Analysis of a Propane Tank Truck Impacting a Concrete Column Using LS-DYNA

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ABSTRACT

Pressure Sciences Inc. used LS-DYNA to model a propane tank truck colliding with a concrete column. The analysis simulates an accident that occurred in 1994 in White Plains, New York. Correlation between the accident and an LS-DYNA analysis of that crash is described. The ultimate purpose of the analyses is to improve the crashworthiness of propane semi-trailers.

To address the stiffening effect of the propane fluid, we correlated several models with drop tests that had been performed on 1/12 scale railroad tank car heads. The heads included unpressurized heads, fluid pressurized heads, and fluid pressurized heads with an air cushion.

In order to model the liquid propane, explicit solid elements were used. The material model used for the propane was the elastic material model with the fluid option. The paper describes the procedure used to incorporate the elastic material model with the fluid option. The propane vapor was modeled using explicit solid elements and the null material model with a linear polynomial equation of state. The paper gives the derivation of a simplified version of the linear polynomial equation of state to simulate Boyle's law.

We were able to use LS-DYNA to obtain good correlations with drop tests when we modeled the liquid using the elastic material model with the fluid option and the vapor with a null material with the linear polynomial equation of state. We also obtained reasonable correlations between our LS-DYNA model and the White Plains, NY accident involving a propane tank truck and a concrete column.

INTRODUCTION

Pressure Sciences Inc. used LS-DYNA to model a propane tank truck colliding with a concrete column. The analysis simulates an accident that occurred in 1994 in White Plains, New York and was documented by the National Transportation Safety Board (NTSB, 1995). This paper presents some of the details of that analysis including how to simulate Boyle's law using a simplified version of the equation of state model.

Pressure Sciences Inc. was funded by the U.S. DOT Research and Special Projects Administration to model a series of accidents involving propane tank trucks. The purpose of this specific task was to correlate LS-DYNA analyses of crashes of propane tank trucks with real world data. The ultimate purpose of the program is to improve the crashworthiness of propane semi-trailers.

Previous work (Selz, 1997) had compared the behavior of several head types (hemispherical, semi-elliptical, and torispherical) of various thicknesses during impact with rigid walls. Direct frontal impact and 45 degree frontal impact at speeds from 5 to 65 miles per hour (MPH) had been studied. That work identified several issues that still needed to be addressed. The most significant issues were the stiffening effect of the propane fluid, the mass of the propane inside the tank, and the pressure of the propane. An additional issue for this specific correlation study was the modeling of a concrete column with finite shear strength.

DROP TEST CORRELATIONS

To address the stiffening effect of the fluid, we correlated several models with drop tests that had been performed on 1/12 scale railroad tank car heads (Phillips, 1972). The heads included unpressurized heads, fluid pressurized heads, and fluid pressurized heads with an air cushion. The actual tests varied the weight and height of an impacting coupler. The drop test correlation model used the Belytschko-Wong-Chiang formulation of the shell element so that warpage was considered. The impacting coupler was modeled using solid elements and mass elements. A bilinear isotropic hardening plasticity material model was used. In later work, this was changed to a kinematic hardening model. The change to kinematic hardening was made because kinematic hardening predicts a Bauschinger effect (i.e., the range of elastic stress remains approximately twice the yield stress under cyclic loading) as observed in real materials, while isotropic hardening does not include the Bauschinger effect.

Because of uncertainties in the material properties of the heads used for the drop tests, the tangent modulus and yield strength were varied in the drop test analyses. The best correlation for the unpressurized heads, as shown in Figure 1, occurred with a realistic tangent modulus of 1,050,000 psi and yield strength of 45,500 psi.

The modeling of the pressure, without consideration of the stiffening effects of the water, was the next step. We modeled the pressure load using the dynamic relaxation technique. In the dynamic relaxation technique, the pressure is applied to the explicit elements and LS-DYNA increases the damping until the kinetic energy is approximately zero. As seen in Figure 2, the modeling of the pressure load, without modeling the water, did not provide a sufficiently accurate correlation to the drop tests performed with the pressurized heads. In order to improve the correlations with the pressurized head tests, the water and air needed to be accounted for.

Modeling of Fluids

This portion of this paper describes in some detail the manner in which we modeled the water and air.

In order to model the water, explicit solid elements were used. The material model used for the water was the elastic material model with the fluid option. It was also decided to model the air, since the air has a cushioning effect. The air was modeled using explicit solid elements and the null material model with a linear polynomial equation of state.

