Data Summary of the National Fire Protection Association's BLEVE Tests

G. A. Melhem and P. A. Croce
Arthur D. Little Inc., Cambridge, MA 02140

and

H. Abraham
National Fire Protection Association, Quincy, MA

In conjunction with the production of a new film entitled BLEVE Update®[2], the National Fire Protection Association (NFPA) sponsored a series of six Boiling Liquid Expanding Vapor Explosion (BLEVE) tests using 1.893 m^3 propane tanks. The purpose of the experiments was to obtain film footage of BLEVEs and to compile test data and documentation that might help to better define failure mechanisms and other important physical processes involved. The experiments included tests with simulated pool fires and tests with liquid and gaseous flame jets. The fill level of each tank was varied for the six experiments. The tanks were instrumented with thermocouples and pressure transducers in both the liquid and vapor space. This paper describes the test setup and summarizes the data measurements obtained.

Previous Experiments

Historically, the majority of accidents where BLEVEs occurred involved flammable liquids such as propane and butane, and ignition resulting in a fireball was caused by surrounding fire. During the last two decades, experimental research efforts have been focused on providing a better understanding of BLEVEs under external fire impingement conditions. BLEVE hazards caused by thermal ruptures (fire exposure) tend to be more severe than those caused by other means such as mechanical damage or overfilling.

A comprehensive summary of experimental work pertaining to BLEVEs under fire impingement is given by Leslie and Birk [*2*]. Their summary covers experimental work as well as computer models, BLEVE theories, projectile modeling, blast and missile effects, and case studies, and includes work done by Roberts et al. [*4*], Moodie et al. [*3*], Droste and Schoen [*1*], Schoen and Droste [*5*], and many others.

Test Facilities and Equipment

The BLEVE tests were conducted at the Stennis Hazards test site in Mississippi during the week of July 15–20, 1991. The tanks used in the trials were commercial cylindrical propane tanks with hemispherical heads. The design characteristics of the tanks are shown in Table 1.

Each tank was equipped with a 25.4 mm safety valve with a burst pressure of 1.724 MPa. All tanks were metallurgically tested.

TABLE 1 TANK CHARACTERISTICS

Volume	1.893 m^3
Length	3.023 m
Outside diameter	0.950 m
Shell thickness	0.0063 m
Head thickness	0.00533 m
Maximum allowable working pressure at 611 K	1.724 MPa
Hydrostatic test pressure	2.58 MPa
Relief valve setting	1.724 MPa
Relief valve diameter	0.0254 m

P. A. Croce is currently with Factory Mutual Research, Norwood, MA.
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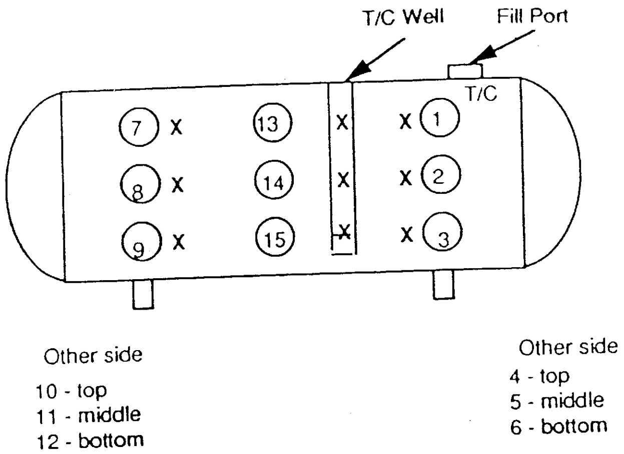

FIGURE 1. Thermocouple locations.

TABLE 3 BLOWDOWN HISTORY OF CYLINDER 5 FOR GASEOUS FLAME JET TEST NO. 1

Time (s)	Pressure (MPa)
0	1.618
30	1.100
60	0.963
90	0.874
120	0.791
150	0.722
180	0.687

Bulk fluid temperatures were measured by means of thermocouples on one vertical tank diameter using a thermowell which was 0.762 m long and 19 mm in diameter. It contained three thermocouples located at 304.8, 558.8, and 762 mm. The number immersed in the liquid at any time depended on the fill level. Some of the thermocouples became uncovered as material evaporated and vented out. No measurements of boundary layer temperatures were obtained for the these tests. Such measurements would have been helpful in investigating the various modes of heat transfer.

Two circumferences of six external type K thermocouples were used (see Figure 1). Thermocouples were attached with epoxy and covered with small amount of insulation held with aluminized tape.

Tank pressures were measured using two Dynisco transducers (Model 842). One transducer was located in the vapor space; the other was located in the liquid space. The vapor space transducer was located at the top away from the pressure relief valve, and the liquid space transducer was located at the bottom of the tank. The transducers were connected to the tanks using 6.35 mm insulated steel tubing.

