**MVFRI RESEARCH SUMMARY**
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# Fire Exposure, Impact Tests, and Finite Element Modeling of Plastic Fuel Tanks

Based on contracts with:
Southwest Research Institute
Dr. Nabih Bedewi

The purpose of this program was to conduct comparison evaluations of existing plastic fuel tanks to performance standards applied in Europe and also to standards applied to tanks for trucks in the US [Machado 2003; Griffith 2005]. The tests also examined degradation in service. Two ages of tanks were tested; 1) "conditioned" tanks, not older than four years, and 2) "new" tanks, from original equipment manufacturers (OEMs). The conditioned tanks were from vehicles that have been operated in a warm climate in the vicinity of San Antonio, Texas. The new tanks were purchased from the OEM supply and not from an after market supplier. The project evaluated three different tank design shapes.

The three tank design shapes are as follows: 1) a "pancake" tank typical of tanks in front wheel drive cars with a thin shape mounted to an underbody near the rear seat area and in front of the rear axle; 2) a "long" tank with a narrow shape mounted inside the frame rail and in front of the rear axle; and 3) a "square" tank mounted behind the rear axle. The three types of tanks are shown in Figures 1-3.

Three types of tests were conducted for new and conditioned tanks for each of the three tank shapes. The tests were: fire resistance, concentrated energy cold impact, and high energy impact.

The fire resistance tests were conducted in accordance with the European Standard for plastic fuel tanks, ECE R 34, Annex 5, Fire Resistance Section. This standard requires the plastic tank to withstand a pool fire for two minutes without leaking. In this test, the tank is mounted on the actual vehicle and filled with gasoline to 50% of capacity. For one minute, the vehicle and tank were subjected to the full intensity of a fuel-fed pool fire positioned directly beneath the tank. For the second minute, the intensity of the fire was mitigated by covering the fire pan with a screen. If the tank survives for two minutes it is said to "pass."

In the research testing conducted under this project, a third condition was imposed. In this third condition, the screen was removed and the high intensity fire was continued until tank leakage occurred. Once leakage was observed, the fire was extinguished quickly by fire suppressants. The results reported in Table 1 shows the number of seconds after removal of the screen at 2 minutes until the tank leakage occurred. Pictures of the tanks after the test are shown in Figures 4 through 6.

In these fire tests, all of the conditioned tanks were the original tanks installed on the 1998 model year vehicles that were subjected to the burn tests. These conditioned tanks were tested before the "new" tanks were installed on the same vehicle. In all cases, the fire exposure caused some loss of body material from the vehicle. Consequently, added area for ventilation might exist in the second test. To reduce the effects of differences in ventilation, the vehicle with the "pancake" tank was rebuilt for the second test. The other vehicles suffered less degradation and were not rebuilt. The second test of the "square" tank resulted in tank leakage at 101 seconds – 19 seconds short of the requirement. This difference could be explained by the increased ventilation permitted by the test buck.

**Table 1. Number of seconds after removal of fire screen until tank leakage occurred**

| Tank Type | New | Conditioned |
|---|---|---|
| Pancake | 90 | 90 |
| Long | 38 | 21 |
| Square | -19 | 10 |

**Figure 1. “Pancake” shaped tank pre-test.**

**Figure 2. “Long” shaped tank pre-test.**

**Figure 3. “Square” shaped tank pre-test.**

**Figure 4. “Pancake” shaped tank post-test.**

**Figure 5. “Long” shaped tank post-test.**

**Figure 6. “Square” shaped tank post-test.**

Other observations made from the tests included the location and size of the initial leak that occurred before the fire was extinguished. The two pancake tanks leaked at the same place – the bottom left rear corner. In both cases, the leaks were very small. The two square tanks both leaked in locations that were associated with loading by the mounting strap. Both tanks also leaked or were severely weakened at the front right top corner due to sagging of the tank. The rate of leakage from the square tank was greater than for the pancake tank. The two long tanks both leaked due to sagging of the front part of the tank that overhung the mounting straps. The leakage occurred at the front of the tank or at the straps. The rate of leakage was greater than the square tank. The post test deformation of the "pancake" tank, the "long" tank, and the "square" tank are shown in Figures 4 through 6.

Impact resistance was conducted on three new and three seasoned tanks. The impact tests were of two types. First tests were conducted in accordance with the European Standard for plastic fuel tanks, ECE R 34, Annex 5, Section 1 "Impact Resistance". Second, tests were conducted in accordance with 49 CFR 393.67, "Liquid Fuel Tanks".

For the ECE R 34 impact resistance test, the tanks are filled to rated capacity and chilled to -40 degrees C. At this temperature, they are impacted by a pyramid shaped 15 kg mass at an energy level of 30.1 Nm. In the research tests, tanks were impacted at the right front corner at energy levels ranging from 30.1 Nm to 43.6 Nm. No leakage occurred in any of the tests.

Federal Motor Carrier Safety Regulation CFR 393.67 "Liquid Fuel Tanks" requires an impact test condition that has not been applied to passenger vehicles. Section (e) (1) of the standard applies to side-mounted tanks and requires a drop test of the tank. In this test, the tank is filled with water to a weight equal to the rated weight of fuel and dropped on its corner from a height of 30 ft. onto an unyielding surface. The standard limits the allowable leakage after the test to 1 oz per minute.