The polynomial equation of state is linear in terms of internal energy and the pressure is given as:

$$P=C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \tag{1}$$

where:

$$\mu=(\rho/\rho_0)-1 \tag{2}$$

ρ/ρ_o is the ratio of current density to initial density,

$$\mu=(1/V)-1 \tag{3}$$

V is the relative volume, and

E=Energy/initial volume, pressure units.

For the Gamma law equation of state, Section 27.2 of the LS-DYNA Theoretical Manual (Hallquist, 1998) explains that the derivation is obtained from adiabatic expansion of an ideal gas.

$$p=(k-1)\rho e \quad (4)$$

where:
p = pressure
k = specific heat ratio ~ 1.4 for an ideal gas
e = specific internal energy
For the Gamma law equation of state:
$C_0=C_1=C_2=C_3=C_6=0$,
$C_4=C_5=(k-1)\sim0.4$ for an ideal gas

Then the pressure is given by

$$P=(k-1)(\rho/\rho_o)E=(k-1)(1/V)E \quad (5)$$

We initially used the gamma law equation of state, but were not satisfied with the pressures produced. (It was later determined that an error exists in the LS-DYNA solver (version 940.2) when 8-point integration null elements are used). Therefore, we subsequently used a simplified version of the linear polynomial equation of state to simulate Boyle's Law ($P_1V_1 = P_2V_2$), which requires that the system be isothermal. For the short duration of the impact event, there is no practical difference between the isothermal assumption and the adiabatic assumption.

Let $C_2=C_3=C_4=C_5=C_6=0$, then

$$P=C_0+C_1\mu+C_2\mu^2+C_3\mu^3+(C_4+C_5\mu+C_6\mu^2)E \quad (6)$$

becomes

$$P=C_0+C_1\mu \quad (7)$$

$$P=C_0+C_1((1/V)-1)=C_1/V+(C_0-C_1) \quad (8)$$

Let $(C_0-C_1)=-14.7$, correction from absolute pressure to gage pressure.

$P=C_1/V$ is Boyle's law.

The test model shown in Figure 3 was used to validate the simplified equation of state developed above. The model consists of fluid elements surrounded by shell elements with the first row of fluid elements replaced with the simplified equation of state elements. C_0 was set to 100 psig and C_1 was set to 114.7 psia. The resulting stresses in the shell elements confirmed that an initial internal pressure of 100 psig was developed.

A second test model using two arbitrary zones of pressure was used to further validate the simplified equation of state model. The first zone was at 85.3 psig (100 psia) and the second zone was at 35.3 psig (50 psia). The combined pressure expected was 60.3 psig and the stress results from the analytical model indicated 60.0 psig indicating the validity of the simplified equations developed.

This simplified equation of state was then used to model a 10% air cushion into the drop test model and the correlation with the actual drop tests is shown in Figure 4.

Because of their low density, the elements used to model the air cushion were extremely prone to hourglassing. Hourglassing modes are the zero energy modes, which arise when using one-point integration. Full integration elements were therefore used for the air cushion to eliminate the hourglassing effects, with substantially longer run times. Alternatively, the one-point integration elements could have been used with an exact integration B matrix.

Closed form expressions for the terms in the B matrix are given by Belytschko, et al. (1984). The exact integration B matrix is achieved in LS-DYNA by using type 3 hourglass control and setting the hourglass parameter to a small number (10^{-6}).

CORRELATIONS WITH WHITE PLAINS, NY ACCIDENT

Having obtained reasonable correlation with the drop tests, we now began the task of correlating the impact of the propane tanker truck with the NTSB report. At impact the NTSB report indicated that the propane trailer was travelling at 37 MPH and impacted a circular concrete column with a static shear capacity of 210,000 pounds. The combined weight of the vehicle and cargo was 80,160 pounds. The front head of the tank buckled and fractured, releasing the propane, which vaporized into gas. The resulting vapor cloud expanded until it found a source of ignition and ignited, propelling the tank some 300 feet.

Figure 5 shows the LS-DYNA model that includes the propane tank, the propane liquid and the propane gas. The trailer and tractor were modeled as lumped masses attached to the bottom of the propane tank. The concrete column was initially modeled as a rigid body, with a breakaway force of 210,000 pounds represented by a spot weld acting as a fuse. The column was modeled as a rigid body with constraints except in the direction of impact. Since a spot weld cannot be directly connected to a rigid body, fictitious stiff beam elements with low density were attached to the column and a spot weld with the break away shear force was added between the beam elements.

