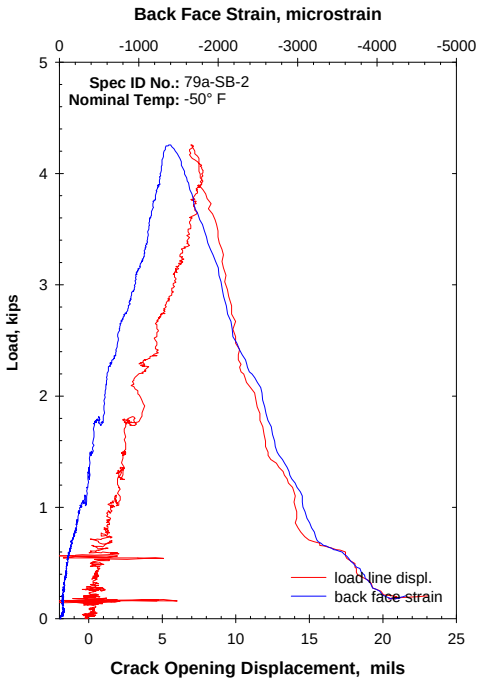


Figure 9: Typical "brittle" behavior (1000 mils = 1 inch).

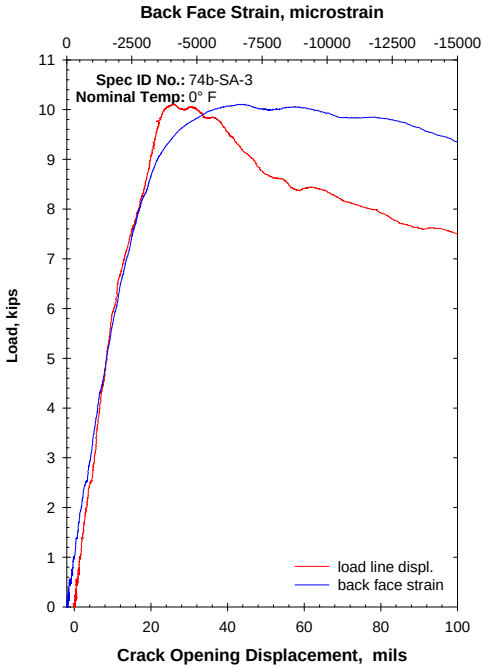


Figure 10: Typical "ductile" behavior (1000 mils = 1 inch).