In addition, two overpressure measurements were obtained on each of the two legs on the test site layout (15 and 46 m positions). All readings were collected with a scan rate of one per second. The digital signals, which were sent to a microcomputer, were displayed in real time in the control room.

The fuel supply for the flame jet and simulated pool fire experiments consisted of five propane cylinders manifolded together and placed behind a protective barrier constructed of bags and sand. Flexible copper tubing (outside diameter of 12.7 mm and inside diameter of 9.525 mm) was used to connect the cylinders. A remotely operated valve was used to initiate flow and a 2.25 kg propane tank was used an an ignitor.

Data Summary

Table 2 presents an overall summary of the tests. Details pertaining to the individual tests are discussed below.

Test No. 1

The test protocol for test No. 1 called for a gaseous propane flame jet to be impinged slightly above the liquid space. The tank contained 0.511 m^3 of saturated liquid propane at 289 K and was approximately 25 percent full by volume. This tank was not equipped with a pressure relief device.

The gaseous flame jet used was fueled by the five manifolded cylinders. The tip diameter was 6.35 mm. An initial experiment was conducted to determine the flame jet length and the blowdown duration of one cylinder. The observed flame jet length

TABLE 2 TESTS SUMMARY

Test No.	Fill Level (%)	Heating Source	Time to Failure (min)	Furthest Projectile Distance (m)	Observations/Comments
1	25	Flame jet Gaseous propane	14	118	Pressure sensors saturated at 1200 psig; significant overpressure in the near field. No fireball observed.
2	40	Flame jet Gaseous propane	No failure occurred	—	Relief device did not function. Weld area next to safety-relief device failed. Overpressure was vented adequately. Single phase flow.
3	40	Simulated pool fire Liquid propane	8	74	Significant overpressure. Fireball approximately 60 m in diameter; constant pressure while tank failed.
4	40	Simulated pool fire Liquid propane	No failure occurred	—	Relief device was adequate; single phase flow only.
5	50	Flame jet Liquid propane	No failure occurred	—	Relief device was adequate; single phase flow only.
6	50	Flame jet Liquid propane	12	195	Significant overpressure. Fireball observed was approximately 65 m in diameter. Constant pressure while tank failed.
7	Detonation of 50 kg of TNT flake				Experiment conducted to verify/calibrate overpressure data.

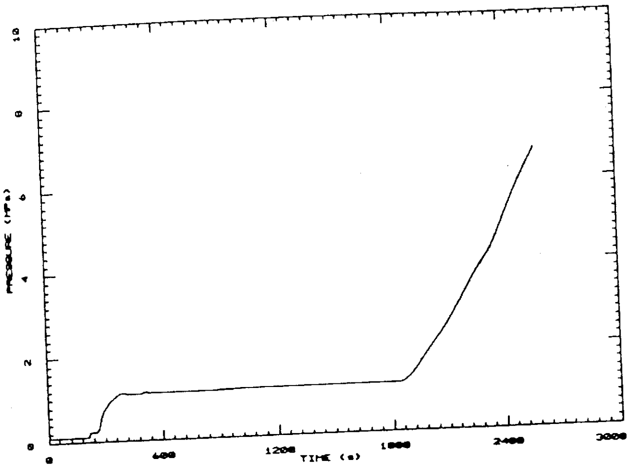

FIGURE 2. Test no. 1 pressure history.

was 1.1 m. The pressure history of cylinder 5, which was used a fuel supply, is shown in Table 3. Approximately 7.712 kg of fuel were used over 4 minutes. This pre-test was conducted at 2:00 pm on July 15, 1991.

Test No. 1 was conducted on July 16, 1991. The time histories of tank pressures and temperatures are shown in Figures 2, 3, and 4. The tank exploded after 14 minutes and 47 seconds. The contents of the tank were vapor at the time failure occurred. No fireball was observed. It should be noted that the tank failure pressure was higher than 1200 psi, the point at which pressure sensors failed. Significant overpressure were observed at 15 and 46 meters. The values are shown in Table 4. Projectiles resulting from the explosion were propelled 30.8 m (small piece), 59.8 m (large piece), and 117 m (dome).

TABLE 4 PEAK OVERPRESSURE MEASUREMENTS FOR TEST NO. 1

Direction	Distance (m)	Peak overpressure (kPa)
East-West	15	30
East-West	46	5.62
North-South	15	32.75
North-South	46	9.51

The temperature histories of thermocouples 1, 2, and 3 show that the flame impingement was very close to thermocouple No. 3. This is evident from the instantaneous temperature rise of the tank skin to 1200 K.

The total amount of fuel used by the flame jet was 35.2 kg over that period of time. The initial pressure for the cylinders was 1.417 MPa.