**Table 2. Leakage rate in oz. per minute for three types of tanks after 30 ft drop test per CFR 393.67 (e) (1)**

| Tank Type | New | Conditioned |
|---|---|---|
| **Pancake** | <1 | <1 |
| **Long** | <1 | 150 |
| **Square** | <1 | 900 |

The results of the 30 ft drop tests are shown in Table 2. All of the new tanks and the seasoned pancake tank passed the test. However, both the long and the square seasoned tanks ruptured at the joining seam or "pinch-off". A typical breach of the tank is shown in Figure 7.

**Figure 7. Seasoned "long" tank post drop test**

This limited research indicates that the tested tanks performed in a repeatable manner when subjected to ECE R 34, Annex 5, “Fire Resistance” Section. However, considerable difference in the margin for passing the test was present for the three tank types. In addition, the amount of leakage that occurred once the leak was initiated was vastly different. The behind the axle location of the “square” tank permitted the greatest amount of ventilation, and consequently may have been the most severe environment. The overhang of the long tank beyond the supporting straps appeared to be the most vulnerable feature of that tank shape. There was no identifiable difference between the performance of new and seasoned tanks in these fire resistance tests.

All three tanks performed satisfactorily when subjected to the ECE R 34 Impact Resistance test, even when subjected to an impact with approximately 50% more energy than required by the test. No degradation was noted in the seasoned tanks.

All three new tanks performed satisfactorily when subjected to the Federal Motor Carrier Safety Regulation CFR 393.67 (e)(1) 30 ft. drop test. However, the seasoned “long” and “square” tanks leaked excessively after the drop. In all cases the tank breach occurred at the joining seam or “pinch-off”, as shown in Figure 7. This result suggests some degradation of the seam to resist severe impact with aging.

To further examine the tensile strength of the tank seam, SwRI conducted tensile tests of coupons cut from new and conditioned fuel tanks. The general layout of the coupons is shown in Figure 8. Tensile tests were conducted in accordance with ASTM D 638-00, “ Standard Test Methods for Tensile Properties of Plastics”. Twelve specimens were tested . Three specimens each from new and conditioned long and square tanks. In each test the specimen failure was within the parent material, not the pinch-off.

**Figure 8 – Material coupons extracted for the tensile testing**

A follow-on investigation of the failure at the pinch-off was undertaken for MVFRI by Dr. Nabih Bedewi [Bedewi 2004, 2007]. The objective of the research was to utilize advanced nonlinear finite element modeling (FEM) for simulating the tests performed by SwRI to understand the complex loading behavior and to analyze the parameters that influence the failure of the tanks.

The research project developed FEM models of the square and rectangular tank and subjected the models to loading that duplicated the drop tests conducted by SwRI. The models predicted that the highest stress were located in the tank region where the failures occurred in the drop tests. FEM models of various coupon tests were then developed and exercised. The results were as follows:

1. A simple tensile test such as the one performed by SwRI is not representative because in the drop test the pinch-off joint is subjected to a bidirectional force along, and perpendicular to, the joint.
2. Applying a hydrostatic force on a curved specimen is more representative of the drop test scenario because the primary loads are generated by the water pressure.

3. This is not a simple test to perform and therefore an alternative is to place the specimen on a curved low friction device (cylinder or pipe) and then apply a tensile force at the ends.
4. The results of the simulations clearly show that the latter provides the same type of load distribution as the hydrostatic case and the stress builds up more at the joint.
5. However, all three cases were not able to generate a higher stress at the joint than the parent material.
6. It is not clear at this point that there exists a simple coupon test that can generate the load conditions to fail the pinch-off joints.
7. The models have a limitation in that they do not represent any micro-cracks in the joint which would initiate an early failure when tested.

Analysis of the pinch-off seams of the two tanks showed a considerable difference in the area of the contact patch, as shown in Figure 9.

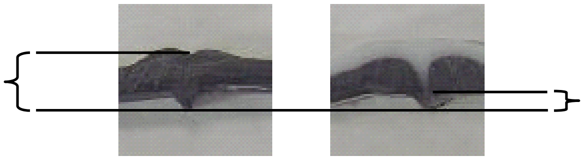

**Figure 9 - Estimated pinch-off region patch for the long and square tanks**

Figure 10 is a the FEM representation of the rectangular tank shown in Figure 8. It may be noted that the tank cross-section is not a pure rectangle, but contains a neck. The presence of the neck influences the stress on the pinch-off.

**Figure 10 – FEM model of the rectangular tank**

The following conclusions were derived from the FEM modeling of the two tanks:

1. The FE analysis predicted the maximum loads near the same location where the pinch-off region ruptured in both the rectangular tank and square tank tests.
2. The presence of a neck section in a rectangular tank, keeping everything else similar, increases the forces in the pinch-off region by 50%.
3. Based on the estimates in Figure 9, the square tank pinch-off contact area is 30% of the rectangular tank pinch-off contact area. Therefore, for the same amount of force, the strength of the joint would be a third of the strength of the rectangular tank. Differences in the pinch-off joint can have a large influence on the burst strength of the tank.

## REFERENCES

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