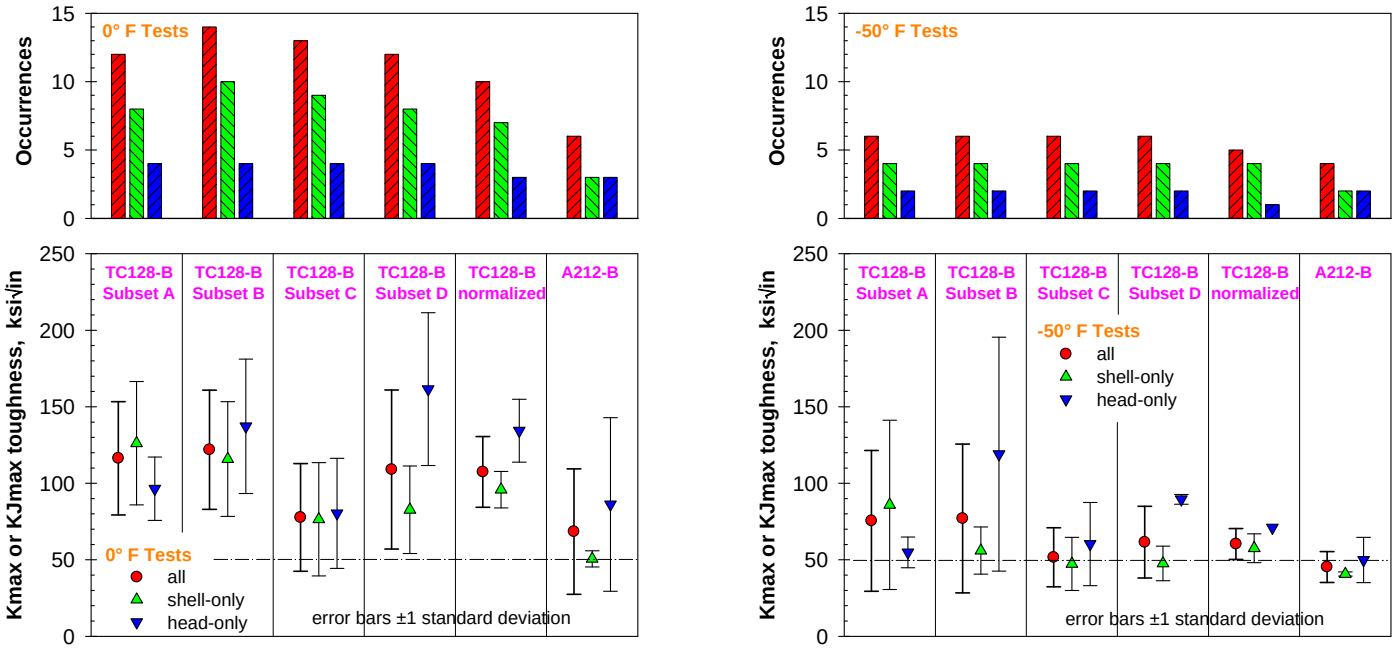
A statistical summary of the fracture toughness test data is shown in Table 4 with toughness measure as a function of the different subsets of the fleet population prior to 1989. In addition, data is also provided for normalized TC128-B (post-1989) as well as a summary of the behavior noted with older A212-B material. The number of datapoints, range, average and standard deviation of the K_{max} or K_{Jmax} measure is indicated for all data, shell-only and head-only material.

Table 4: Statistical analysis (averages and standard deviations) of TC128-B and A212-B fracture toughness.

Subset A:	1969 and before build date,	25% of the pre-1989 pressure car fleet
Subset B:	1970 to 1976 build date,	25-52% (27% total) of the pre-1989 pressure car fleet
Subset C:	1977 to 1979 build date,	52-72% (20% total) of the pre-1989 pressure car fleet
Subset D:	1980 and later build date,	28% of the pre-1989 pressure car fleet

		K_{max} or K_{Jmax} fracture toughness, ksi√in (for different materials or subsets of a given material)																	
Test	**Tank**	**TC128-B Subset A**			**TC128-B Subset B**			**TC128-B Subset C**			**TC128-B Subset D**			**TC128-B Normalized**			**A212-B**		
Temp	**Posn**	**N**	**avg**	**SD**	**N**	**Avg**	**SD**	**N**	**avg**	**SD**	**N**	**avg**	**SD**	**N**	**avg**	**SD**	**N**	**avg**	**SD**
0°F	H&S	12	116	37	14	122	39	13	78	35	12	109	52	10	107	23	6	68	41
71	S-only	8	126	40	10	116	38	9	77	37	8	83	29	7	96	12	3	51	5
	H-only	4	96	21	4	137	44	4	80	36	4	162	50	3	134	21	3	86	57
-50°F	H&S	6	76	46	6	77	49	6	52	19	6	62	23	5	60	10	4	45	10
	S-only	4	86	55	4	56	15	4	47	17	4	48	11	4	58	9	2	41	1
	H-only	2	55	10	2	119	76	2	60	27	2	90	3	1	71	n/a	2	50	15

H = head, **S** = shell, **avg** = average, **2SD** = 2 std. deviations



(a) **(b)**

Figure 11: Graphical summary of measured fracture toughness at (a) 0°F and (b) -50°F.

