REPORT

Evaluating the Possible Extension of the Propane Cargo Tank Inspection Interval – Phase 1

To

National Propane Gas Association

1150 17th Street NW, Suite 310

Washington, D.C. 20036

March 2007

NPGA/PERC Docket 11726

Battelle
The Business of Innovation

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Final Report

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Washington, DC 20036

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by

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This project would not have been a success without their assistance.

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EXECUTIVE SUMMARY

Currently, the U.S. Department of Transportation requires that propane cargo tanks ("bobtails") of MC330 and MC331 specifications be pressure-tested every five years [49CFR180.407)] as part of the requalification process to continue in service. The pressure test is performed at 1.5 times the maximum allowable working pressure and is typically a hydrostatic test (commonly referred to as a "hydrotest"), with water as the test medium.

The required hydrostatic testing of bobtails is a burden to the propane industry for several reasons. Bobtails must be taken out of service for a period of up to a week. Before being put back into use, the tank must be completely free of any water. In addition to the cost of the test itself, the removal of bobtails from propane service can hamper a company's operations.

Battelle performed this Phase 1 project for the National Propane Gas Association (NPGA). The objectives of this Phase 1 effort were addressed by the following tasks:

- Task 1 – Determine the projected life of a propane cargo tank based on "thermodynamic" loading only. Thermodynamic loading occurs from ambient and lading temperature cycles and loading/unloading.
- Task 2 – Continue interaction with the U.S. DOT on our analysis activities
- Task 3 – Perform a survey of the current cargo tank population to determine the characteristics of the population – age, size, manufacturing methods and materials, and the presence of manholes.
- Task 4 – Identify possible alternative inspection methods to the currently used hydrotest.

In Task 1, Battelle used fracture growth models to estimate the time to failure of a tank that has undergone several pressure cycles. The initial crack size was estimated from the maximum crack size that could go undetected in a radiographic inspection. This maximum crack size was 70 percent of the thickness (0.481 inch), or 0.337 inch deep, with a width of twice this dimension, or 0.674 inch. The yearly pressure cycles used in the study are shown in Table ES-1. When the model was exercised with this initial crack size and the pressure cycles shown in Table ES-1, the estimated time to rupture was more than 2000 years.

Table ES-1. Assumed annual pressure history for propane delivery tank life assessment.

Cycles	Temperature (degrees F)		Pressure (psi)	
	Maximum	Minimum	Maximum	Minimum
1	120	-10	226	16
61	120	80	226	130
242	80	40	130	65
61	40	-10	65	16

This estimate of the tank's time to failure was encouraging in that it is nearly two and one half orders of magnitude over the currently used five-year inspection period. This analysis will be expanded in the Phase 2 project, where we will include road loads in addition to the thermodynamic loads.

In Task 2, we continued interactions with the DOT PHMSA staff that would oversee any rule change on the inspection requirements. While the staff were satisfied with the progress made thus far, they also raised a caution that they were not approving these modeling activities, nor were they approving the proposed road testing in Phase 2.

In Task 3, the ADEPT Group surveyed several propane marketers for information about their bobtails. These marketers provided a sample set of 2388 bobtails, which included tanks manufactured as early as 1948. The information that was gathered included the manufacturer, age, size, and other characteristics of the bobtails. Of the 47 different manufacturers identified, two manufacturers, Trinity and Arrow, accounted for over 56 percent of the bobtails. For the age of tanks, the largest percentage of the surveyed sample was found in the following five years of manufacture (in order of size): 1998 and 1970, 1973, 1977, 1974 (each with over 4 percent of the sampled population). The most common tank size was 3000 to 3099 gallons, accounting for 31 percent of the sample population; the second most common tank size was 2600 to 2699 gallons, accounting for 22 percent of the sample population. Information on the steel type, the wall thickness, the presence of manways, and the use of methanol was also included in the survey.

In Task 4, alternative inspection technologies were reviewed for use on bobtails. Six inspection technologies and the hydrostatic test, as a baseline, were ranked according to ease of use and several other parameters. The result of this comparison indicated that the acoustic emission method and the ultrasonic method have the most favorable ratings. It is recommended that these methods be considered further as alternatives to the hydrotest method. It is also recognized that US DOT approval must be obtained as part of the final evaluation before any alternative propane cargo tank inspection method can be introduced.

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TERMINOLOGY

ksi	thousands of psi (unit of pressure, stress, and material strength)
MAWP	maximum allowable working pressure
NDE	non-destructive evaluation
psi	pounds per square inch (unit of pressure, stress, and material strength)
PTW	part through the wall (crack)
SMYS	Specified Minimum Yield Strength
TW	through the wall (crack)

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Final Report – Phase 1

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BACKGROUND

Currently, the U.S. Department of Transportation requires that propane cargo tanks ("bobtails") of MC330 and MC331 specifications be pressure-tested every five years [49CFR180.407)] as part of the requalification process to continue in service. The pressure test is performed at 1.5 times the maximum allowable working pressure and is typically a hydrostatic test (commonly referred to as a "hydrotest"), with water as the test medium. To pass the test, the container must hold the pressure for 10 minutes without exhibiting leaks, distortion, or excessive permanent expansion.

The required hydrostatic testing of bobtails is a burden to the propane industry for several reasons. Bobtails must be taken out of service for a period of up to a week. Water is introduced into the tank, which is detrimental to the tank and the fuel contained in the tank. Before being put back into use, the tank must be completely free of any water. In addition to the cost of the test itself, the removal of bobtails from propane service can hamper a company's operations.

In Phase 0 (Osborne, 2005) of this project, Battelle performed a feasibility study for the National Propane Gas Association (NPGA) to determine if the DOT was open to discussing a change to the inspection period. Staff from DOT's Research and Special Programs Administration (RSPA), now the Pipeline and Hazardous Materials Safety Administration (PHMSA)[†] indicated that they were open to reviewing engineering analyses that could show an equivalent level of safety for an extended inspection period. The study also reviewed international standards that addressed cargo tank inspection periods. Many international standards are very similar to those of the United States, and some countries require no inspections (e.g., Mexico) or require no periodic inspections after the initial construction inspection (e.g., Australia). Based on the results of this phase of work, NPGA funded the Phase 1 effort.

The objectives of this Phase 1 effort are addressed in four tasks:

- Task 1 – Determine the projected life of a propane cargo tank based on "thermodynamic" loading only. Thermodynamic loading occurs from ambient and lading temperature cycles and loading/unloading. The engineering model of the tank developed during this Phase 1 effort will be used in Phase 2 to determine the projected life under real, field-validated loads.

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[*] This effort was funded by NPGA through a research grant from the Propane Education & Research Council, Washington, D.C., Docket 11726.

[†] The DOT was reorganized in 2005, and the cognizant RSPA staff are now in the Pipeline and Hazardous Materials Safety Administration (PHMSA).

- Task 2 – Continue interaction with the U.S. DOT on our analysis activities.
- Task 3 – Perform a survey of the current cargo tank population to determine the characteristics of the population – age, size, manufacturing methods and materials, and the presence of manholes.
- Task 4 – Identify possible alternative inspection methods to the currently used hydrotest.

Each of these tasks is discussed below.

Task 1 – Determine the Projected Life of a Propane Cargo Tank Based on "Thermodynamic" Loading Only

Battelle's approach to this engineering analysis includes two phases, where this Phase 1 effort develops the engineering model of the cargo tank and the thermodynamic loading exposed to the tank. The thermodynamic loads, that is, the pressure history of a tank caused by the temperature changes of the propane lading, are considered simpler to determine than the potentially more severe dynamic road loads. Using the tank model, the size of a flaw that might go undetected and enter service was estimated. Then, the growth rate of this flaw due to the assumed thermodynamic loading was estimated, and the projected life of the tank was estimated. Figure 1 presents an overall technical outline for the analysis.

Tank Engineering Model

Fracture mechanics is used routinely to estimate service lives and inspection intervals for air and space vehicles, nuclear power plants, pipelines, and a wide range of other devices and structures. In this project, we used fracture mechanics to provide a highly effective framework for estimating the service life of propane cargo tanks. With this approach, flaws were represented as infinitely sharp cracks; therefore, the time or load cycles required to sharpen blunt flaws is ignored, resulting in a conservative (shorter) estimate on the service life. For this application, an infinitely sharp crack would be assumed to be present in the wall of the propane tank, or elsewhere in the tank or its support structure, and the number of load cycles required to grow the crack to a size sufficient to cause failure is calculated. This approach is well-suited to assess crack growth resulting from pressure and load cycles due to filling and emptying the tank and the load cycles applied to the tank when it is transported on the truck.

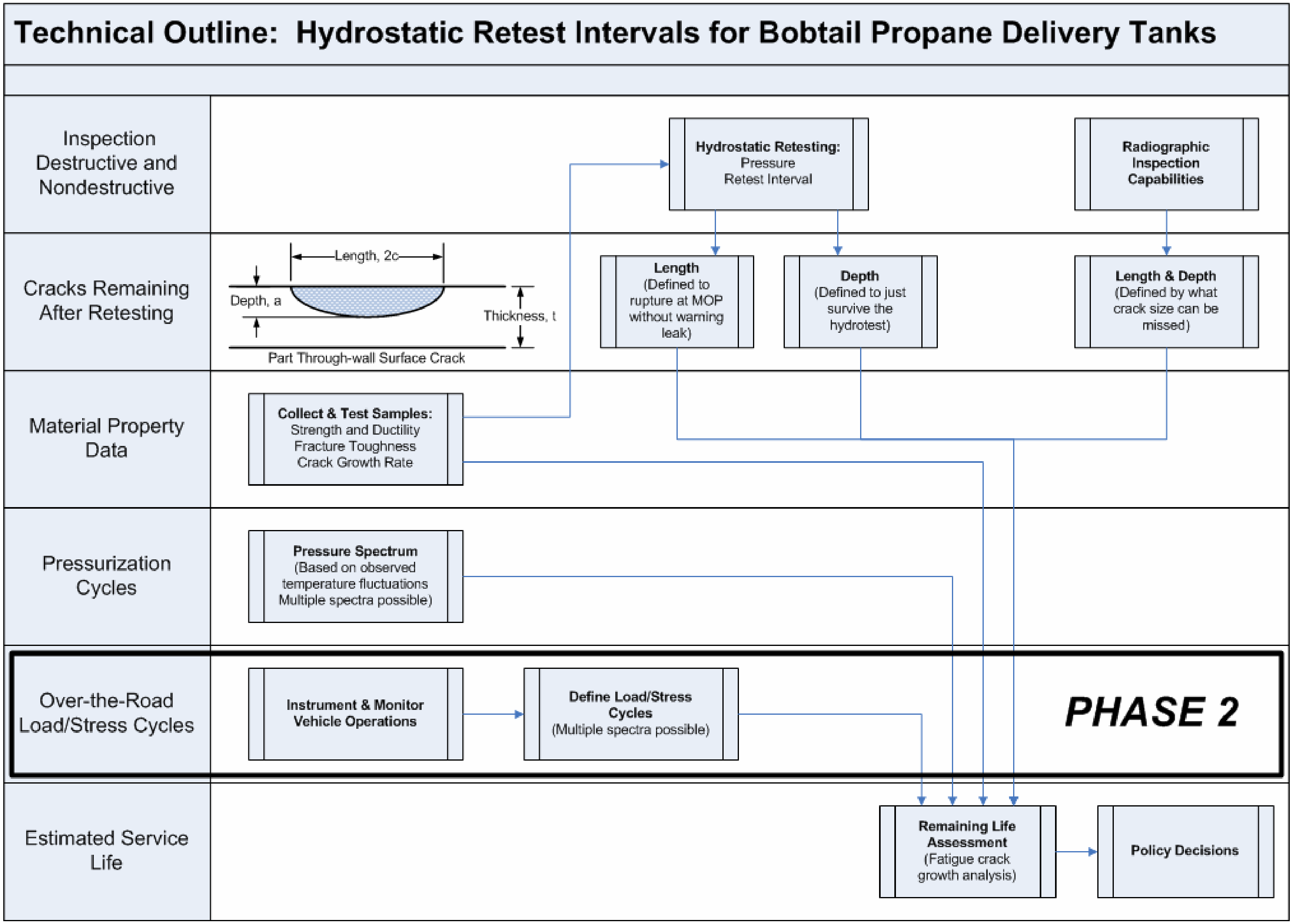

Figure 1. **Technical overview of service life estimation.**

For a typical crack growth analysis, Equation 1 is the governing fracture mechanics equation that is used to compute the number of cycles to failure.

$$N = \int_{a_i}^{af} f\left(\Delta K\right)\, da \tag{1}$$

where:

a_i = initial crack size

a_f = final crack size

N = number of load cycles to grow the crack from the initial to the final crack size

ΔK = change in the stress intensity factor, K, during a load cycle

f(ΔK) = function of the geometry of the structure containing the crack, the shape and size of the crack, and the material of which the structure is made

da = crack growth increment during a load cycle.

Similar to many pipeline applications, the critical crack for the tank is a part through wall (PTW) crack oriented along the longitudinal axis of the pipe and that can be characterized by its depth (*a*) and total length (*2c*), as illustrated schematically in Figure 2[*]. Circumferentially orientated cracks are less of a threat than longitudinal cracks because the stress applied to a circumferential crack due to the internal pressure is only one-half of the stress applied to the longitudinal crack.

Crack Growth Rate Data. The functional relationship f(ΔK) is based on a curve fit of crack growth rate data derived from many studies over several years. For the most part, steels like those used in the tank have a fairly narrow range of crack growth rates when subjected to classical fatigue. In addition, when the value of ΔK is less than the threshold for crack growth in the material containing the crack, no crack growth occurs. As a result, the threshold could be ignored to provide conservative life estimates. “Typical” (average) and upper bound estimates of the crack growth rate parameters, including the crack growth rate threshold, would be used rather than generating new data for the tank material. In addition to being dependent on ΔK, i.e., the change in the stress intensity during the loading cycle, the function is also sensitive (but to a lesser degree) to the ratio $R = K_{min} / K_{max}$, where K_{min} and K_{max} represent the respective minimum and maximum values of K during the cycle. The dependence on R will be included in the use of the upper bound crack growth rate data.

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[*] The analytical procedure is applicable to cracks located on the interior and the exterior surfaces. The primary difference is that the crack faces of the interior crack are exposed to the pressure contained within the vessel. Given that the internal pressure is so low compared to the stress in the vessel wall, the effect is not significant. Nevertheless, both cases will be considered.