Test No. 2

Test No. 2 was also conducted on July 16, 1991. The test setup was similar to that of test No. 1. However, the tank fill level was increased to 40 percent by volume, and the tank was equipped with a pressure relief device. The total volume of saturated liquid propane in the tank was 0.795 m^3 corrected to 298 K. The initial pressure in the fuel supply cylinders was at 1.487 MPa. The flame jet was directed at the area to the left of thermocouples 8 and 9. This is evident from the instantaneous temperature rise shown by thermocouple No. 9 in Figure 7. About 290 seconds into the test, a small pin hole

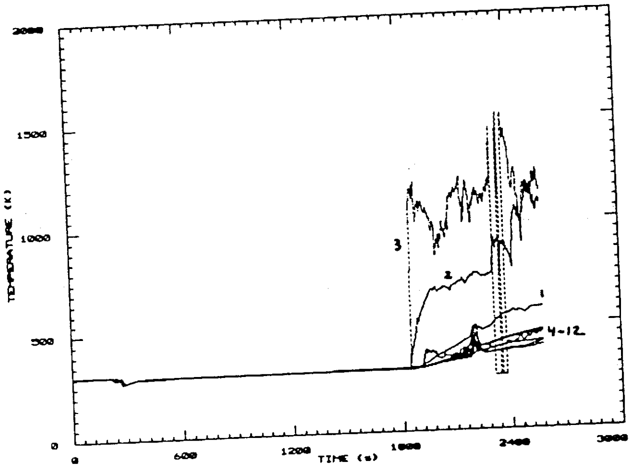

FIGURE 3. Test no. 1 temperature history (external nodes).

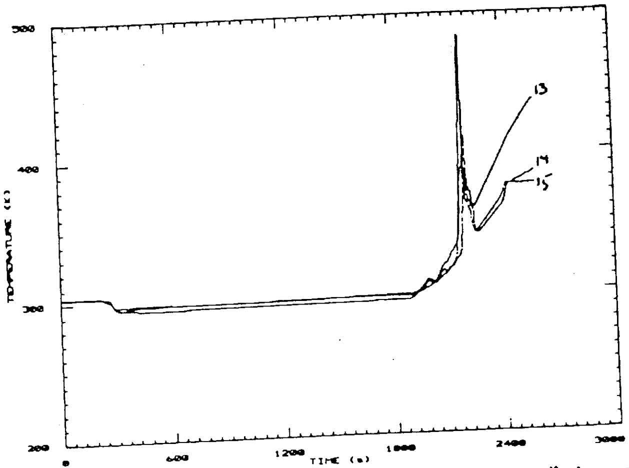

FIGURE 4. Test no. 1 temperature history (internal nodes).

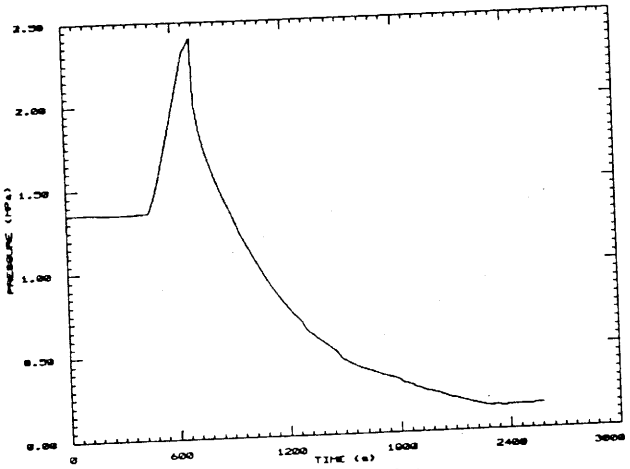

FIGURE 5. Test no. 2 pressure history.

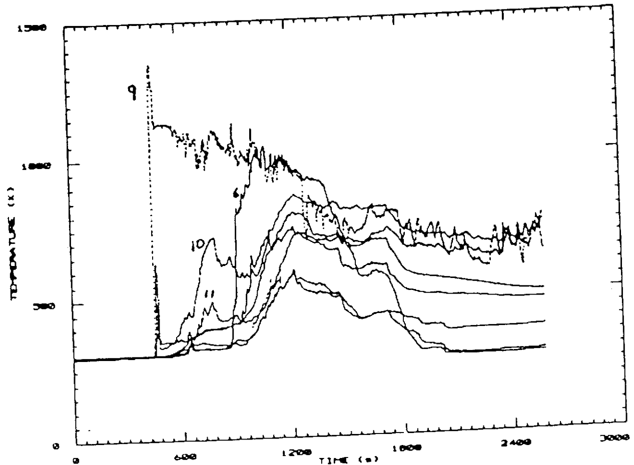

FIGURE 6. Test no. 2 temperature history (external nodes).