The data in Table 4 are plotted in Figure 11. There is no question that for TC128-B material subset A and B (the oldest 50% of the fleet), the global average behavior at 0°F is of a higher magnitude toughness than observed in the youngest 50% of the fleet. This is counter-intuitive and suggests that the newer vintage fleet is not as tough as the older vintage fleet. Nevertheless, the broad standard deviations clearly suggest that the toughness variability is too high to conclude that this is a statistically significant finding.

The data in Figure 11(a) at 0°F also shows that the poorest performing material is the A212-B. Average toughness values are lower than observed in any of the other materials and the lower bound levels also the lowest when taking into account variability. Clearly any type of TC128-B outperforms the

A212-B material. The wide variability and low average also suggests that a large percentage of the A212-B fleet will exhibit "poor" toughness levels.

One advantage with the post-1989 normalized TC128-B is that the apparent variability in toughness appears less than with the older vintage TC128-B. Although the average toughness observed with the newer vintage, normalized material is not significantly different from the pre-1989 fleet (the averages are actually less than observed in the older 50% of the fleet), the smaller standard deviation band means that the lower bound toughness when subtracting 2 standard deviations still is in excess of 50 ksi√in. This suggests that the post-1989 normalized material outperforms all other materials or conditions in Figure 11(a).

Material performance in Figure 11(b) for -50°F is generally poor with low average values. The sample size is small too, and this presumably influences the standard deviation bands indicated. A similar trend is observed as with the 0°F data though, with higher average toughness for the oldest half of the fleet when compared to the younger half. On balance, the best behaving material at -50°F is the post-1989, normalized TC128-B. However it is clear that if the error bar were extended to ±2 standard deviations, the range would dip below 50 ksi√in and into the poor toughness regime.

Toughness Correlations

The word 'toughness' is used for two separate quantities: impact toughness and fracture toughness. Impact toughness is an energy measurement (e.g., Joules or ft-lb) which is commonly obtained from the CVN test. Fracture toughness is a calculated value for the critical stress intensity factor (in units of MPa√m or ksi√in) based on standard fracture mechanics tests. Relationships between these quantities are empirical.

The correlation between high-rate fracture toughness and CVN energy at a temperature of 0ºF is shown in Figure 12. The error bars represent variability in the measurements in terms of one standard deviation above and below the mean value. Also shown in Figure 12 is the Roberts-Newton equation [12], which was developed for lower shelf or transition behavior. Similarly, Figure 13 shows the correlation for results at –50ºF. Except for a few outliers, the test data lie above the Roberts-Newton equation. Moreover, the Roberts-Newton equation appears to provide a reasonable lower-bound estimate of fracture toughness for non-normalized TC128-B tank car steel.

DISCUSSION

The high rate fracture toughness testing performed herein has generated structural results, not material property results in the strictest sense of ASTM "valid" properties. Reasons for the invalid test results were insufficient thickness and occasionally non-linear load displacement behavior. Therefore there is some structural dependence of these results and the data would therefore be expected to exhibit size effects. A clear indication of the structural nature of the test results can be obtained by examining the limit ratio defined as the percent of limit load (calculated as per ASTM E813 using flow stress) for the specimen at the maximum applied load (see Figure 14). A value of 0.8 would imply that at the maximum load, the specimen sustained 80% of the limit load possible with that specimen/material combination. Conversely a value of 1.25 would imply that the load was at 125% of limit load. Had the specimens been larger, the limit load ratio would have been less. However, these specimens were about as large as possible without significantly thinning the specimen and not testing full wall thickness (e.g. they would have been too curved to test).

Also shown on Figure 14 is a line illustrating the limit ratio of 0.67, which can be arguably used to represent the limit of applicability for K-based linear-elastic fracture mechanics (LEFM). For the specimens whose limit ratio was underneath (less or below) this line, LEFM would apply. For the tests above the line, plasticity conditions dominated and an elastic-plastic parameter governed toughness (such as the K_{Jmax} parameter utilized herein). K_{Ic} is clearly an unsuitable test method or toughness quantifier for this non-LEFM regime.