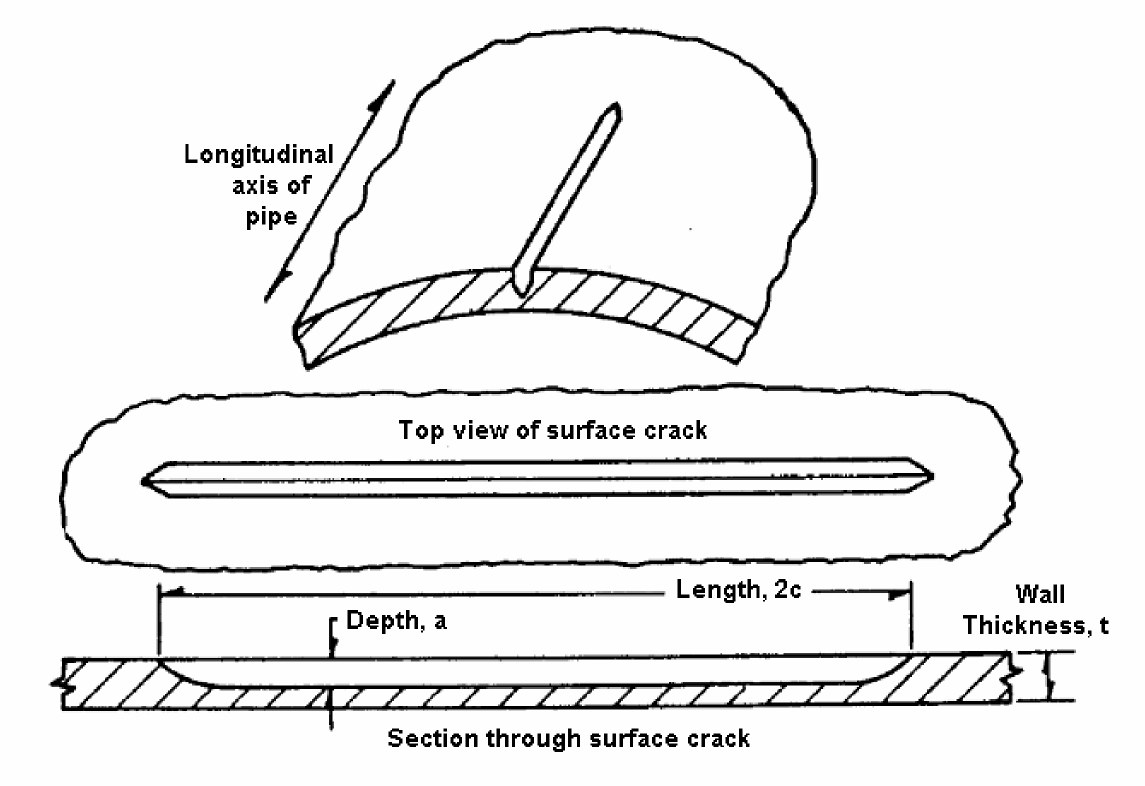

Figure 2. Schematic view of an exterior, part through wall axial crack in a cylinder.

Stress Intensity Factor, K. The stress intensity factor equations that characterize the behavior of PTW cracks and through wall (TW) cracks have been taken from the open literature. These are active research areas and the equations being used are based on the latest validated information. A description of the analytical procedure, along with the data used for the curve fit and the equations used for K will be given in a later section.

Numerical Integration. The analytical service life estimation procedure involves solving Equation 1 via numerical integration. In effect, the analysis grows the crack numerically from the initial size and checks for possible failure after each increment of growth. The final crack size is the size of the crack when one or more of the failure criteria are satisfied. The failure criteria are discussed later. Likewise, when failure is detected, the service life is taken as the total number of load cycles that had been applied up to the point when failure is predicted.

For PTW cracks, Equation 1 is solved simultaneously for growth in the depth and length directions using techniques that have been validated through previous research on pipeline applications. For TW cracks, Equation 1 is solved for growth in the length direction only.

Failure Criteria. Several failure criteria are considered in the analysis. The primary criterion is the dependence of the failure pressure on the size of the crack, i.e., length and depth for PTW cracks and length for TW cracks. The failure pressure criterion that is used is based on the results of full-scale burst tests (Leis and Ghadiali, 1994).

The failure pressure versus crack size data for PTW and TW cracks are built into the analysis software. At each crack growth increment in the integration of Equation 1, the failure pressure versus crack size criteria are evaluated to determine if a PTW crack will breach the wall, and if it does whether it will leak or rupture. For TW cracks an assessment is made to determine if a leaking crack will continue to leak or if it has grown long enough to cause a rupture. Typically the pressure used in the check for failure is the maximum value of the pressure cycle being applied at the time the failure check is made. For the tanks, a more conservative approach will be to assume that the tanks are expected to survive the maximum allowable working pressure (MAWP) even if the maximum pressure being applied during a particular pressure cycle is less than MAWP.

Initial Crack Size. The size of the initial crack often is the dominant factor in defining the service life. The method used in this study was to base the initial crack size on reasonable estimates of what crack sizes might have gone undetected during fabrication and pre-service inspection and testing. Before entering service, the welds of each tank are radiographed to ensure their structural worthiness. Table 1 presents minimum initial crack sizes for fracture analysis based on several standard nondestructive examination (NDE) methods (Forth, et al., 2005). In other words, smaller initial cracks sizes should not be used to assess the remaining life of a structure. These initial crack sizes depend on: (i) the location of the crack, namely on an open surface, on the edge of a hole or on the edge of a sheet or plate, and (ii) the type of crack, namely a TW crack or a PTW (surface) crack. For the propane tank, with a nominal thickness of 0.481 inch, the initial crack size that could enter service following a valid radiographic inspection is semi-circular in shape, with a depth of 0.7 times the thickness of the plate (i.e., the tank wall thickness). As such, the minimum depth acceptable for use in an analytical service life estimate for the tank would be 0.337 inch (= 0.7 · 0.481) and a total length of 0.674 inch (= 2 · 0.7 · 0.481).

Table 1. Minimum Initial Crack Sizes for Fracture Analysis Based on Standard NDE Methods (Forth, et al., 2005)

Units (inches)*

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a	Crack Dimension, c
Eddy Current NDE				
Open Surface	$t \le 0.050$	Through	t	0.050
	$t > 0.050$	PTC**	0.020	0.100
			0.050	0.050
Edge or Hole	$t \le 0.075$	Through Corner	t	0.100
	$t > 0.075$		0.075	0.075
Penetrant NDE				
Open Surface	$t \le 0.050$	Through	t	0.100
	$0.050 < t < 0.075$	Through	t	$0.150 - t$
	$t > 0.075$	PTC	0.025	0.125
			0.075	0.075
Edge or Hole	$t \le 0.100$	Through	t	0.100
	$t > 0.100$	Corner	0.100	0.100
Magnetic Particle NDE				
Open Surface	$t \le 0.075$	Through	t	0.125
	$t > 0.075$	PTC	0.038	0.188
			0.075	0.125
Edge or Hole	$t \le 0.075$	Through	t	0.250
	$t > 0.075$	Corner	0.075	0.250
Radiographic NDE				
Open Surface	$0.001 \le t \le 0.004$	PTC	$0.7t$	0.075
	$t > 0.004$		$0.7t$	$0.7t$
Ultrasonic NDE Comparable to a Class A Quality Level (MIL-STD-2154)				
Open Surface	$t \ge 0.100$	PTC	0.030	0.150
			0.065	0.065

*1 mm = 0.039 inches.

**PTC = Partly Through Crack (surface crack).

Technical Challenges

Single and Multiple Cracks. The combination of depth and length derived using the pre-service radiographic non-destructive evaluation criteria would provide a realistic estimate of the service life of the propane tank. Using the initial crack size derived from the hydrotest/MAWP criteria would provide a minimum service life for the worst-case scenario. Each of these initial crack size estimates presupposes a single dominant crack in the wall of the tank. However, there is the possibility for multiple cracks, arranged in such a manner that would allow them to survive the hydrotest and then grow sufficiently during service to link up, forming a single crack that is larger than either of the assumed initial cracks. In general, the stress intensity factor and therefore the growth rate will be significantly less for smaller cracks than for the assumed single large crack derived form the hydrotest/MAWP criteria. As indicated above, the growth in the TW direction dictates the failure mode: short PTW cracks tend to produce leaks if they grow through the wall; long PTW cracks tend to produce ruptures if they grow through the wall. The difference between the hydrotest pressure and MAWP is a significant factor in determining whether multiple cracks that could be close enough to link up during service could actually survive the hydrotest without linking during the hydrotest. The significance of multiple cracks will be investigated in the future Phase 2 effort; the evaluation will use the crack coalescence criteria derived from previous research on the linkup of stress corrosion cracks (Leis, 1995).

Pressure-Induced Bulging. Many of the formulations used to assess the service life of the tanks have been derived from pipeline research findings. Since they were developed from research on infinitely long cylinders subjected to internal pressure, modifications may be required to account for the difference in length between an infinitely long pipeline and a short cylindrical propane tank. The need for possible modifications will be evaluated based on the conservatism added to service life prediction. For example, a crack in the pipeline or tank weakens the wall and causes it to bulge. Conceivably, the tank wall will bulge less and have lower stresses acting on the crack because the tank wall is stiffened at each end by the end caps. Bulging affects the rate of crack growth and the failure pressure as follows:

- Crack growth rate. Applying the pipeline crack growth model directly to the tank should result in shorter life predictions and therefore would be **conservative** because there would be less bulging and lower stresses in the tank relative to the pipeline.

- Failure pressure. Due to the possible reduction in the amount of bulging and therefore a reduction in stress, applying the pipeline failure pressure model directly to the tank should be **conservative** when used to determine the end of the useful service life.

Therefore, the resulting service life calculated will be more conservative (shorter) than if those effects were included. Bulging will also be considered during the Phase 2 modeling efforts, and the level of this conservatism will be addressed.

Tank Material Properties. The specific properties of the steel tank materials are also related to the failure pressure versus crack size curves. The material used in the tank is similar to the line pipe steels typically considered by Battelle; therefore, existing relationships that involve Charpy impact energy can be used to assess the fracture toughness and hence the likelihood for fracture. The greater the fracture toughness, the greater the material's resistance to fracture. An important characteristic of these steels is the dependence of their fracture toughness on temperature, within the range of the service temperature of the propane tanks. Two tensile tests and a set of Charpy impact tests that were conducted on a sample of material donated by a tank manufacturer support the assertion that the tank steels are similar to the line pipe steels. These tests also confirmed the strength specifications of the material sample. Relative to the tanks, a sensitivity study will be conducted in Phase 2 to assess the effect of typical variations in the yield and ultimate strengths and in the Charpy fracture energy. The goal would be to conservatively estimate the service life.

Crack Growth Retardation. Detailed observations of crack growth in ductile materials have shown that the rate of growth can be reduced substantially when the crack is subjected to an "overload" stress cycle, that is, a cycle with a maximum stress greater than those that follow. This is because a ductile material will undergo yielding in the region surrounding the crack tip due to the high stress concentration that exists there. Applying the overload increases the size of the yield zone; releasing the overload can create a residual compressive stress, through which the crack would grow at a slower rate. Likewise, in a ductile material the overload may blunt the crack tip; thus, the rate of growth would be retarded while the crack is resharpened. Retardation of the rate of growth would occur following the hydrotest, but in the interest of conservatism, it will be ignored.

Damage Due to Repeated Hydrotesting. Although this condition is not addressed specifically, the damage caused by repeated retesting will be evident in the results generated in Phase 2 of this study. Some ductile tearing can occur during a hydrotest. On the next pressurization, the onset of ductile tearing at the new, longer crack length will occur at a lower pressure than was reached in the previous test. As such, ductile tearing during a hydrotest can significantly reduce the failure pressure for a subsequent test. This phenomenon was identified many years ago in pipelines (Leis, et al., 1991). It explains why pipelines or pressure vessels can fail at a pressure that is lower than the maximum pressure applied and successfully contained in the previous test. Furthermore, because ductile tearing is time dependent, hydrotest protocols often limit the time at the peak pressure in order to minimize damage due to crack growth by ductile tearing, followed by an extended period at a lower pressure during which time leaks may be detected. The current strategy is based on determining the minimum service life that can be anticipated after a hydrotest, when the vessel is subjected to pressure cycles related to temperature variations and fill-empty operations. As mentioned previously, ductile tearing during the hydrotest is selectively included or ignored to obtain the shortest service life estimates.

Other Damage Mechanisms. In this Phase 1 effort, the goal is to estimate the service life of the tank as it is affected by fatigue due to pressure cycles produced by the thermodynamic loading on the tank. Over-the-road load cycles will be addressed in Phase 2 of this project. Nevertheless, the approach for estimating the service life due to fatigue when the transport loads are included will be similar to the current approach.

Application of Engineering Model

The previous section of this report describes an engineering model for estimating the service life of truck-mounted propane cargo tanks. It presented several important issues related to the application of the model and highlighted a number of techniques for ensuring conservative estimates of the service life. This section presents important information and data used in the model and defines a set of baseline conditions that are used as a reference for assessing the significance of the analysis parameters.

Propane Saturation Curve. For Phase 1, the stresses in the tank depend only on the pressure in the tank. The tank and associated fill and drain apparatus are designed so that the pressure in the tank depends only on the saturation vapor pressure of the propane, which is a function of the temperature of the propane. As shown in Figure 3, the saturation pressure of propane equals MAWP (250 psi) at approximately 127 F. Should the propane in the tank reach this pressure, the tank is equipped with a pressure relief system to prevent over-pressurization. A small amount of liquid propane will remain in the tank because the pump flange is located above the lowest point of the tank. Therefore, the tank cannot be completely emptied during service unless the tank is vented. This design feature serves to ensure that the pressure (and stresses) in the tank are not cycled with each fill and drain event. Instead, the pressure (and stresses) cycle only in response to changes in the temperature of the propane in the tank, which depends on the ambient temperature of the tank and propane. Consequently, the history of pressure (and stress) cycles that is required for the fatigue analysis can be derived from the temperature history experienced by the tank using the saturation pressure curve for the propane presented in Figure 3.