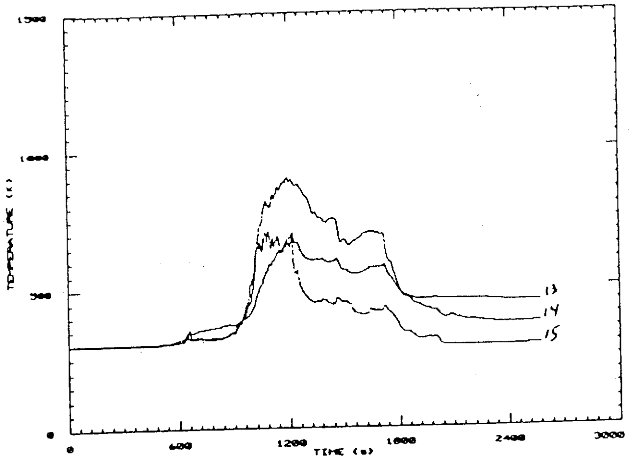

FIGURE 7. Test no. 2 temperature history (internal nodes)

developed under the dome next to the safety relief device. This is evident from the small dip in pressure shown in Figure 5. About 300 seconds later, the weld where the pressure relief device was located failed, resulting in an opening 51 mm long and 6.35 mm wide. The rate of energy loss through this small opening was larger than the rate at which energy was added to the tank. The resulting gas jet ignited. The fuel supply was terminated after 56 minutes. The contents of the tank were depleted 22 minutes later.

It is interesting to note that in addition to the pinhole leak and weld failure pressure relief device failed to function as well. The pinhole and weld failures both occurred at a pressure higher than the relief device's set pressure.

Test No. 3

Test No. 3 was conducted on July 17, 1991. A simulated pool fire was used as an external heating source using liquid propane. A pipe with an outside diameter of 20.63 mm and a length of 2.134 meters was used to simulate the pool fires. Seven holes, each with a diameter of 2 mm, were drilled and spaced at 153 mm intervals. The pipe was connected to the fuel supply. A test was performed to estimate the mass flow for each hole using one propane cylinder. The initial cylinder pressure was 1.136 MPa. After 5 minutes, the pressure of the cylinder dropped to 0.998 MPa, and 29.5 kg of fuel were depleted. This gave an average mass flow of about 0.0136 kg/s per hole.

The tank was filled to 40 percent volume, i.e., 0.795 m^3, at 289 K. The actual temperature was around 306 K. The tank was not equipped with a relief device. Failure occurred after 8 minutes and 13 seconds. Measured peak overpressure values are shown in Table 5. Dome pieces were propelled 46 and 74 m. The tank was propelled 10.5 m. The tank failed at the top. A small crack developed first followed by a flame jet. Shortly afterwards the weld at the top started to "unzip" and failure occurred about 20 seconds later. A fireball was also observed. Figure 8 illustrates the development of the flame jets and the subsequent fireball following vessel rupture. Grass and sands bags were burned within a 23 m radius of the tank's center.

The pressure history is shown in Figure 9. Temperature histories for all thermocouples, including internal ones, show instantaneous rise to 1200 K caused by fire engulfment of the tank. Therefore, the temperature measurements are likely to be in error.

TABLE 5 PEAK OVERPRESSURE MEASUREMENTS FOR TEST NO. 3

Direction	Distance (m)	Peak overpressure (kPa)
East-West	15	30.8
East-West	46	7.8
North-South	15	25.5
North-South	46	5.40