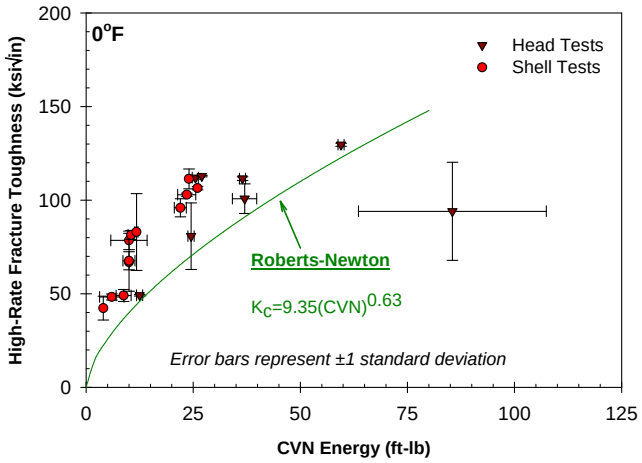


Figure 12: Toughness trend with TC128-B energy at 0ºF.

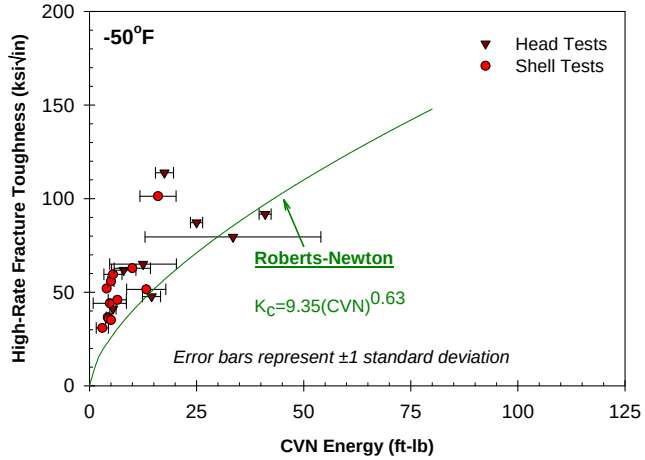


Figure 13: Toughness trend with TC128-B energy at –50ºF.

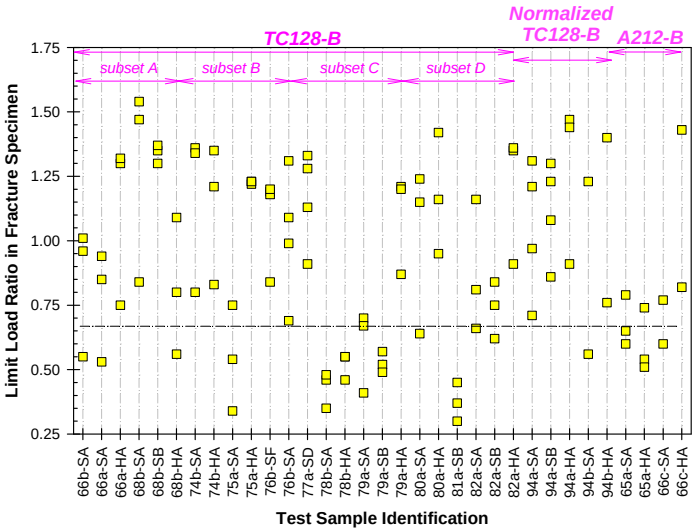


Figure 14: Limit load ratio observed in fracture tests.

It is likely that plane-strain dominance was observed in the test specimen involved in this program. The first clear indication of this is the extent of flat fracture (without shear lips) observed in the specimen and documented in Figure 8. Although the specimens are flat, at high applied K-levels a significant amount of through-thickness "necking" is observed. Nevertheless, the most recent version of E399 has relaxed the thickness requirement. In fact, there currently is no thickness requirement, but a remaining ligament size requirement of $2.5(K_{Ic}/\sigma_{YS})^2$ is still present in the standard.