Cyclic Pressure History. The ultimate goal is to develop a pressure history via an industry survey. In the interim, the cyclic pressure history will be assumed and used for establishing a preliminary service life estimate. The assumed pressure history is based on the ambient temperature to which the tank and propane are exposed. The history is formulated to represent one year of service in terms of the daily temperature variations for each of the four seasons; for simplicity, spring and fall seasonal temperature variations are taken as the same. On this basis, the history includes one temperature cycle per day, with three distinct temperature blocks – summer, winter, and spring/fall. The history also includes one cycle between the maximum and minimum temperatures to ensure that any fatigue crack growth due to the annual cycle is included. The assumed cyclic temperature history is converted to a cyclic pressure history using the propane saturation curve in Figure 3. The assumed cyclic temperature and pressure histories are listed in Table 2.

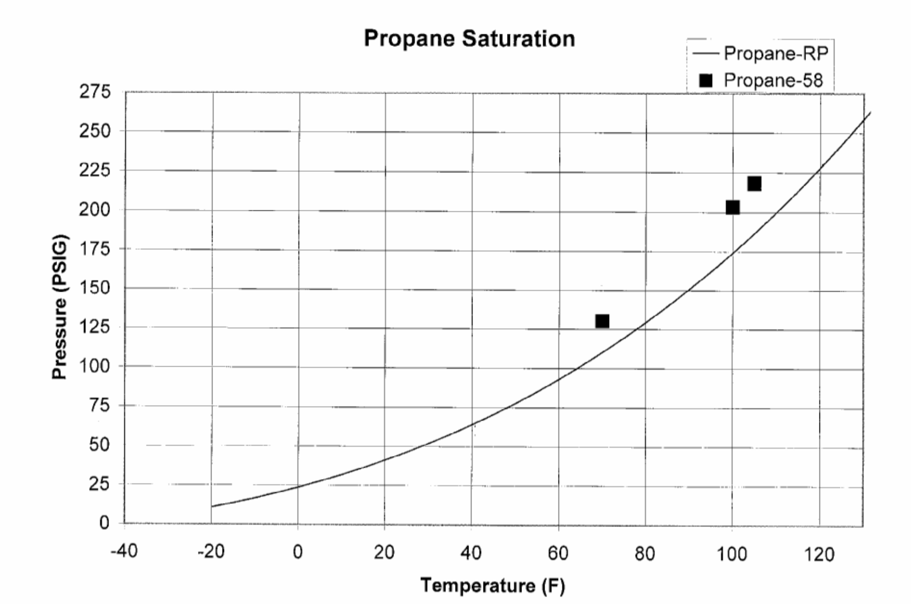

Figure 3. Saturation pressure versus temperature for propane.

Table 2. Assumed annual pressure history for propane delivery tank life assessment.

	Temperature (degrees F)		Pressure (psi)	
Cycles	Maximum	Minimum	Maximum	Minimum
1	120	-10	226	16
61	120	80	226	130
242	80	40	130	65
61	40	-10	65	16

Fracture Mechanics. Linear elastic fracture mechanics (LEFM) provides a framework for analyzing structures with sharp cracks (Broek, 1974). In a typical elastic analysis the stress concentration at the crack tip approaches infinity. LEFM defines the stresses at the crack tip in terms of the strength of the discontinuity[*] at the crack tip, referred to as the stress intensity factor, K. In this formulation, fracture occurs at equal values of stress intensity factor, independent of the geometry or the loading that produces the stresses acting on the crack tip. The same is true for fatigue crack growth using the change in the stress intensity factor corresponding to the fatigue stress cycle. As a result, the critical stress intensity factor, K_{Ic}, and the fatigue crack growth rate can be determined for a particular material using standardized test specimens; once determined, these can be applied to a structure of arbitrary configuration.[†] The stress intensity factors for the cracks in the tank have been derived from finite element analyses of cylinders with surface cracks (Anderson, et al., 2002), and through wall cracks (Anderson, et al., 2003).

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[*] The stress concentration factor is infinite at the tip of sharp crack.

[†] The critical value of K depends on the mode of the loading at the crack tip, as follows: I = opening mode, II = in-plane shear mode, and III = out-of-plane shear mode.

In practice, the structure will yield at the crack tip. LEFM is appropriate when the size of the yield zone is small compared to the size of the crack. However, when yield zone is large, the fracture process zone can be characterized by elastic plastic fracture mechanics (EPFM). EPFM uses the J-Integral, which is analogous to K used in LEFM. In the current analysis, EPFM is used to generate the failure pressure curves.

Material Property Data. The cargo tanks being considered in this phase are fabricated from steel plate corresponding to American Society of Mechanical Engineers (ASME) specification number SA-612. Among other requirements, this specification mandates minimum yield and ultimate tensile strengths of 51 and 80 ksi, respectively for thicknesses greater than 0.5 inch but not greater than 1 inch. The test report presented in Appendix A confirms that the steel provided for this study satisfies this requirement. It also presents Charpy impact test results for 72 F and -40 F. The average Charpy impact energy at 72 F was 141 ft-lb and 47 ft-lb for -40 F.

The fatigue crack growth rate data used for the analysis are shown in Figure 4. These data are typical of linepipe steels for representing Grades X46 through X52, having Specified Minimum Yield Strengths (SMYS) of 46 and 52 ksi, respectively. In the figure, the y-axis is the crack growth rate and the x-axis is the change in the stress intensity factor, ΔK. The term ΔK is the range of K of the pressure cycle. These data show the typical power-law cracking response[*] and that the slope of the trend line through the data is 3.0, which lies in the range typical of construction steels. The figure also shows that the threshold for propagation for these materials is approximately 4 ksi√in. Therefore, these data should be acceptable for the current analysis, and no additional crack growth rate experiments should be required.

Analysis Results. Table 3 presents the parameters and values used for the service life prediction. Referring to the capabilities of radiographic inspection techniques to estimate the initial crack size, the resulting initial crack has a semi-circular shape with a depth of 0.337 inch (70 percent of the shell thickness) and length of 0.674 inch (twice the depth). This initial crack size was used in the crack growth models previously discussed, with the pressure cycles of Table 2. The estimated service life for this crack exceeds 2,000 years, indicating a significant margin over the currently used five-year inspection period.

Figures 5 and 6 present a series of service life contours for which the initial crack length and depth vary systematically. These results show the significance of the initial crack depth and length. Figure 5 shows the number of years of service to form a leak. Figure 6 shows the total life, i.e., the number of years of service until a rupture occurs.

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[*] This typical power-law response is displayed as a straight line on a log-log plot, such as Figure 4.

Table 3. Parameters for baseline reference life assessment.

Features	Parameters	Values
Tank Size	Diameter:	80 inches
	Wall thickness:	0.481 inch
Tank Design	Maximum allowable working pressure (MAWP):	250 psi
	Hydro-test pressure:	375 psi
Tank Pressure History (see Table 2)	Cycles per day:	1
	Extreme temperature range:	-10 F to 120 F
	Extreme pressure range	16 to 226 psi
Initial Crack	Number of cracks:	1
	Crack orientation:	Axial
	Crack location:	Cylindrical section
		Internal
	Hydro-test temperature:	72 F
	Length:	0.674 inch
	Depth:	0.337 inch (70% t)
	Tank bulging:	Yes
	Ductile tearing:	No
	Elastic modulus:	30,000 ksi
Material	Yield strength:	57.4 ksi
	Ultimate strength:	85.1 ksi
	Flow stress:	60 ksi
	CVN impact energy:	47 ft-lb at -40 F
		141 ft-lb at 72 F
	Fatigue crack growth rate data:	Nominal
	Fatigue crack growth rate threshold:	4 ksi√in
	Crack growth retardation:	No

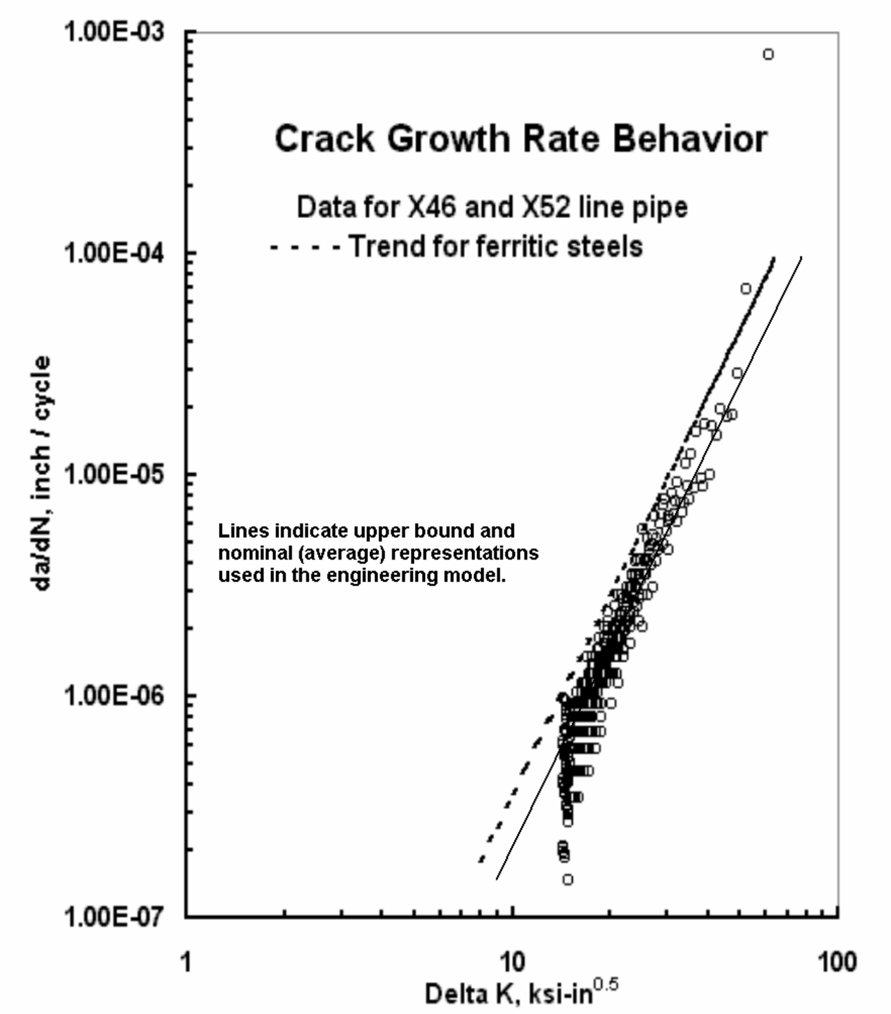

Figure 4. Fatigue Crack Growth Rate Data.

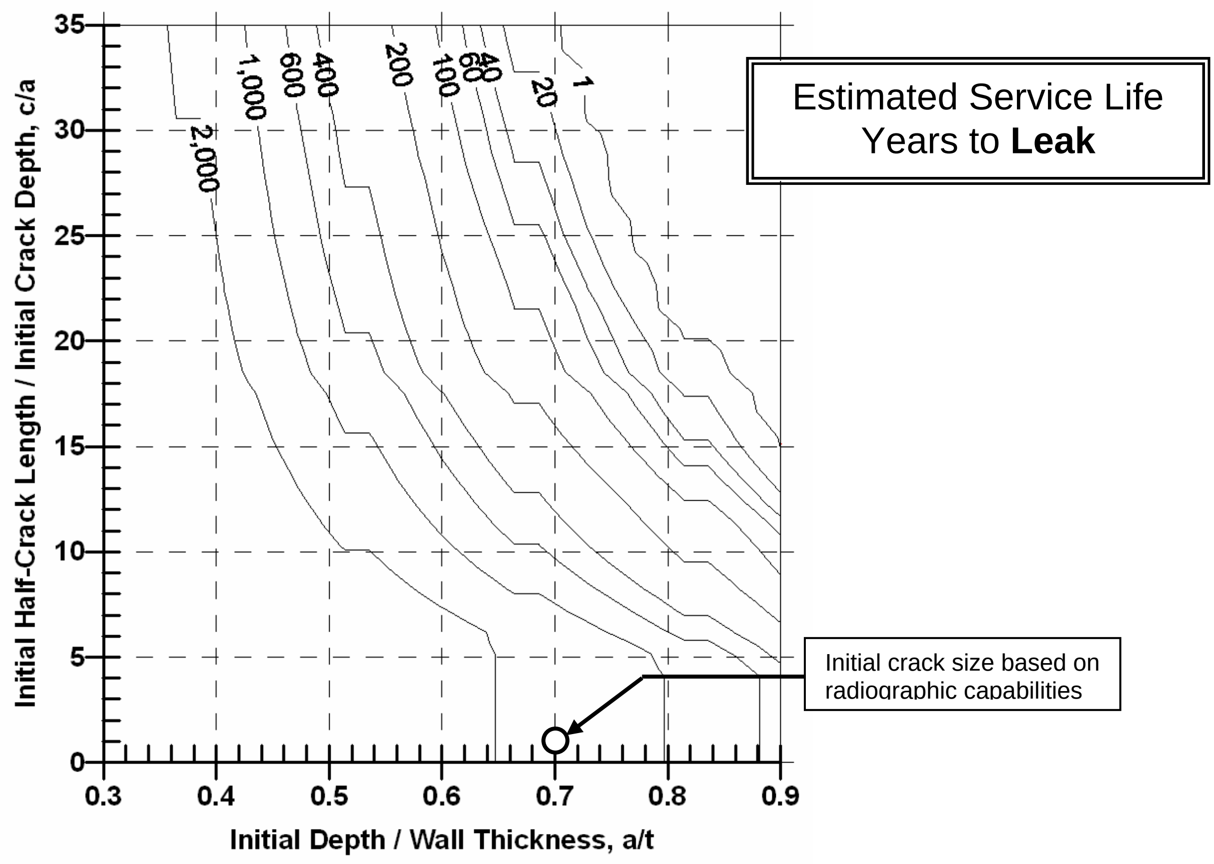

Figure 5. **Service life contours showing the initial crack size estimate on the number of pressure cycles required to cause a leak.**