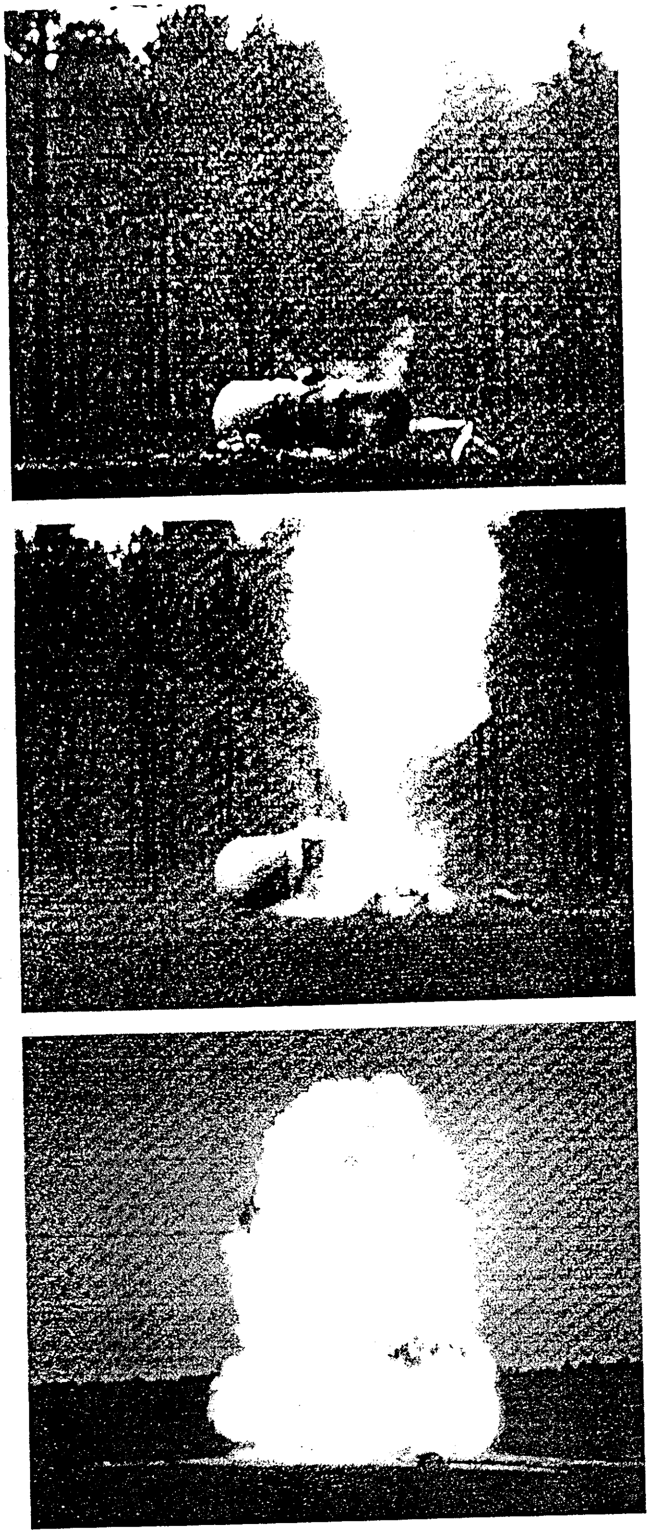

FIGURE 8. Flame jet and fireball development for test no. 2.

Test No. 4

The setup for test No. 4 was similar to that of test No. 3. However, the tank was equipped with a relief valve. As shown in Figure 10, the relief valve opened at 735 seconds and the tank energy was adequately vented, as shown the decreasing pressure. A flame jet resulted after the valve opened. After

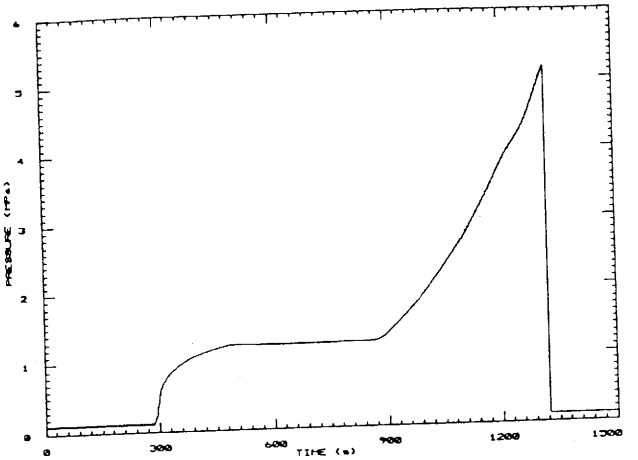

FIGURE 9. Test no. 3 pressure history.

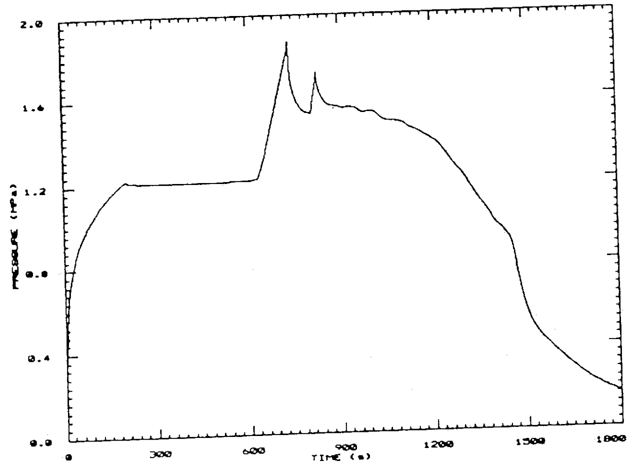

FIGURE 10. Test no. 4 pressure history.