These structurally significant fracture toughness data, though not material properties, are still useful when assessing the damage tolerance of rail tank cars. Kushner [13] provides an extensive discussion in a recent NTSB document related to the significance of dynamic fracture toughness to the tank car integrity program. He makes several excellent points regarding the significance of toughness. Since the NTSB recommendations that led to this work, there has been a considerable amount of work trying to better understand what occurs in a tank car accident (for instance, the recent Next Generation Rail Tank Car Program co-sponsored by Dow Chemical Company, Union Pacific Railroad and Union Tank Car Company). We have the benefit today of making use of this and other recently derived expertise when examining the structural integrity issues.

Controlling the material strength and fracture toughness alone are likely not sufficient for preventing all failures in current tank car designs. Understanding the material parameters that control puncture is an active area of research for the tank car industry. It is likely that static strength and fracture toughness play an important role in controlling whether rupture and puncture occur, although how the two contribute to the failure behavior is as yet not fully understood.

For the more typical accident, shell and head puncture are the critical occurrences that must be avoided. Despite what others have publically stated, an individual with extensive failure analysis experience was given access to the Minot wreckage and the observation was made that most if not all of the fractures observed on the different tank cars involved in the incident also had some form of puncture in or adjacent to them. This individual's belief was that the first step in the failure process was likely puncture and the second step, given sufficient energy, was separation of the tank. Given this scenario, the critical property, and the parameter most critical for design, is not the fracture toughness of the material but rather the puncture resistance.

Unfortunately we do not have a firm and definitive understanding yet of what material properties contribute to enhanced puncture resistance. Some of this work is currently underway, and initial findings appear somewhat promising in terms of better understanding what parameters drive puncture. Properties such as a materials fracture toughness and static strength likely play some type of role, however the significance of these parameters in dictating puncture performance is not yet clear or well-understood.

CONCLUDING REMARKS

The testing program described in this paper yielded the following major conclusions:

1) No clear trend was observed between chemical, tensile, or CVN impact energy properties and tank car build date. In total, 61 different pre-1989 TC128-B conditions were examined. Eighteen other conditions were examined including non-TC128-B material as well as post-1989 normalized TC128-B.
2) The vast majority of the TC128-B samples extracted from retired tank cars met current TC128-B material specifications.
3) Fifty-nine of sixty-one samples satisfied the chemistry requirements for TC128-B. In one case, the two anomalies included high carbon content, and in the other case, high sulfur content.
4) Eighty-two percent of the tank car samples met tensile property requirements for TC128-B. Two TC128-B conditions exhibited slightly lower yield strengths than allowed. Three tank car conditions exhibited slightly lower ductility than allowed. Nine tank car conditions violated the required range of ultimate strength (two exceeded and seven were less).
5) The pre-1989 tank car fleet was subdivided into four groups, or quartiles, depending on age. High-rate, low-temperature fracture toughness testing was performed on samples from each quartile. Criteria developed by Anderson and McKeighan [11] were used to quantify toughness performance. Considering the oldest quartile, 100 percent of the 0ºF and 50 percent of the –50ºF tests exhibited adequate or better toughness. Considering the second oldest quartile, 100 percent of the 0ºF and 83

percent of the –50ºF tests exhibited adequate or better toughness. Considering the second youngest quartile, 58 percent of the 0ºF and 33 percent of the –50ºF tests exhibited adequate or better toughness. Considering the youngest quartile, 83 percent of the 0ºF and 83 percent of the –50ºF tests exhibited adequate or better toughness.

6) Testing was also performed on newer TC128-B material as well as A212-B material. Considering the post-1989 vintage, normalized TC128-B material, 100 percent of the 0ºF and 80 percent of the –50ºF tests exhibited adequate or better toughness. Considering the A212-B material, 67 percent of the 0ºF and 25 percent of the –50ºF tests exhibited adequate or better toughness.
7) The extent of scatter observed in the fracture toughness testing was quite large, which prevents making definitive conclusions regarding toughness variations with age.

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