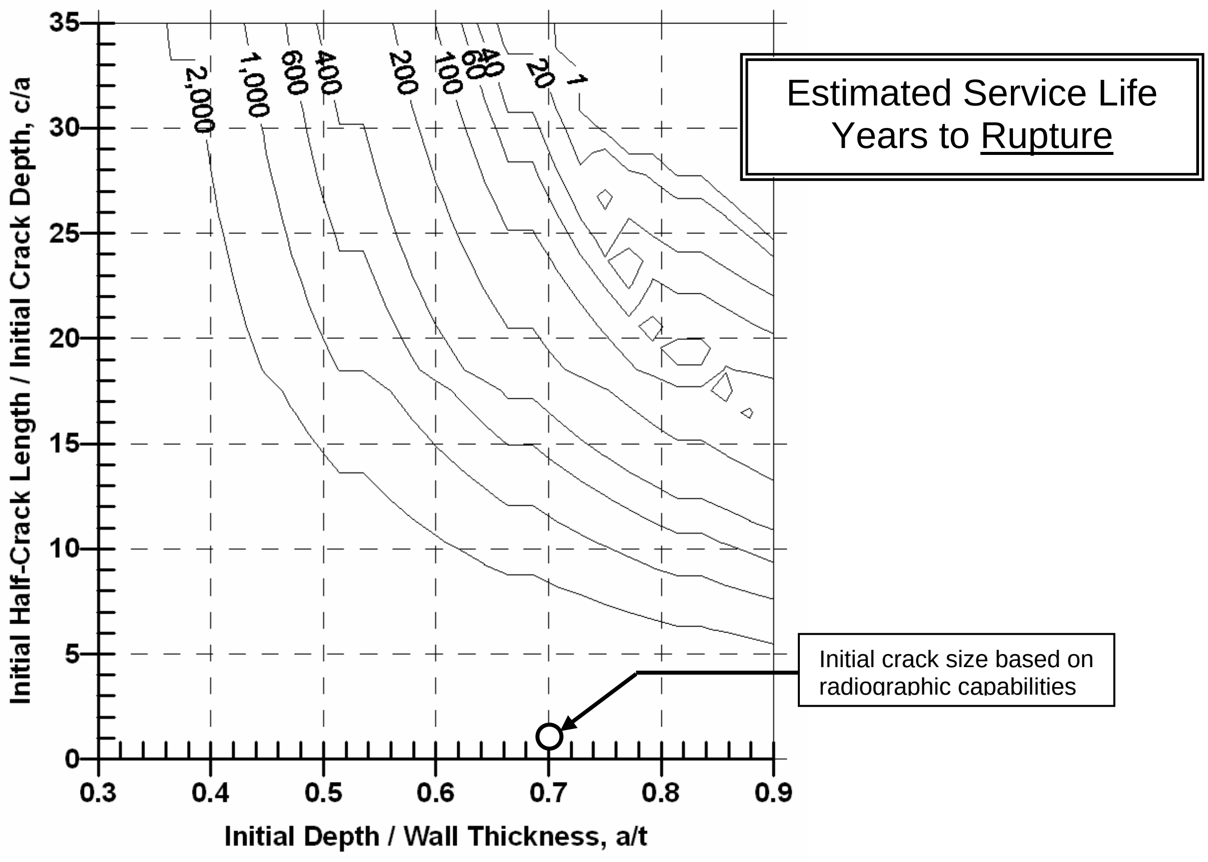

Figure 6. **Service life contours showing the initial crack size estimate on the number of pressure cycles required to cause a rupture.**

Task 2 – Continue Discussions with DOT on Cargo Tank Inspection Period Extension

A white paper was submitted to DOT PHMSA staff that described the modeling methodology performed in Task 1. This white paper (included here as Appendix B) served as the basis for a meeting held between NPGA and Battelle staff and DOT PHMSA staff, at DOT offices in Washington, DC, on April 27, 2006. The objective of this meeting was to provide an update of Battelle's engineering analyses of cargo tanks to the PHMSA staff. The presentation used during this meeting is presented in Appendix C.

Battelle presented the plans for the next phase of the project, where includes mounting an instrument on a standard truck-mounted cargo tank and measuring the loads induced by travel on roads. We also suggested that DOT staff witness some of these tests.

Feedback from the DOT staff was cautiously encouraging. DOT staff mentioned some points:

- If the analyses address particular materials or manufacturing methods that have only recently been implemented, then any modifications that are made to the regulations will apply only to those materials/methods. The more general the analyses, the better.
- Historical data are important (such as the many years of safe performance of these cargo tanks), but thorough analyses using sound, recognized technology (such as fracture mechanics methods) are required for regulation modifications.
- DOT staff attendance and interest in this meeting and even witnessing the field test should not be construed as supporting the possible requalification period extension. Extensive analysis of the modeling and testing results would have to be conducted before a decision would be made.

NPGA and Battelle will continue to interact with DOT PHMSA staff during the next phase of the project, including test plan development, instrumentation and data collection, and analytical analyses.

Task 3 – Survey of the Cargo Tank Population

During an early meeting with DOT staff and subsequent phone conversations, the DOT staff indicated interest in the population characteristics of cargo tanks. Examples of characteristics of interest included the age, the range of volumes that exist, and the presence of manways. To generate this information, the ADEPT Group performed two sets of surveys: a pilot survey on a small group of cargo tank owners/operators to refine the survey questions and a more extensive survey on a larger owners/operators group.

To collect and compile the results presented in this report, ADEPT first conducted a pilot survey among propane marketers in California, with assistance from the Western LP Gas Association. In this pilot survey, 23 survey questionnaires were sent out and 13 fully completed replies were received, representing a population of 156 bobtails. Feedback received during the pilot survey allowed ADEPT to modify the survey questions to be more clear and more complete. Approximately 250 survey forms were sent out; 89 propane marketing companies replied with usable forms, covering 2,232 bobtails.

Final Survey Questions

The final survey consisted of the following 13 questions, designated general and tank-specific.

General questions:	1.	How many LP Gas bobtails does your company currently operate?
	2.	What is the average accumulated annual mileage per bobtail?
	3.	Is methanol currently used in the LP Gas you deliver?
Tank-specific questions:	1.	Tank manufacturer
	2.	Date of tank manufacture
	3.	Water capacity
	4.	Does the tank have a manway?
	5.	Head Type: Welded (Segmented), One-piece stamped, Don’t know
	6.	Date of last pressure test
	7.	Shell steel grade
	8.	Head steel grade
	9.	Shell thickness
	10.	Cap thickness

A survey form is included in Appendix D.

Collected Data Analysis

The bulk of the analysis commentary below is for the combined results of both the pilot and the final survey. Those which do not include both are noted.

General Questions Regarding Propane Bobtails:

1. The average number of bobtails for the surveyed companies was seven. When one of the majors (with over 1,600 bobtails) was included, the average number of bobtails per company surged to 23.
2. The average accumulated mileage per bobtail was 22,434 miles/year.
3. Methanol was used with 83 percent of a total of 2388 bobtails (replied either “Yes” or “Sometimes”).

Tank Specific Questions:

1. Tank manufacturer - 47 different tank manufacturers were mentioned. Trinity and Arrow were the top two manufacturers mentioned, each with over 28 percent of the sample population. The next eight top manufacturers were: Texas Welding, Mississippi Tank, The National Butane Gas Co., Inc., Trans Western, National Tank, Delta, Ameritank, and

Dalworth. Each accounted for less than 8 percent of the sample, with the last four accounting for a combined 10 percent of the replies. Table 4 gives the complete data set.

2. Tank manufacture date – The five years that comprise the largest percentage of the surveyed sample (in order of size) are: 1998 and 1970, 1973, 1977, 1974 (each with over 4 percent of the sampled population). The responses included tanks manufactured as early as 1948. The results are shown in Table 5.

3. Water capacity (volume) – The five most popular tank sizes were:
    - 3,000-3,099 gallons, with 31 percent of 2388 total tanks,
    - 2,600-2,699 gallons, with 22 percent,
    - 2,800-2,899 gallons, with 19 percent,
    - 2,500-2,599 gallons, with 8 percent,
    - 2,400-2,499 gallons, with 8 percent.

4. Tank manway – Of the tanks surveyed, less than 30 percent have manways. Over 68 percent of the sampled population was comprised of tanks **without** manways. It is interesting to note that tanks **with** manways consistently made up over 60 percent of the tanks produced each year after 1994 (and typically more than 70 percent of the tanks made that year). Before 1994, only in 1957 and in 1958 did tanks **with** manways make up a majority of those produced that year.

5. Head type (welded or one-piece stamped) – The final survey, consisting of 2232 bobtails, indicated that over 71 percent of the tanks had one-piece stamped head types. Slightly over 16 percent of the bobtails had welded head pieces. Slightly less than 13 percent of the responses were “Don’t know” responses or were not available. Note: The pilot survey replies are not included in these results because this question was unclear in the pilot survey.

6. Date of last pressure test – Over 90 percent of the bobtails surveyed had a pressure test within the last five years. Almost one percent of the tanks had their last pressure test over five years ago, with one tank as far back as 1993. Additionally, over 15 percent were last tested in 2001. This means that at the time of the survey, about 7.5 percent of the bobtails had their last pressure test over five years ago (assuming that the tests are performed uniformly throughout the year). Therefore, approximately 8.5 percent of the bobtails surveyed could be considered to be outside current DOT requirements.

7. Shell steel grade – Twenty-three shell steel grades were listed. SA202B was listed on 43 percent of the surveys, and SA612 was listed on 40 percent of the surveys. SA202 was listed on two percent of the replies. The rest of the listed steel grades collectively accounted for approximately four percent of the responses. “Not available” and “Other” responses accounted for 12 percent of the replies.

8. Head steel grade – Twenty-four cap steel grades were listed. SA612 was listed on 39 percent, SA202B was listed on 35 percent of the responses, and SA455A was approximately 11 percent of the surveyed bobtails. SA202 accounts for almost two

percent of the sample. The rest of the listed steel grades collectively accounted for four percent of the responses. “Not available” and “Other” responses accounted for nine percent of the responses. This question was not included in the pilot survey.

9. Shell thickness – Over 53 percent of the tanks in the survey had shell thicknesses of between 0.40 inch and 0.449 inch. Thirty six percent had shell thicknesses of between 0.45 inch and 0.499 inch.

10. Cap thickness – The three most represented cap thicknesses were 0.23 to 0.239 inch (30 percent of responses), 0.26 to 0.269 inch (20 percent of responses), and 0.24 to 0.249 inch (20 percent). The next two top cap thicknesses were 0.25 to 0.259 inch and 0.30 to 0.309 inch, each comprising about seven percent of the sampled bobtails.

Table 4. Survey Results: Tank Manufacturer.

Manufacturer	# of Tanks	% of Surveyed Market	Manufacturer	# of Tanks	% of Surveyed Market
Trinity	683	28.60%	Columbian	5	0.21%
Arrow	673	28.18%	Ransome	5	0.21%
Texas Welding	187	7.83%	N/A	5	0.21%
Mississippi Tank	97	4.06%	Master	4	0.17%
National Butane Gas Co. Inc.	92	3.85%	Dallas Tank	3	0.13%
Trans Western	87	3.64%	Downington	3	0.13%
National Tank	69	2.89%	North Texas	3	0.13%
Delta	68	2.85%	Petroleum	3	0.13%
Ameritank	63	2.64%	Steel Tank Co	3	0.13%
Dalworth	47	1.97%	Atlas	2	0.08%
Bulk Truck & Transport	38	1.59%	Beaird	2	0.08%
East Fabricators	38	1.59%	Consolidated Western	2	0.08%
Superior	28	1.17%	Lide Vessels Inc.	2	0.08%
American Bridge	27	1.13%	Rheem Superior	2	0.08%
Kleespie	26	1.09%	Roy Hansen	2	0.08%
Lubbock Tank & Trailer	21	0.88%	US Steel	2	0.08%
American Welding & Tank	17	0.71%	Westmore Industries	2	0.08%
Allis Chalmers	15	0.63%	651-01	1	0.04%
Cherokee	12	0.50%	Eaton Metal	1	0.04%
Gaskell Co	9	0.38%	Harmon	1	0.04%
Missouri Tank	9	0.38%	Lang	1	0.04%
Pasley	7	0.29%	Southern Company	1	0.04%
Charlotte	6	0.25%	Waner	1	0.04%
Tri State Tank	6	0.25%	Western	1	0.04%
US Fabrication	6	0.25%	**Total**	**2388**	**100.00%**

Table 5. Survey Results: Tank Manufacturer.

Year	# of Tanks	% of Surveyed Market	Year	# of Tanks	% of Surveyed Market
1998	110	4.61%	1993	43	1.80%
1970	100	4.19%	1976	41	1.72%
1973	95	3.98%	1982	41	1.72%
1977	93	3.89%	1965	40	1.68%
1974	92	3.85%	1966	40	1.68%
1999	85	3.56%	1984	40	1.68%
1969	82	3.43%	1991	38	1.59%
1972	80	3.35%	1992	35	1.47%
1997	77	3.22%	2002	34	1.42%
1968	70	2.93%	2005	31	1.30%
1975	67	2.81%	1983	24	1.01%
1971	66	2.76%	2004	23	0.96%
1980	63	2.64%	2003	22	0.92%
1989	63	2.64%	1964	18	0.75%
1979	62	2.60%	1963	17	0.71%
1990	60	2.51%	1962	8	0.34%
1987	55	2.30%	1961	6	0.25%
1978	54	2.26%	2006	6	0.25%
1996	53	2.22%	1959	4	0.17%
1967	52	2.18%	1960	4	0.17%
2000	52	2.18%	1958	3	0.13%
1995	51	2.14%	1948	1	0.04%
2001	51	2.14%	1952	1	0.04%
1994	50	2.09%	1954	1	0.04%
1981	46	1.93%	1955	1	0.04%
1988	46	1.93%	1957	1	0.04%
1985	43	1.80%	N/A	4	0.17%
1986	43	1.80%	**Total**	**2388**	**100.00%**

Task 4 – Identify possible alternative inspection methods

One possible outcome of the interaction with DOT is that inspection methods other than pressure testing and visual inspections may be accepted. Any alternative methods must be operationally cost-effective in that the overall inspection cost to the marketer cannot increase over that of the currently accepted inspections. In addition, the equipment costs cannot be prohibitively expensive to the inspector. In this optional task, alternative inspection methods will be investigated and compared to the currently accepted internal inspection and pressure testing methods.

The ADEPT Group performed a cursory review of the alternative inspection methods that are available for pressure vessels and piping. Although these technologies are not extensively used in the U.S. propane industry, at least on the period inspections of bobtail tanks, they are being used regularly in other industries such as petrochemical plants and product transmission (such as interstate pipelines), power generation, and aerospace. The advantages of these non-destructive evaluations (NDE) techniques is that the system being inspected is removed from service for a shorter period of time, if at all, than is the case with more traditional (and potentially destructive) methods such as hydrostatic and aerostatic pressure testing.