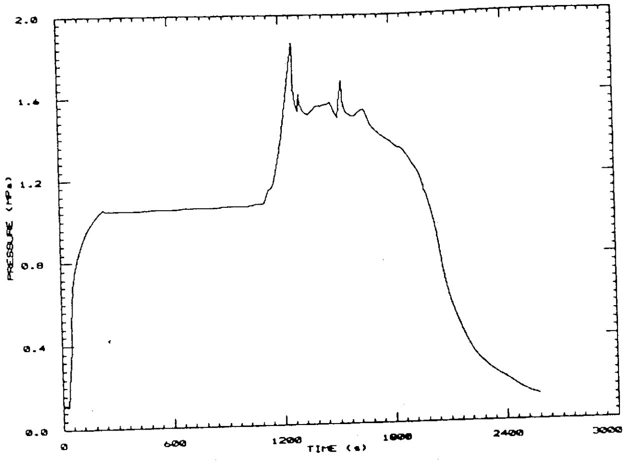

FIGURE 11. Test no. 5 pressure history.

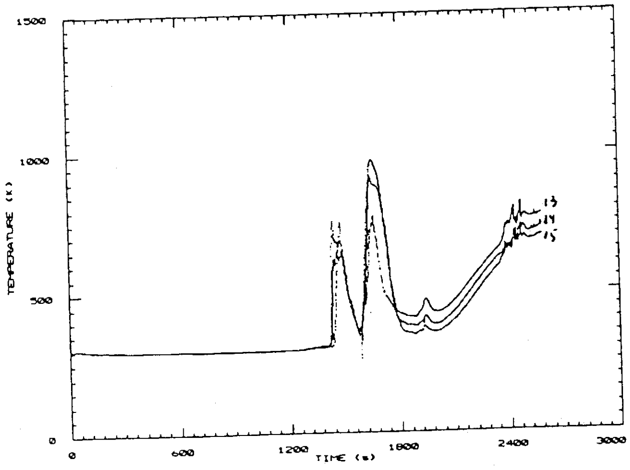

FIGURE 12. Test no. 5 temperature history.

two cycles, the relief valve failed open, and the tank contents were allowed to be depleted.

Test No. 5

The heating source for test No. 5 was a liquid propane flame jet issuing from a 5 mm tip directed at the center of the dished end of the tank. The tip was located 0.76 m from the metal surface. The tank was filled to 40 percent by volume (0.795 m^3 at 298 K) and was equipped with a pressure relief device. The outcome of this test was similar to that of test No. 4. The pressure relief vent was shown to be adequate for this particular heat load. Figure 11 shows the pressure history of the tank. The vent failed open and the tank contents were allowed to burn to depletion. The temperatures recorded in thermocouples 7-12 were about 1200 K in the first few seconds since they were close to the flame jet. The temperatures profiles of the internal thermocouples are shown in Figure 12.

Test No. 6

The setup for test No. 6 was similar to that of test No. 5. However, the pressure relief device was removed and the fill level was increased to 50 percent (0.985 m^3 at 289 K). The tank failed after 12 minutes and was followed by a fireball as well as a blast wave. The fireball was approximately 60 m in diameter. Overpressure data are shown in Table 6. A large piece of the tank shell was propelled 138 meters after bouncing eight times on the ground. The end cap was propelled 195 meters after bouncing six times on the ground surface. The temperature and pressure profiles are shown in Figures 13 and 14.

TABLE 6 PEAK OVERPRESSURE MEASUREMENTS FOR TEST 6

Direction	Distance (m)	Peak Overpressure (kPa)
East-West	15	37.2
North-South	15	32.1

Test No. 7

Overpressure measurements obtained from tests 1, 3, and 6 consisted of peak values. With the exception of test No. 6 where time-of-arrival data were obtained for the 15 m overpressure sensors, no time-of-arrival data were obtained for all other tests. The time-of-arrival data shown in Figure 16 seem

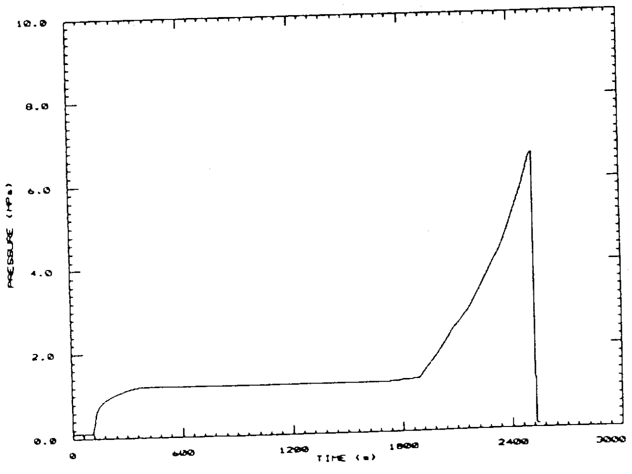

FIGURE 13. Test no. 6 pressure history.