The initial evaluations produced buckling of the front head that was remarkably similar to the buckling that actually occurred. However, the amount of hourglassing energy associated with the liquid propane elements was greater than 10 percent of the internal energy. Hourglass control type 5, Flanagan-Belytschko stiffness form with exact volume integration for solid elements, was used to reduce the hourglassing energy of the liquid propane elements. This type of hourglass control, however, had the adverse effect of eliminating the buckling of the front head. In order to eliminate the hourglassing energy and still obtain good correlations with the observed behavior, full integration elements were used for the liquid propane. It was subsequently determined that one-point integration elements with an exact integration B-matrix, as described above, gave similar results to the full integration elements with substantially reduced run times.

When the breakaway force of the concrete column was set to 210,000 pounds the amount of permanent deformation of the tanker was 6.5 inches, which was smaller than the observed deformation of 21 inches. If the concrete column was modeled with an infinite breakaway force, the amount of permanent deformation of the tank head was 38 inches. However, it was observed that the maximum force generated at the spot weld for this case was slightly greater than 3,000,000 pounds. When a breakaway force of 3,000,000 pounds was used the amount of permanent deformation was 19.5 inches.

Note that it is not uncommon for a stationary object such as the concrete column to seem much stronger under dynamic loading than it does under static loading. Impact energy is transmitted in all directions at the speed of sound. The larger the object struck, the more time it takes to reach distant locations, the more diffuse the energy is, and the more excess energy that is required to produce failure. It is not surprising that the concrete column exhibits a high ratio of dynamic to static failure load.

We wanted to run several models with various head types and various thicknesses to determine if the crashworthiness of the propane tank head could be improved. In order to reduce the longer runtimes associated with the full integration elements and the finer mesh size required to calculate accurate strains, a reduced model of the front head was developed that incorporated ¼ symmetry. Since a cylindrical steel vessel of length greater than 4.9 $(r/t)^{0.5}$ acts as if it were infinitely long, the shell length included was greatly reduced. The mass of the remainder of the vessel and propane was modeled by increasing the density of the last row of elements. Furthermore, in the reduced model the elements used to model the propane vapor were replaced with a surface pressure loading and balancing nodal forces at the last row of elements.

Figure 6 shows the reduced model of the head that buckled and produced a permanent deformation in the head of 19.5 inches. The 23% maximum strain observed in this analysis, when compared to the specified 16% minimum elongation for the head material, is indicative of likely failure. This model indicates good correlation with the actual permanent deformation of 21 inches of the buckled head and has strain values that are consistent with the failure observed.

SUMMARY

We were able to use LS-DYNA to obtain good correlations with drop tests when we modeled the water using the elastic material model with the fluid option and the air with a null material with the linear polynomial equation of state. We also obtained reasonable correlations with the White Plains, NY accident involving a propane tank truck when we accounted for the liquid propane as described above and modeled the concrete column using rigid elements with a finite breakaway force.