The methods considered here were:

- Ultrasonic
- Acoustic emission
- Magnetic particle
- Liquid penetrant
- Radiographic
- Eddy current.

Each method is briefly discussed below, followed by a summary comparison table that considers the advantages and disadvantages of each method.

Ultrasonic Testing (UT)

In ultrasonic testing, a handheld transducer connected to a diagnostic machine is passed over the object being tested. The transducer sends pulsewaves into the surface of the object, returning the “sound” back to the device whenever an imperfection is detected. The screen on the diagnostic machine will show these results in the form of amplitude, and pulse readings, as well as the time it takes for the waves to return to the transducer.

Possible benefits of ultrasonic examination are:

- External to the tank, with no need to empty the contents of the tank.
- Advanced systems can offer paper record to document inspection results.
- Portable, with the ability to bring the instrument to bobtail location.

Possible challenges include:

- Sensitivity to surface contact. The surface may need to remove paint and/or sand surface to ensure good transducer/tank acoustic contact.
- It may be difficult and time consuming to examine entire vessel. Typically all welds are examined, as well as areas that are targeted for further inquiry.

Acoustic Emissions (AE)

Acoustic emission (AE) is a naturally occurring phenomenon whereby external stimuli such as mechanical loading generate sources of elastic waves. AE occurs when a small surface displacement of a material is produced. This occurs due to stress waves generated when there is a rapid release of energy in a material or on its surface. This rapid release can come when materials begin to fail, such as the extension of a fatigue crack.

Transducers are attached to the material in order to detect these waves. AE tools do not actively produce waves as in conventional ultrasonic testing. Rather, they passively detect emissions from acoustic sources. For tanks, the initiating event for these acoustic waves is a pressurization of the tank, usually to the design pressure. The transducers then record the acoustic emissions from the tank. An emissions profile is then reviewed and compared to earlier test results to determine if significant variation exists.

Possible benefits of acoustic emissions examination are:

- External to the tank.
- Relatively quick, especially compared to ultrasonic testing and hydrotesting.

The main challenge is that there is no convenient means of raising the pressure of a tank containing a saturated liquid, such as propane. Either the tank must be heated or the tank must be emptied and then pressurized with a gas or liquid.

Magnetic Particle Inspection

Magnetic particle inspection processes are non-destructive methods for the detection of defects in ferrous materials. An externally applied magnetic field or DC current passes through the material, and deviations are analyzed. These techniques are based on the principle that the magnetic susceptibility of a defect is markedly poorer (the magnetic resistance is greater) than that of the surrounding material.

The presence of a surface or near-surface flaw (void) in the material causes distortion in the magnetic flux through it, which in turn causes leakage of the magnetic fields at the flaw. This deformation of the magnetic field is not limited to the immediate locality of the defect but extends for a considerable distance, even through the surface and into the air if the magnetism is intense enough. Thus, the size of the distortion is much larger than that of the defect and is made visible at the surface of the part by means of the tiny particles that are attracted to the leakage fields.

The most common method of magnetic particle inspection uses finely divided iron or magnetic iron oxide particles, either in powder form or held in suspension in a suitable liquid. The particles are often colored and usually coated with fluorescent dyes that are made visible with a hand-held ultraviolet (UV) light. The suspension is sprayed or painted over the magnetized specimen during magnetization with a direct current or with an electromagnet, to localize areas where the magnetic field has protruded from the surface. The magnetic particles are attracted by the surface field in the area of the defect and hold on to the edges of the defect to reveal it as a buildup of particles.

Possible benefits of magnetic particle inspection include:

- Results may be documented via pictures.
- If applied external to the tank, tank may not have to be emptied of its contents.
- No additional pressure must be placed on the tank.

Possible challenges of this method include:

- Test is best done on the tank's internal surface, which means tank must be empty and the tank must have a manway.
- Arcing at prods may be an ignition risk.
- Overheating or burning of the surface may be an issue.
- May have difficulties near welds.
- May not be sensitive to defects perpendicular to the magnetic flux lines.
- Magnetic particles may become a fuel contaminant if not completely removed.
- Possible complications due to induced tank magnetism.
- Operator intensive.

Liquid Penetrant

Liquid penetrant examination (LPE), also known as dye penetrant inspection is used in the detection of surface breaking flaws where magnetic particle inspection is difficult to apply. Variations include the use of fluorescent dyes, where a black light is used to illuminate the residual penetrant. This technique has even higher sensitivity than normal LPE, but can be used only in the absence of other light sources.

Once the die and the developer have been applied to the surface, the flaws are more visible and have a high contrast. Also, the developer draws the penetrant out of the flaw over a wider area than the real flaw, making it look wider.

The benefits of LPE are:

- Surface discontinuities are readily visible.
- Test results can be documented via photos.
- Low testing costs.
- Limited training is required for the operator, although experience is valuable.

The possible challenges related to LPE are:

- Test is best done on the tank's internal surface, which means tank must be empty and the tank must have a manway.
- Flaws must extend to the surface.
- Proper cleaning is necessary as surface must be bare.
- Penetrant, developer and cleaner are relatively toxic.

Radiographic Inspection

Radiographic testing is a method of inspecting materials for hidden flaws by using the ability of short wavelength electromagnetic radiation (high-energy photons) to penetrate various materials.

Either an X-ray machine or a radioactive source (Ir-192, Co-60, or in rare cases Cs-137) can be used as a source of photons. Since the amount of radiation emerging from the opposite side of the material can be detected and measured, variations in this amount (or intensity) of radiation are used to determine thickness or composition of material.

The beam of radiation is directed to the middle of the section under examination. The specimen to be inspected is placed between the source of radiation and the detecting device, usually the film in a light tight holder or cassette, and the radiation is allowed to penetrate the part for the required length of time to be adequately recorded. The result is a two-dimensional projection of the part onto the film, producing an image of varying densities according to the amount of radiation reaching each area. This image is known as a radiograph.

The benefits of radiographic inspection are:

- A well-established technology.
- Results are documentable.
- Ability to detect discontinuities not extending to the surface.

The challenges related to radiographic inspection are:

- Radiation source and detector/film must be on opposite sides of a shell wall, therefore the tank must be empty and the tank must have a manway.
- Equipment is expensive and not typically mobile.
- Extensive operator training is required.
- Inspection area of one radiograph is small, therefore inspection of the entire tank is extremely time consuming.
- Radiation exposure can be a serious health effect.

Eddy Current

Eddy current testing uses electromagnetic induction to detect flaws. It can detect very small cracks in or near the surface of the material, and the surfaces need minimal preparation. The testing devices are portable, provide immediate feedback, and do not need to contact the item in question.

There are several limitations, among them: only conductive materials can be tested, the surface of the material must be accessible, the finish of the material may cause bad readings, the depth of penetration into the material is limited, and flaws that lie parallel to the probe may be undetectable.

The benefits of eddy current testing include:

- Test is conducted on the external surface, and tank does not have to be emptied.
- Results may be documented via printouts.
- Provide immediate inspection information.

The challenges in using eddy current testing include:

- Requires high level of inspector expertise.
- Inspection area is small; therefore, inspection of the entire tank is extremely time-consuming.

- Possible residual magnetic field issues (may need to de-magnetize tank before/after test).

Comparison of Alternative Inspection Methods

To compare the various characteristics of the alternative methods discussed here, eleven parameters were considered, as shown in Table 6.

Table 6. Parameters for comparison of alternative inspection technologies

Parameter	Details
Non-destructive	Method should be non-destructive to the tank
External	Method should be applied to the exterior of the tank, eliminating the need to empty the tank if possible
Cost effective	Method should be cost comparative to hydrotesting
Fast	Method should be no more time consuming than a hydrotest
Reliable	Method should identify flaws
Provides a clear Go/No-Go result	Method's test result should be non-subjective
Straight-forward to perform	Method should require minimal additional training
Improves operational characteristics	Method should minimally affect returning the tank to service,
Instrument portability	Method's equipment should be able to move to the bobtail location
Tank coverage	Method should cover the entire tank
Recognition by US Regulatory Agencies	Method should be recognized as an acceptable method of inspecting cargo tanks

A ranking of 0 to 5 points was assigned to these parameters for each of the alternative inspection methods, in which 0 represents least favorable and 5 represents most favorable. The currently used hydrostatic testing is included as a baseline comparison. Table 7 shows the resulting numerical ranking of these inspection methods.

Table 7. Comparison of alternative inspection technologies (higher rating is better)

	Ultrasonic	Acoustic Emissions	Magnetic Particle	Liquid Penetrant	Radiographic	Eddy Current	Hydrostatic
Non-destructive	5	4	5	5	5	5	2
External	5	5	0	0	0	5	0
Cost effective	4	5	2	2	0	3	2
Fast	4	5	0	0	0	3	1
Reliable	5	5	5	4	5	5	3
Provides a clear Go/No-Go result	5	5	5	5	5	5	5
Straight-forward to perform	0	2	3	3	0	0	5
Improves operational characteristics	5	3	2	2	0	5	0
Instrument portability	5	5	3	5	2	3	2
Tank coverage	2	5	5	5	2	2	5
Recognition by US Regulatory Agencies	0	0	5	5	5	0	5
Total	**40**	**44**	**35**	**36**	**24**	**36**	**30**

The result of this comparison indicates that the acoustic emission method and the ultrasonic method have the most favorable ratings. It is recommended that these methods be considered further as alternatives to the hydrotest method. It is also recognized that the final evaluation of any method must come as being approved by the US DOT as a propane cargo tank inspection method.

Conclusions

In Phase 1 of this project, we estimated the service life of a propane cargo tank based on the thermodynamic cycles that are impressed on a tank in one year. The Battelle team considered what we believe were reasonable extreme temperatures that generate the propane pressure cycles. These cycles were used in the crack growth models that have been used in the past to model pipeline failures. The initial crack size was estimated from the maximum size of a flaw that would be missed during a radiographic inspection. The result was that a typical propane tank with the assumed annual pressure cycles and the initial crack would take over 2000 years for the crack to grow through the wall. These results will be expanded during work in Phase 2, in which we will consider the road loads in addition to the thermodynamic pressure loads.

Battelle continued discussions with DOT PHMSA staff on these modeling efforts. While the PHMSA staff expressed general interest in the overall project, they are withholding approval until they are presented all the modeling and test data. The PHMSA staff were invited to comment on the road test plan that will be developed in Phase 2 and to witness some of the road testing.

A survey was performed on various characteristics of propane cargo tanks, including the age, size, materials of construction, and constructors of the tank. Nearly 2400 tanks were covered in the survey. Over half of the tanks were manufactured by two companies, Trinity and Arrow. The date of manufacture of the surveyed tanks ranged from 1948 to 2006, with no year having more than five percent of the sample population. Thirty-one percent of the tanks were between 3000 and 3099 gallons, and 22 percent were between 2600 and 2699 gallons and 19 percent between 2800 and 2899.

Alternatives to the hydrostatic test inspection method were considered and were ranked using a point system on eleven parameters. This ranking listed the acoustic emissions and the ultrasonic methods as promising techniques that should be considered further as alternatives to the currently used hydrostatic test method.

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Appendix A
Laboratory Report — Charpy Testing

BOWSER-MORNER, INC.
CORPORATE: 4518 Taylorsville Road. • P. O. BOX 51 • DAYTON, OHIO 45401 • 937/236-8805

LABORATORY REPORT

TO: Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Attention: Ron Galliher

BMI NO.: 10017636
GROUP NO.: 52116
SAMPLE NO.: 601823-601824
P.O. NO.: Credit Card
DATE: February 15, 2006

ON: Mechanical Testing.

1.0 SAMPLE INDENTIFICATION:

Steel Plate

2.0 TEST PROCEDURES:

Machining and mechanical testing were conducted in accordance with ASTM test procedures: E8, E23 and clients instruction.

3.0 TEST RESULTS:

Tensile Testing:

Mechanical Properties	Tensile #1	Tensile #2
Dimensions, inches	0.503 x 0.490	0.502 x 0.491
Area, square inches	0.2465	0.2465
Maximum Load, lbs.	20970	20940
Yield Load, lbs.	14160	14180
Tensile Strength, psi	85100	84900
Yield Strength, psi	57400	57500
Elongation, %	32.5	32.5

Note: Yield determined at 0.2% offset, elongation measured from a 2.00” gage.

Impact Testing:

Test Temperature, °F	Breaking Energy, Ft./Lbs.	Lateral Expansion, mils	Shear, %
72	146.0	80	80
72	152.0	77	80
72	125.0	68	80
-40	138.0	78	80
-40	38.0	34	10
-40	56.0	37	10

If there are any questions concerning this report, please contact me.

Respectfully Submitted,

BOWSER-MORNER, INC.

James J. Duncan
Supervisor, Metallurgical Testing

JJD/acm

Appendix B
Service Life Estimation Procedure for Propane Cargo Tanks

Service Life Estimation Procedure for Propane Cargo Tanks

Tom Forte, Brian Leis, Rod Osborne
Battelle – Applied Energy Systems

December 21, 2005

The National Propane Gas Association is approaching the US Department of Transportation, Pipeline and Hazardous Materials Safety Administration, with a request to consider extending the requalification period of propane cargo tanks. This period is currently specified in 49CFR180.407 as five years. Specifically, NPGA's request addresses only cargo tanks ("bobtails") of less than 3500 gallons, of non-quenched and tempered (NQT) materials, in dedicated propane service. Battelle is performing engineering analyses that will address NPGA's request.

Battelle's approach to this analysis is a two phase approach, where Phase 1 develops the engineering model of the cargo tank and the thermodynamic loading exposed to the tank. The thermodynamic loads, that is, the pressure history of a tank caused by the temperature changes of the propane lading, are considered simpler to determine than the more severe dynamic road loads. Using the tank model, Battelle will first determine the maximum crack size that would go undetected in the standard pressure test, and then determine growth of this flaw for the assumed loading. Using this crack growth, Battelle will estimate the projected life of the tank, based on a through-the-wall crack. If the order-of-magnitude of this projected life is significantly longer than the current five year requalification period, then there may be merit in continuing the study to address the vehicle dynamic loading. Phase 2 will use the engineering model developed in Phase 1 to consider the tank stresses induced from the dynamics of lading–tank–truck–road interactions. Similar to Phase 1, in Phase 2 Battelle will determine the maximum crack size, the projected life, and resultant safety factor on the inspection period for the quasi-static loading from Phase 1 combined with the over-the-road loading. This document addresses the methodology for these analyses.