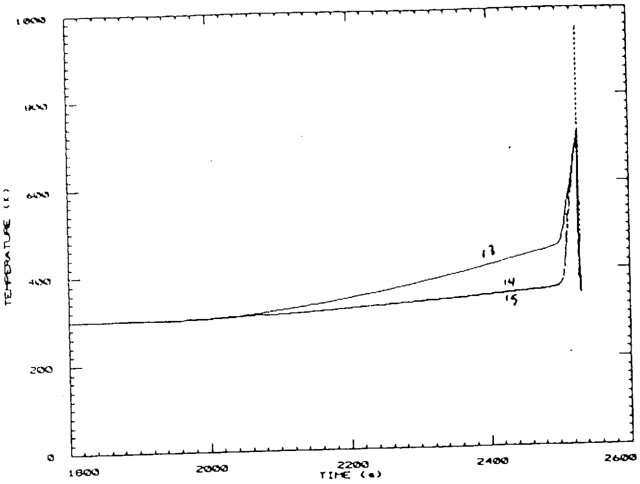

FIGURE 14. Test no. 6 temperature history

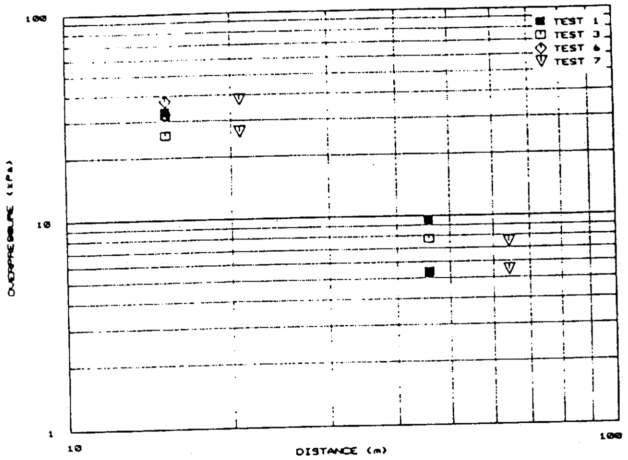

FIGURE 15. Overpressure data summary

to indicate that the blast wave was travelling at a speed that was in excess of the speed of sound in air. To investigate the validity of this observation further, an experiment was conducted on July 18, 1991, in which 50 kg of TNT flake (orthohombic) were detonated to obtain overpressure calibration data (see Figure 15). The PV energy content in the tank in test No. 1 was estimated to be equivalent to 500 kg of TNT. The pressure-time histories obtained from this test were very similar to those obtained in tests 1, 3, and 6. This seems to further support the contention that the blast waves that resulted from tests 1, 3, and 6 were travelling at supersonic speeds. A crater measuring 4.5 m in diameter and 0.9 m in depth was formed as a result of the TNT explosion.

Failure Assessment

Tank rupture is caused by the increase in a vessel's internal energy and insufficient energy relief provided by the safety valve. When the vessel ruptures, the internal energy of its contents is used as fragmentation/deformation energy for the shell, kinetic energy imparted to fragments, and blast wave energy. Under external heating by a fire, the temperature of the tank walls increases, the yield and tensile strength of the vessel walls decrease, and resistance to internal pressure decreases as well. The type of material used in the construction of the pressure vessels used in the trials is shown in Table 7.

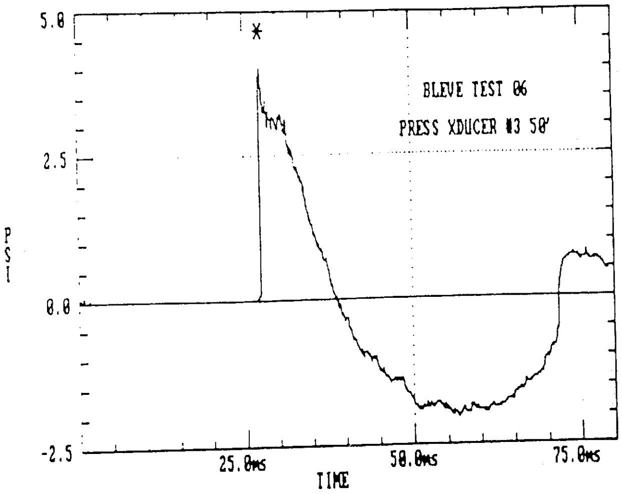

FIGURE 16. Time of arrival data for test no. 6

TABLE 7 MATERIALS USED IN TANK CONSTRUCTION

		σ_y (MPa)
Shell	SA-455	258
Heads	SA-414-C	206.4
Couplings and flanges	SA-105	248.2

In tests 1, 3, and 6 the tank failed at two to three times the maximum allowable pressure limit. If one assumes that the tank failed because of longitudinal force resulting from internal pressure, then the maximum pressure than can be sustained is:

$$P_{\text{burst}} = \frac{2t}{r}\sigma \tag{1}$$

where r is the tank radius, σ is the stress, and t is the wall thickness. The simplest criterion for establishing the critical value for σ is the yield strength:

$$\sigma = \sigma_y \tag{2}$$

If one uses this simple failure criterion, a value of 4.63 MPa is calculated. The actual failure pressures recorded in tests 1, 3, and 6 are shown in Table 8. Also shown is the ratio of σ over σ_y.