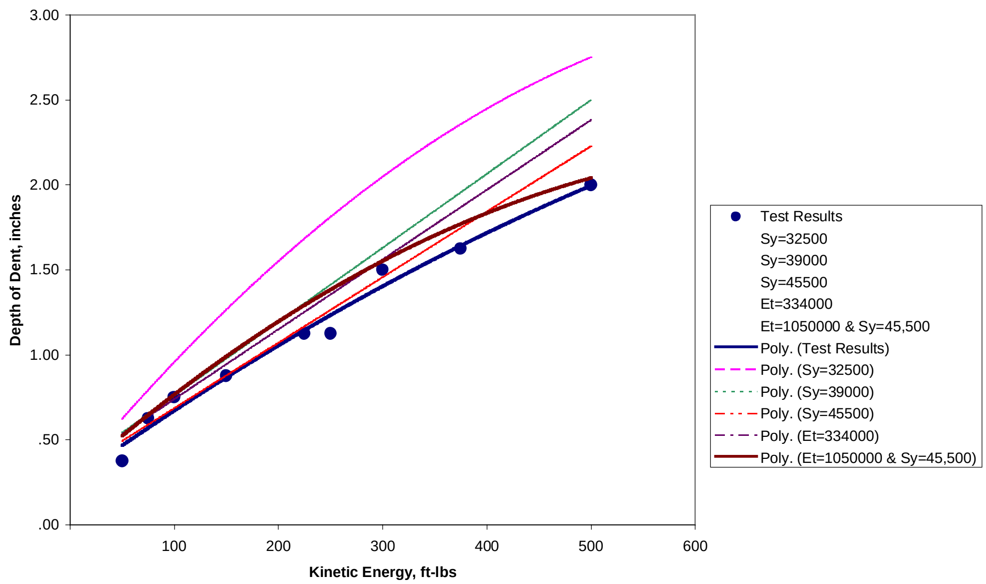

Figure 1. Correlation with Drop Tests using Unpressurized Heads

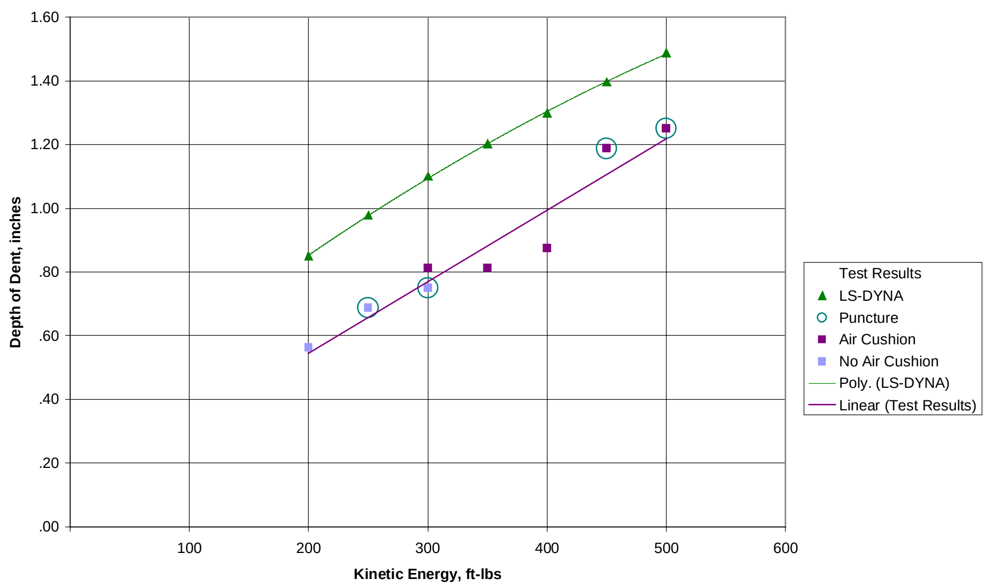

Figure 2. Correlation without Fluid Elements with Drop Tests using Pressurized Heads