Fracture mechanics is used routinely to estimate service lives and inspection intervals for air and space vehicles, nuclear power plants, pipelines, and a wide range of other devices and structures. We expect to show that fracture mechanics provides a highly effective framework for estimating the service life of propane delivery tanks. With this approach, an infinitely sharp crack is assumed to be present in the wall of the propane tank, or elsewhere in the tank or its support structure, and the number of load cycles required to grow the crack to a size sufficient to cause failure is calculated. This approach is well suited to assess crack growth resulting from pressure and load cycles due to filling and emptying the tank and the load cycles applied to the tank when it is transported on the truck.

For a typical crack growth analysis, Equation 1 is the governing fracture mechanics equation that is used to compute the number of cycles to failure.

$$N = \int_{a_i}^{af} f(\Delta K)\ da \tag{1}$$

where:

a_i = initial crack size
a_f = final crack size
N = number of load cycles to grow the crack from the initial to the final crack size
ΔK = change in the stress intensity factor, K, during a load cycle
$f(\Delta K)$ = function of the geometry of the structure containing the crack, the shape and size of the crack, and the material of which the structure is made
da = crack growth increment during a load cycle.

The equation used for $f(\Delta K)$ is based on a curve fit of data derived from open literature. In addition, the equations for ΔK have been taken from the literature. These are active research areas and the equations being used are based on the latest validated information. A description of the analytical procedure, along with the data used for the curve fit and the equations used for ΔK will be given in a final report.

The analytical service life estimation procedure involves solving Equation 1 numerically. In effect, the analysis grows the crack numerically from the initial size and checks for possible failure after each increment of growth. Several failure criteria are considered in the analysis. The primary criterion is the dependence of the failure pressure on the size of the crack, i.e., length and depth for part through wall cracks and length for through wall cracks. The failure pressure criterion used is based on the results of full-scale burst tests. When failure is detected, the service life is taken as the total number of load cycles that had been applied up to the point when failure is predicted.

In addition, when the value of ΔK is less than the threshold for crack growth in the material containing the crack, no crack growth occurs. As a result, ignoring the threshold would provide conservative life estimates.

Similar to many pipeline applications, the initial crack for the tank is a part-through wall crack that is represented as having a depth, *a*, and a total length, *2c*, as illustrated schematically in Figure 1[1]. For this type of crack, Equation 1 will be solved simultaneously for growth in the depth and length directions using Battelle-developed software that has been validated through previous research on pipeline applications. This software should be applicable to crack growth in

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[1] The analytical procedure is applicable to cracks located on the interior and the exterior surfaces. The primary difference is that the crack faces of the interior crack are exposed to the pressure contained within the vessel. Given that the internal pressure is so low compared to the stress in the vessel wall the effect is not significant. Nevertheless, both cases will be considered.

short cylinders because of their potential for reduced stress amplification due to bulging at the crack tip.

The size of the initial crack often is the most dominant factor in defining the service life and will be based on two assumptions: (1) the crack will be deep enough to just survive the hydrotest, and (2) it will be long enough so that when it breaches the wall thickness, the tank will rupture at the operating pressure without first exhibiting an observable leak. In other words, a deeper crack will be detected by the hydrotest and will not enter service, and shorter cracks will result in a leak that might be detected before the tank can rupture. The proposed combination of depth and length will provide the shortest life for a single dominant crack in the wall of the tank. The possibility of multiple cracks that might produce a shorter life will be evaluated using the crack coalescence criteria based on previous research. In general, the stress intensity factor and therefore the growth rate will be significantly less for smaller cracks than for the single large crack. In addition, cracks smaller than the single crack that will just survive the hydrotest will result in leaks rather than ruptures. Therefore, detecting leaks must continue to be an important inspection priority.

For part-through wall cracks in pipelines (infinitely long cylinders) subjected to internal pressure, the initial and final crack sizes are functions of the pipe's diameter and wall thickness, the pressure, and the toughness of the pipe material. Battelle's pipeline software will be used to predict failure pressures for part-through wall cracks and to determine whether a part-through wall crack will leak or cause an immediate rupture should it propagate through the wall. A modification may be required to this software to account for the difference in length between the pipeline and short cylindrical propane tank. The need for a possible modification will be evaluated based on the conservatism added to service life prediction. For example, a crack in the pipeline or tank wall will weaken the wall and cause the wall to bulge locally. Conceivably, the tank wall will bulge less than the pipeline wall because the tank wall is stiffened by the heads. As a result, a deeper crack could survive the hydrotest and longer through-wall crack could resist rupture in the tank than in the pipeline. Therefore, based solely on the initial crack size, the predicted service life for the tank could be less than for the pipeline. This would be a non-conservative result because the analysis is based on the pipeline research and full scale testing. Conversely, including the full bulging effect in the crack growth portion of the analysis will result in a shorter service life for the tank than for the pipeline. These competing effects will be assessed with the intent of achieving a conservative service life estimate for the tank.

Figure 2 presents an example of a family of failure pressure versus crack length and depth curves. For this example, note that the curves for the part-through wall crack cover the range of crack depth-to-thickness ratios with the range from 0.1 to 0.9. The zero-depth curve refers to a plastic-collapse condition, wherein failure is due to general yielding. Also presented in the plot is a failure pressure versus crack length curve for a through wall crack. Graphs of this type relate failure pressure; pipe strength, toughness, diameter, and wall thickness, and crack length for through wall cracks, and crack length and depth for part-through wall cracks.

As already mentioned, the initial crack length and depth will be determined from both the service and hydrotest conditions. The length will be estimated first. Figure 2 presents a step-by-step graphical description of the process. Using the maximum allowable working pressure, MAWP, we will estimate the length of a through wall crack that will be on the verge of rupturing. In other words, if a part-through wall crack reaches this length before it penetrates the wall, it will cause an immediate rupture when it penetrates the wall, i.e., it will rupture catastrophically without warning. This is considered a worst-case situation. Using this length, we will then estimate the corresponding depth of the deepest crack that could just survive the hydrotest. Therefore the initial crack depth used in the service life assessment will correspond to the depth that will just be on the verge of failing at the hydrotest pressure, HTP. Our crack growth software will make these initial crack size estimates automatically. This approach will provide conservative life estimates for a pressurized cylinder because crack growth through the wall of the cylinder is faster than crack growth along the surface. In addition, the crack growth life should be conservative because our crack growth software currently includes the full bulging effect for infinitely long cylinders that results in greater local stresses and therefore faster crack growth.

Additional issues related to the failure pressure versus crack size curves include:

- ***Tank Material*** – The material used in the tank is similar to the line pipe steels Battelle deals with typically, therefore we can use relationships that involve Charpy fracture energy to assess the likelihood for fracture. A sensitivity study will be conducted to assess the impact of the yield strength of the tank material. The Charpy fracture energy of the tank material is not known. However, we will attempt to bound the effect of the lower and upper limits of the Charpy energy in relation to the crack size estimates. The goal is to conservatively estimate the service life, and not necessarily to be conservative on the estimate of the Charpy fracture energy, as the latter may be non-conservative relative to the life.

- ***Hydrotest and Service Temperatures*** – Charpy fracture energy can be highly temperature dependent in the range of temperatures encountered by the tanks. To ensure conservatism relative to the service life, it may be necessary to define the initial crack length and depth at the test temperature and to check for failure-at-MAWP at a lower temperature. If the difference between the test and service temperatures affects the service life estimates in a non-conservative manner, we will modify our analysis software to include the effects at both temperatures and thereby ensure conservative life estimates.

- ***Crack Growth Rate*** – For the most part, steels like those used in the tank have a fairly narrow range of crack growth rates when subjected to classical fatigue. We will use these “typical” (or “upper bound”) parameters, including the crack growth rate threshold, rather than generate new data for the tanks.

- ***Ductile Tearing*** – Materials commonly used in piping and pressure vessels generally exhibit some amount of ductile tearing before catastrophic failure. The result is that at the instant of failure the crack will be slightly larger in size than it was before the vessel was pressurized. This small amount of growth is included in the estimate of the initial crack size to ensure a conservative estimate of the service life. Figure 3 provides a modification to the approach used in Figure 2 to estimate the initial crack size. The modification is to ignore ductile tearing. As a result, the initial crack will be shorter and deeper than the crack based presented in Figure 2. The preferred approach is therefore to use the longer length from Figure 2 and the deeper depth from Figure 3, as this combination will give the shortest, most conservative estimate of the service life.

With regard to the final crack size in Equation 1, the failure pressure versus crack size data for part-through wall cracks, and for through wall cracks, are built into the analysis software. At each crack growth increment in the evaluation of Equation 1, the failure pressure versus crack size criteria are evaluated to determine if a part-through wall crack will breach the wall, and if it does whether it will leak or rupture. For through wall cracks an assessment is made to determine if a leaking crack will continue to leak or if it has grown long enough to cause a rupture. Typically the pressure used in the check for failure is the maximum value of the pressure cycle being applied at the time the failure check is made. For the tanks, a more conservative approach will be to assume that the tanks are expected to survive MAWP even if the maximum pressure being applied during a particular pressure cycle is less than MAWP.

Other issues related to the service life estimates include:

- ***Cyclic Pressure History*** – The nature of the pressure cycles that are applied to the tanks, and of the temperature extremes to which it will be exposed are yet to be defined. It is our intention that this important information and data will be compiled as part of an industry-wide survey being funded in parallel with this service life assessment. We will use this information to generate duty cycle scenarios so that we can better establish a fatigue life that is conservative.

- ***Crack Locations*** – An important issue with any crack growth analysis is where to put the cracks that might just survive the hydrotest. Currently we can analyze cracks oriented along the barrel of the tank (i.e., longitudinal cracks in a pipe). We have the potential to assess cracks in hemispherical heads and circumferential cracks; however some simplifying assumptions or supporting analyses will be required.

  Crack placement decisions will involve engineering judgment and will consider several criteria including: (1) high stress sites identified in an industry-supplied stress analysis report, (2) identification of previously observed cracks sites via the industry-wide survey mentioned above, and (3) survey of fabricators and/or of fabrication records or other documentation that identify the possible occurrence of systematic fabrication anomalies or the need for systematic repairs before the tanks entered into service. In addition, it will be beneficial to determine the likely cause(s) of cracks that have been detected, e.g., whether they resulted from fabrication issues, pressure cycling, vehicle induced cyclic loading, etc.

- ***Other Damage Mechanisms*** – Currently, our goal is to estimate the service life of the tank as it is affected by the pressure cycles due to filling and emptying the tank only. Over-the-road load cycles are scheduled for evaluation in a later phase of the program. Nevertheless, the approach for estimating the service life when the transport loads are included will be similar to the current approach.

Although corrosion is unlikely due to the low moisture content of the propane delivered in the tanks, it is possible to modify the fracture mechanics approach being used to estimate the impact of corrosion.