Homogeneous Nucleation

In the last 20 seconds before failure occurred in tests 3 and 6, photographic records showed the formation and propagation of a large opening in the upper part of the vessel, followed by vessel rupture. A large flame jet was developed almost instantaneously after the opening formation. Figures 17 and 18 show the pressures profiles of tests 3 and 6 over the last 30 seconds. It is interesting to note that the pressure was increasing slightly, even after formation of a large opening which was more than adequate to vent the energy of the vessel contents.

A possible explanation (see Venart [*6*]) is that, upon formation of the crack, vapor was first discharged. Because the vessel liquid contents were already homogeneously nucleated,

TABLE 8 ACTUAL FAILURE PRESSURES

Test	Pressure (MPa)	σ (MPa)	σ/σ_y
1	>8.27	269	>1.786
3	5.16	230	1.114
6	6.61	295	1.427

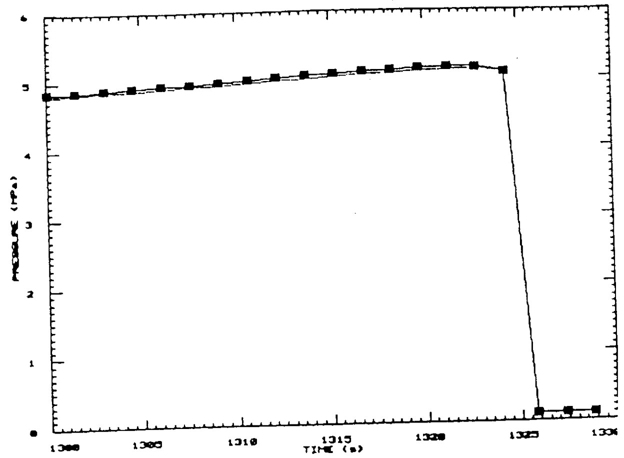

FIGURE 17. Pressure history for test no. 3

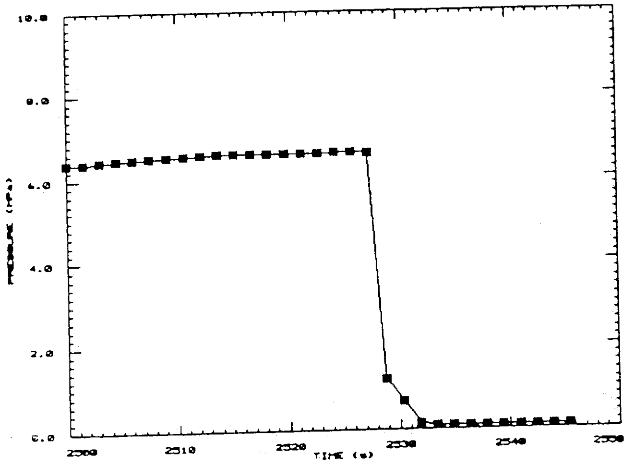

FIGURE 18. Pressure history for test no. 6.

the subsequent pressure drop caused rapid generation of void followed by two-phase swell. Flow through the opening became choked and repressurization occurred inside the vessel, causing collapse of the newly formed vapor bubbles, which caused cooling of the vapor walls, crack propagation, and vessel rupture shortly after.

Upon vessel failure, the superheated liquid exhibited a pressure drop to ambient pressure. The internal energy stored in the liquid as superheat was used to vaporize a fraction of the liquid. The rapid vapor bubble growth caused the remaining liquid to break up into fine aerosols that became entrained in the vapor cloud. If the cloud is dispersed to within the flammable limits, immediate ignition could lead to an explosion.

Conclusions

The experiments conducted in this study showed that significant blast effects occurred in the near field following vessel ruptures. Homogeneous nucleation constitutes a credible BLEVE theory for tests 3 and 6, and a container failure criterion based on yield strength seems to be conservative.

More experimental work is needed to futher our understanding of BLEVE mechanisms, container failure mechanisms, the effect of liquid fill level and vessel size on explosion severity, projectile hazards, etc. Such information is crucial to firefighters and design engineers involved in siting storage, loading, or processing facilities.

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