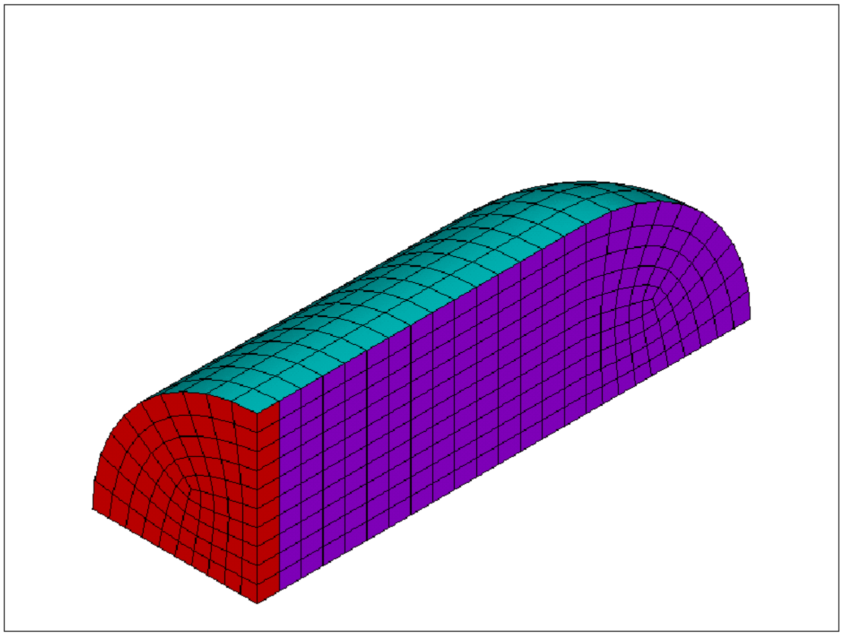

Figure 3. Model Used to Validate Simplified Equation of State

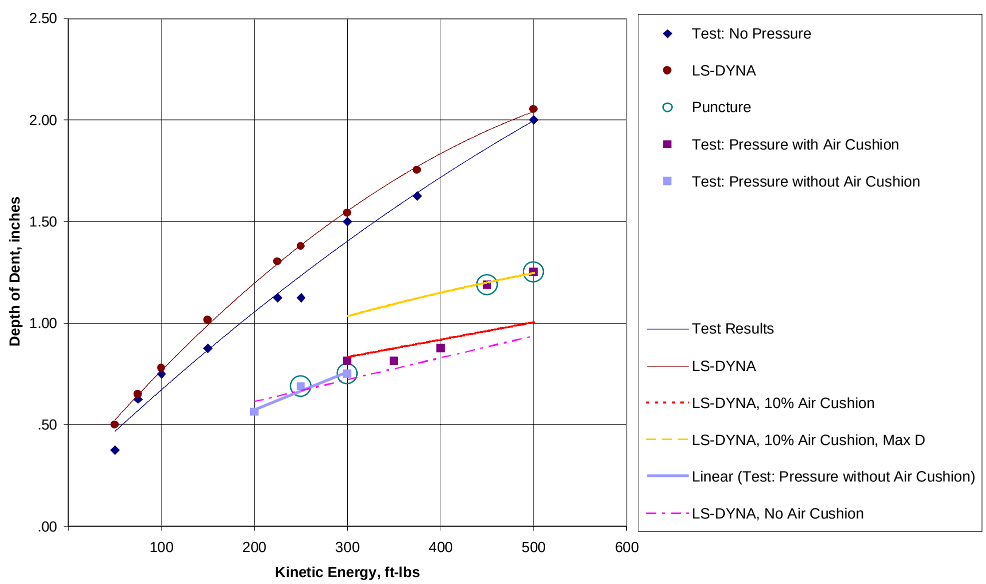

Figure 4. Correlation with Fluid Elements with Drop Tests using Pressurized Heads