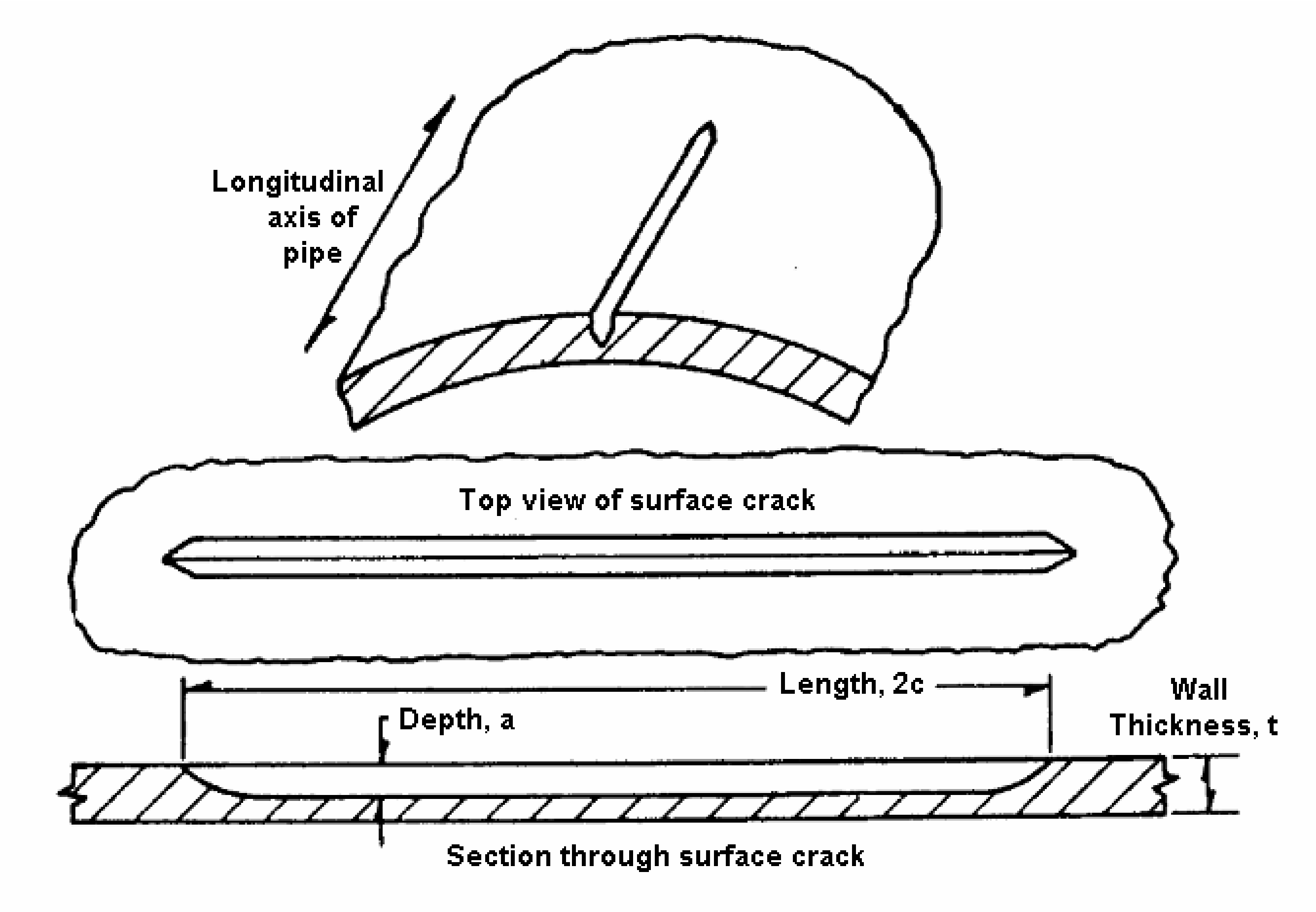
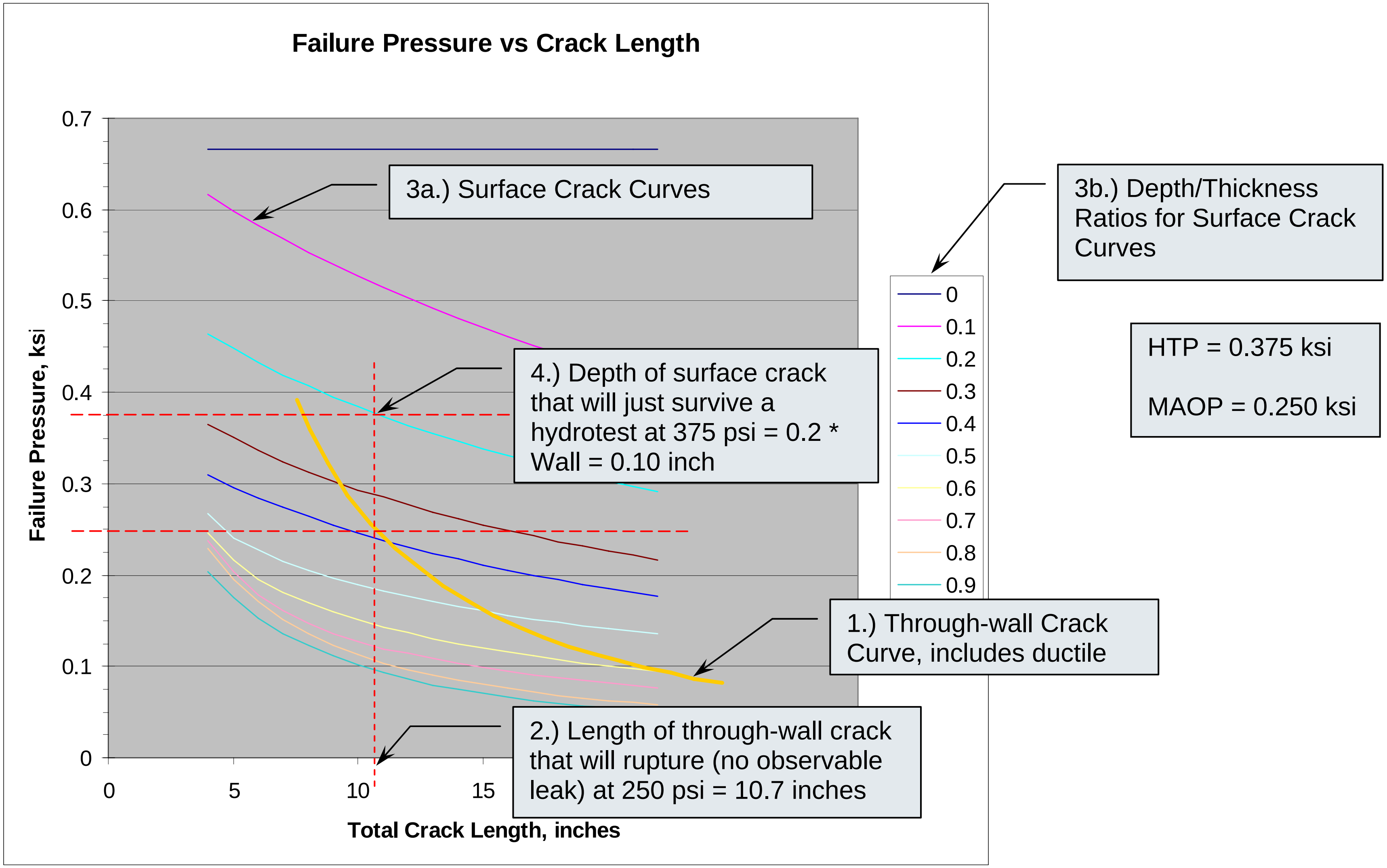


Figure 1. Schematic view of an exterior, part-through wall axial crack in a cylinder.



3a.) Surface Crack Curves

3b.) Depth/Thickness Ratios for Surface Crack Curves

HTP = 0.375 ksi

MAOP = 0.250 ksi

4.) Depth of surface crack that will just survive a hydrotest at 375 psi = 0.2 * Wall = 0.10 inch

1.) Through-wall Crack Curve, includes ductile

2.) Length of through-wall crack that will rupture (no observable leak) at 250 psi = 10.7 inches

Figure 2. Failure pressure curves for pressurized cylinder showing 4 steps used to estimate the initial crack size, with ductile tearing.

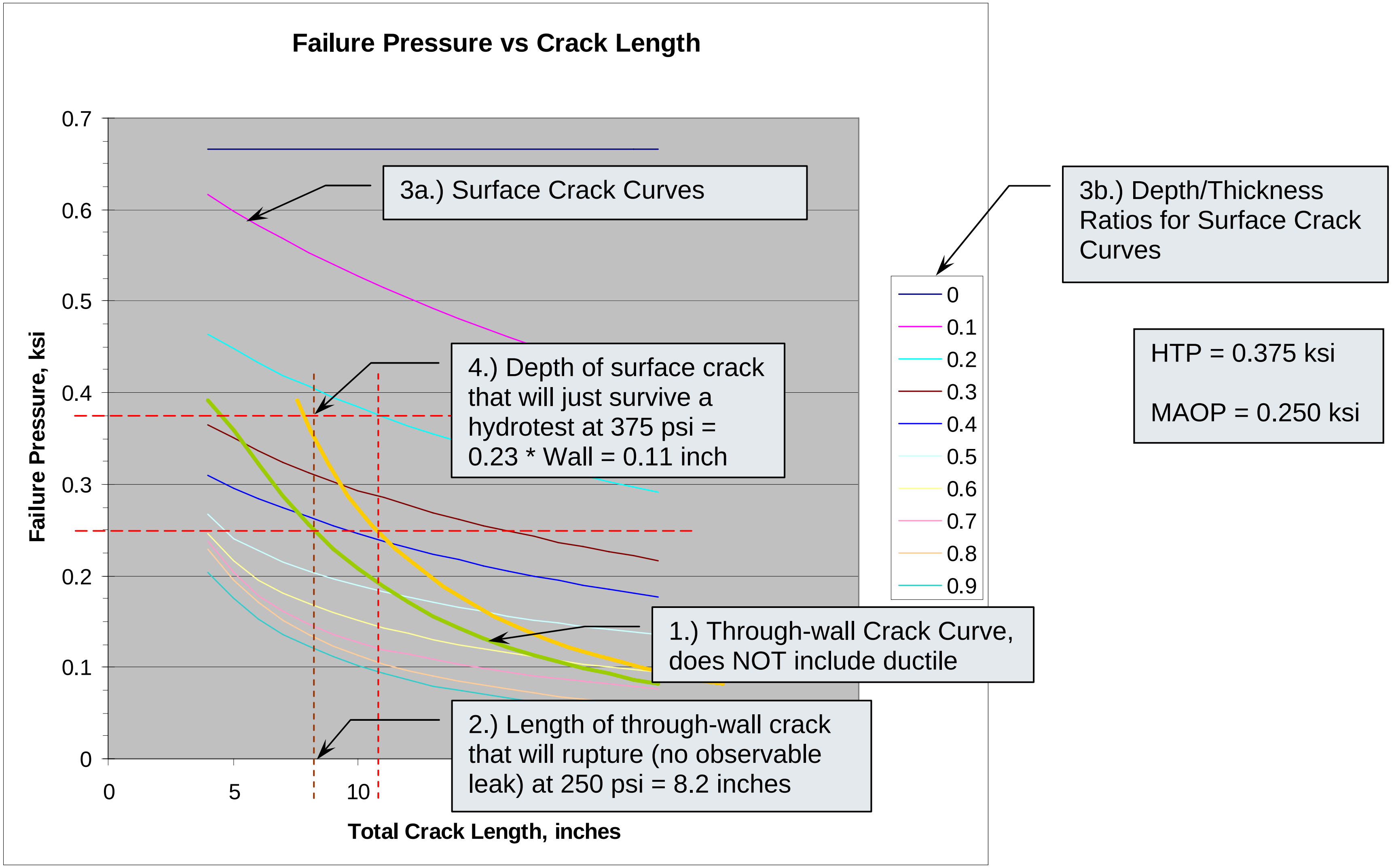
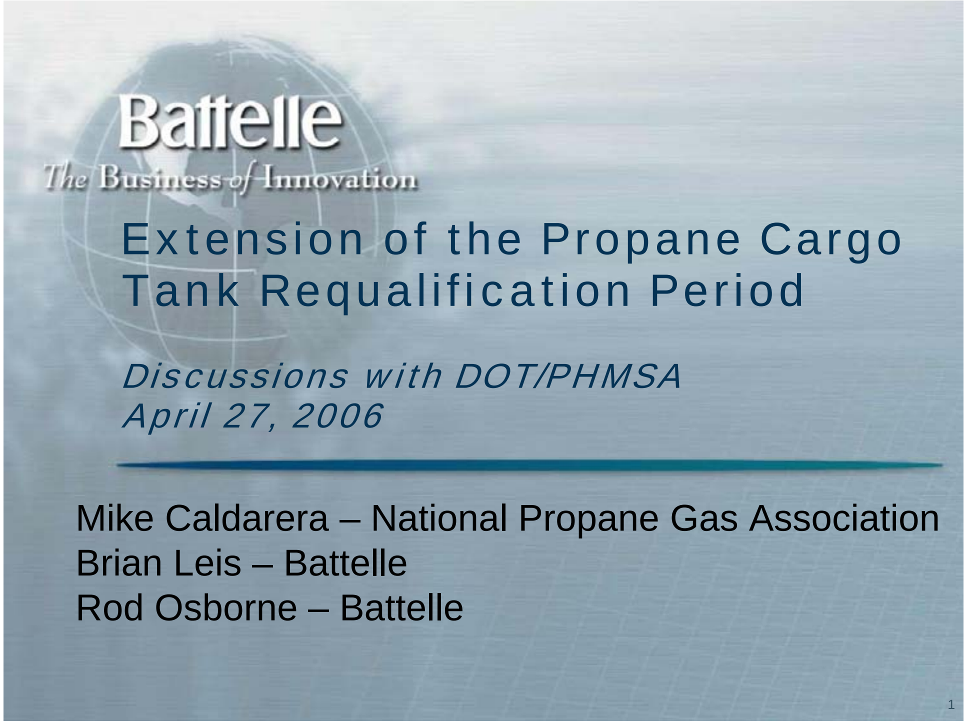


Figure 3. Failure pressure curves for pressurized cylinder showing 4 steps used to estimate the initial crack size, without ductile tearing.

Appendix C
Extension of the Propane Cargo Tank Requalification Period

Presentation
April 27, 2006



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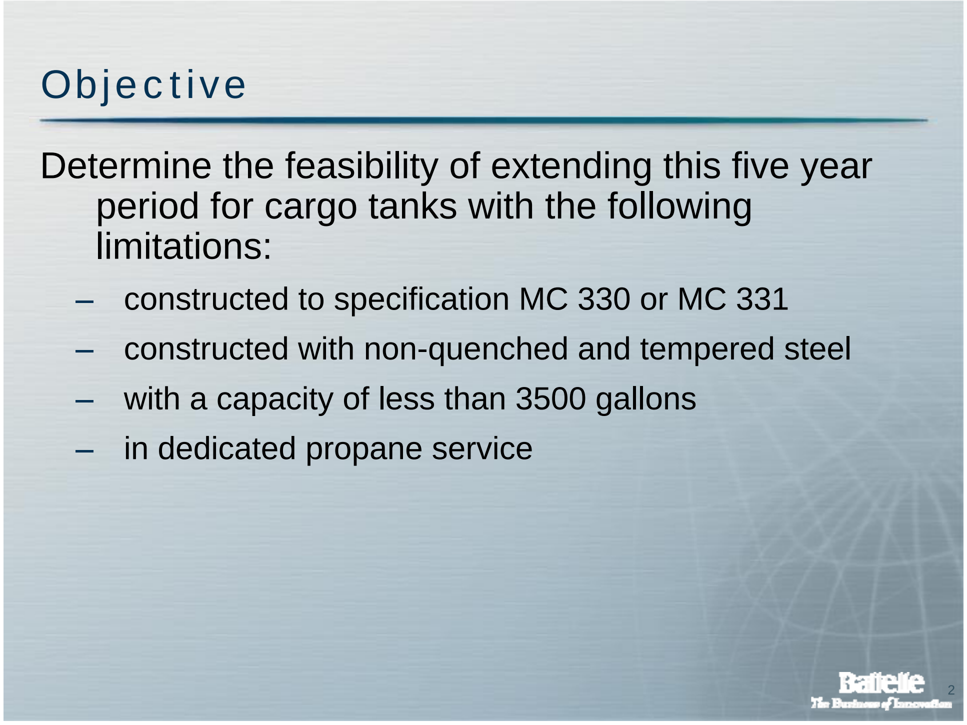
Extension of the Propane Cargo Tank Requalification Period

Discussions with DOT/PHMSA
April 27, 2006

Mike Caldarera – National Propane Gas Association
Brian Leis – Battelle
Rod Osborne – Battelle



Objective

Determine the feasibility of extending this five year period for cargo tanks with the following limitations:

- constructed to specification MC 330 or MC 331
- constructed with non-quenched and tempered steel
- with a capacity of less than 3500 gallons
- in dedicated propane service

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Analysis Approach

Conduct fatigue and fracture analyses to:

- Estimate the length and depth of a part through-wall crack that could be missed in a radiographic inspection
- Estimate the number of pressure cycles and over-the-road cycles required to grow the initial part through-wall crack to a size larger enough for failure at MAWP