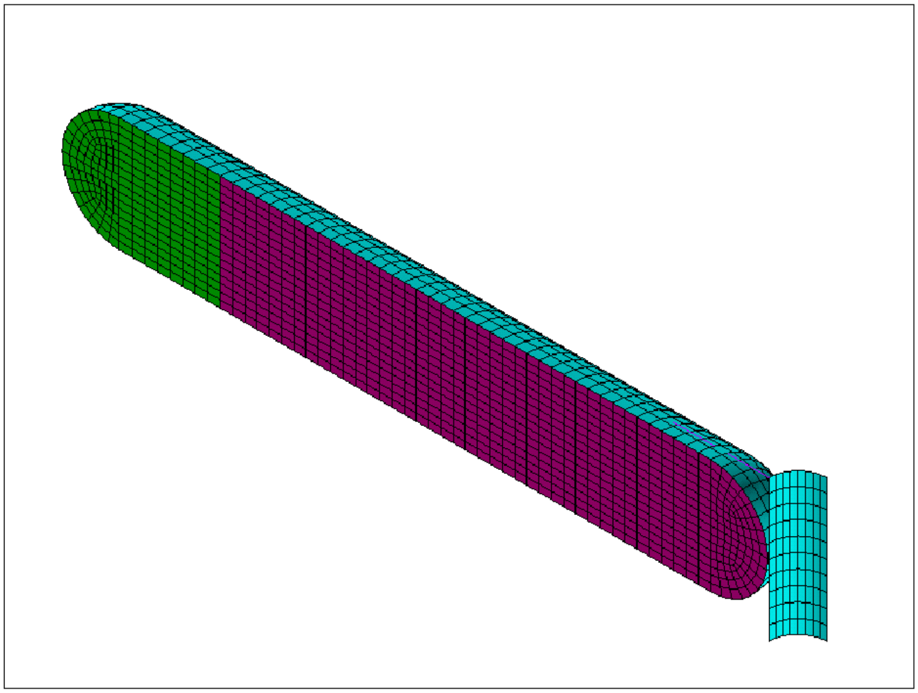

Figure 5. LS-DYNA Model of Propane Tank

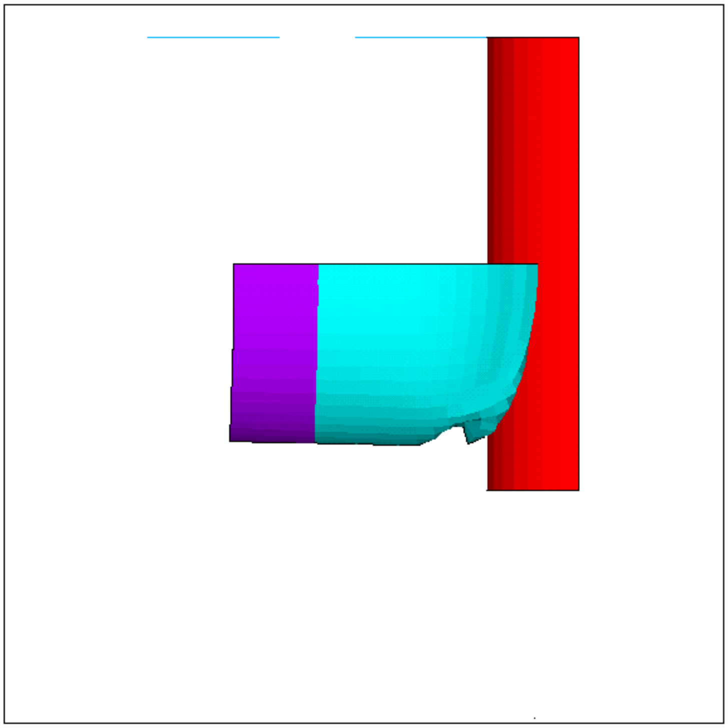

Figure 6. Buckling in Model of Propane Tank Head

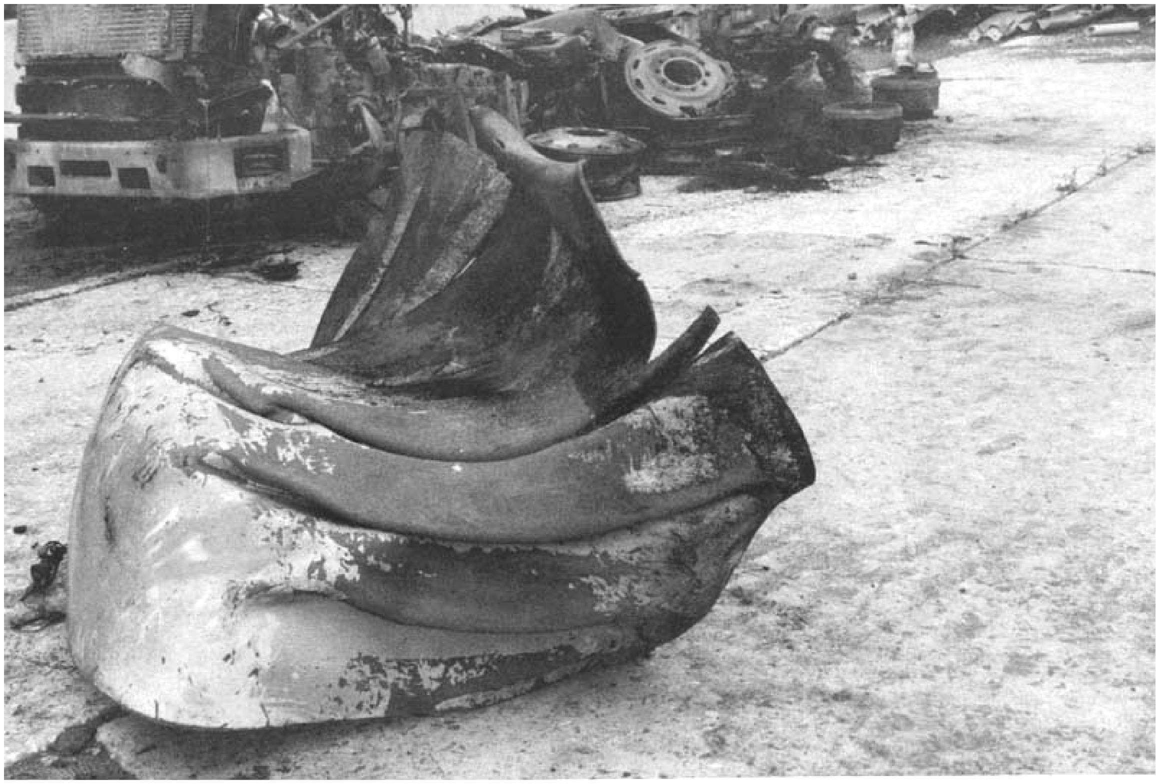

Figure 7. Actual Propane Tank Head

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