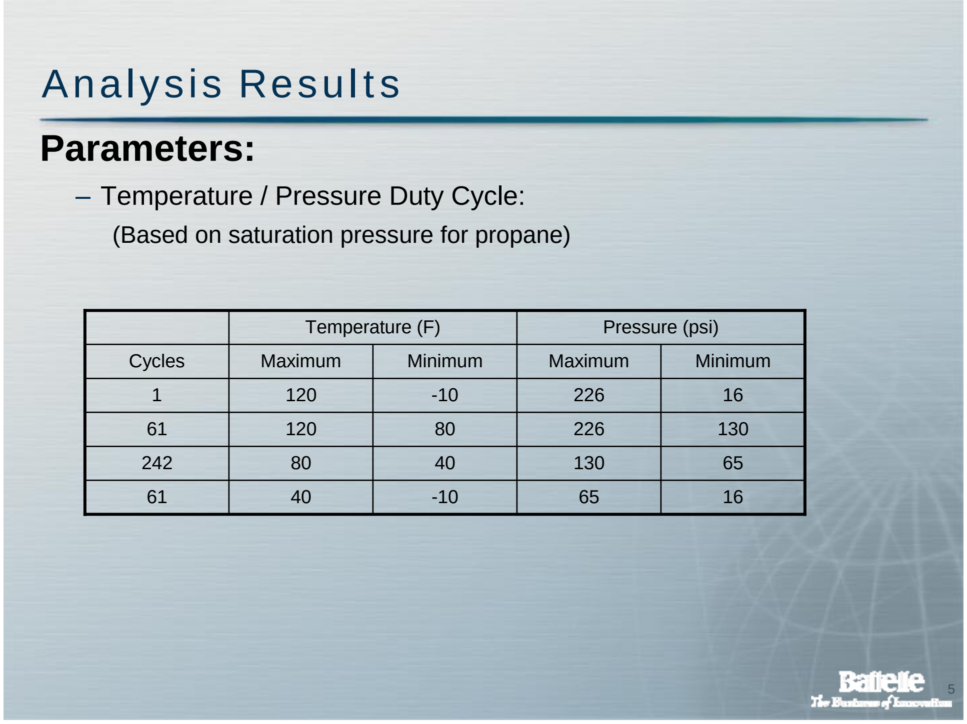
Conservatively estimate the fatigue life of a propane cargo tank:

- Phase 1: Consider only the pressure cycles due to ambient temperature changes (daily, monthly)
- Phase 2: Include the transport-induced load cycles due to the operation of the delivery truck

Analysis Results

Parameters:

- Material:
  - SA-612 Steel
  - Tests conducted on one sample
  - Tensile Strength = 85.1 ksi
  - Yield Strength = 57.4 ksi
  - Charpy Impact Fracture Toughness:
    - 47 ft-lb at -40°F
    - 141 ft-lb at +72°F
- Vessel (pipe) Size: 80-inch diameter x 0.481-inch wall
- Maximum Operating Pressure: 250 psi
- Hydrotest Pressure: 375 psi



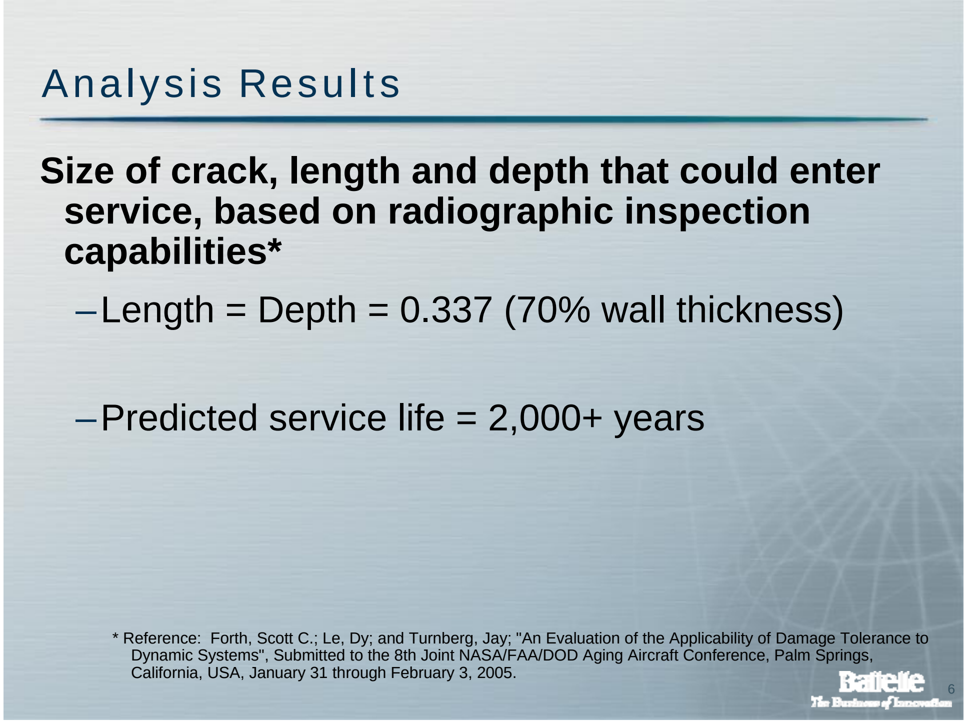
Analysis Results

Parameters:

- Temperature / Pressure Duty Cycle:

  (Based on saturation pressure for propane)

	Temperature (F)		Pressure (psi)	
Cycles	Maximum	Minimum	Maximum	Minimum
1	120	-10	226	16
61	120	80	226	130
242	80	40	130	65
61	40	-10	65	16



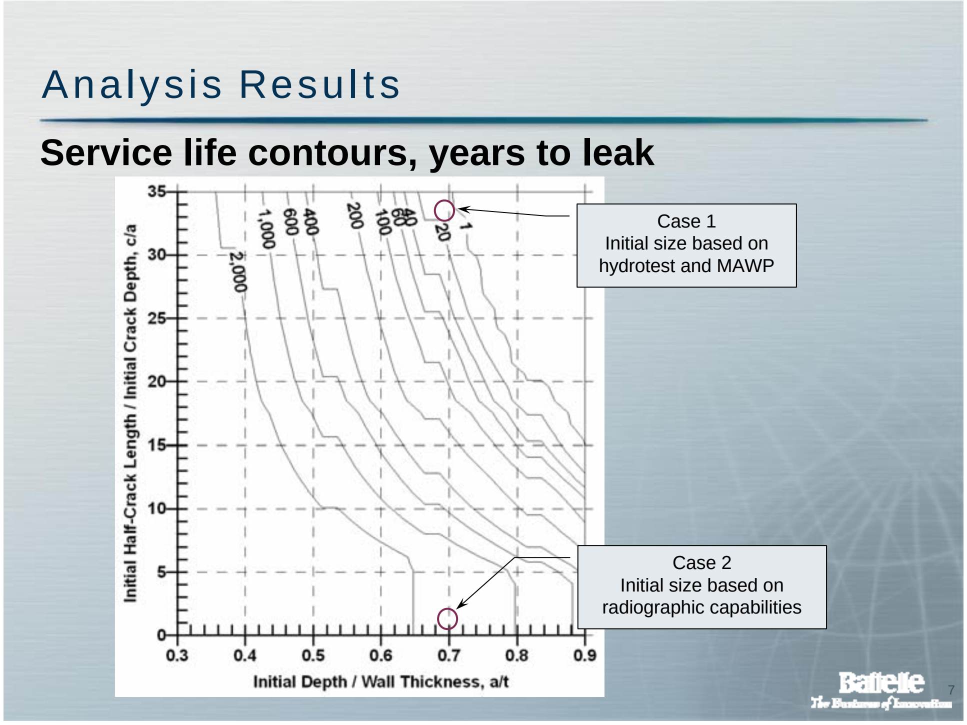
Analysis Results

Size of crack, length and depth that could enter service, based on radiographic inspection capabilities*

- Length = Depth = 0.337 (70% wall thickness)

- Predicted service life = 2,000+ years

* Reference: Forth, Scott C.; Le, Dy; and Turnberg, Jay; "An Evaluation of the Applicability of Damage Tolerance to Dynamic Systems", Submitted to the 8th Joint NASA/FAA/DOD Aging Aircraft Conference, Palm Springs, California, USA, January 31 through February 3, 2005.

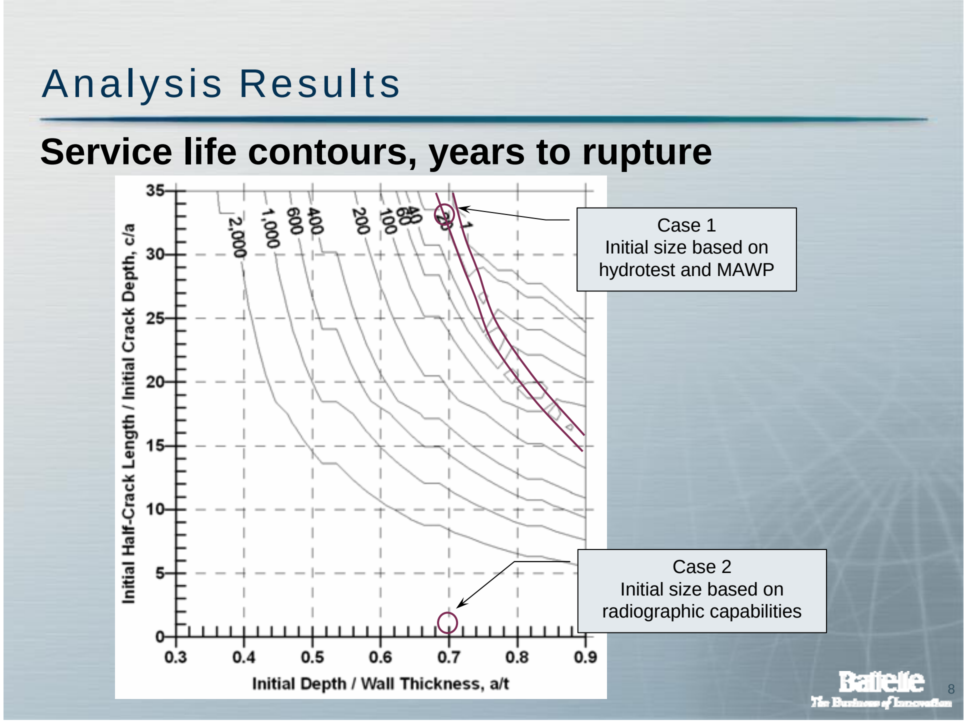


Analysis Results

Service life contours, years to leak

Case 1
Initial size based on
hydrotest and MAWP

Case 2
Initial size based on
radiographic capabilities

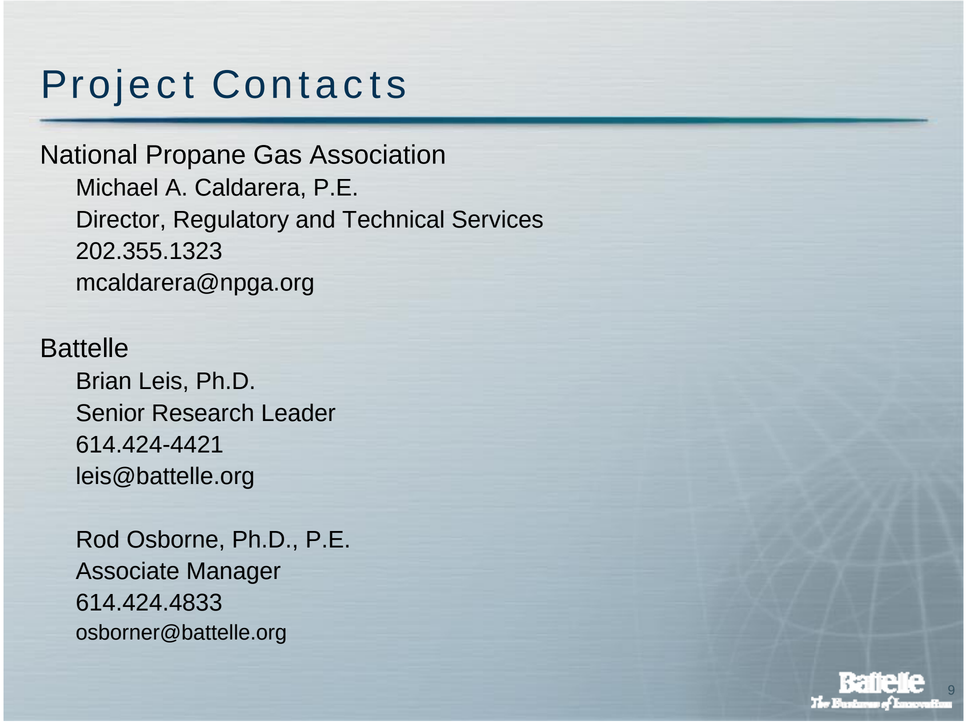


Analysis Results

Service life contours, years to rupture

Case 1
Initial size based on
hydrotest and MAWP

Case 2
Initial size based on
radiographic capabilities



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Appendix D
LP Gas Bobtail Survey

The ADEPT Group, Inc.

Services at the interface of energy, economics and environment

10866 Wilshire Blvd., Suite 350, Los Angeles, CA 90024-4350 USA
Telephone: (310) 441-4404 • Fax: (310) 441-3001

Submission Deadline:

LP GAS BOBTAIL SURVEY

GENERAL INFORMATION

Date completed: ____________________

Company name:	
Address :	
City:	State:
Zip Code:	
Phone number:	Fax number:
E-mail address:	

How many LP Gas bobtails does your company currently operate?

____

What is the average accumulated annual mileage per bobtail?

________miles/year

Is methanol commonly used in the LP Gas you deliver?

☐ Yes ☐ No ☐ Sometimes

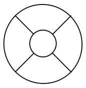
(Please continue on next page)

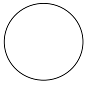
BOBTAIL TANK INFO

Please fill out the below information from the **nameplate** of **each bobtail tank**.
(This page can be copied for additional bobtails.)

1. Tank manufacturer:
2. Date of tank manufacture: / /
3. Water capacity (or diameter of tank):
4. Does the tank have a manway? ☐ Yes ☐ No
5. Head type: ☐ Welded ☐ One-piece stamped ☐ Don't know

   End View:





6. Date of last pressure test (5 yr "P"): / /
7. Shell steel grade (if available): ☐ SA202 ☐ SA612 ☐ SA 455
   ☐ SA 212 other _________
   [**Please note** – MC331 and NQT are tank specs, **not** steel grades]
8. Cap steel grade (if available): ☐ SA202 ☐ SA612 ☐ SA 455
   ☐ SA 212 other _________
   [Again, **please note** – MC331 and NQT are tank specs, **not** steel grades]
9. Shell thickness:
10. Cap (Head) thickness:

Please provide a brief description of any past repairs to the tank, if any:

Please note any current damage to the tank (dents, gouges, if any):

When completed, please fax this form to: (310) 441-3001. Thank you.