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INITIATION STEP OF BOILING LIQUID EXPANDING VAPOUR EXPLOSIONS

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ABSTRACT

Two sets of experiments have been performed to study the initiation of a BLEVE (Boiling Liquid Expanding Vapour Explosion). One litre tanks were caused to BLEVE while the pressure at the end of the tank was recorded. Experiments were then conducted in a shock tube equipped with windows. Liquid at the same conditions as the previous experiments was suddenly exposed to atmospheric pressure while a spark schlieren photograph was taken and the pressure response recorded. R12 and R22 were the fluids used in these experiments. Results show that the initial drop in pressure is followed by a rapid pressure rise, caused by the boiling of liquid. The initial depressurization results in superheated liquid in the vicinity of the break. The homogeneous nucleation of this liquid results in a local explosion. The blast wave from this explosion can be the cause for the catastrophic failure of the container.

INTRODUCTION

A BLEVE is by definition a major container failure, into two or more pieces, at a moment in time when the contained liquid is well above its normal boiling point at atmospheric pressure. The acronym was first used by Factory Mutual in 1957 to describe an explosion driven by the boiling of a fluid. (ref. 1)

In the standard scenario a tank of liquefied gas, usually propane, is engulfed in a fire. As the fire heats the tank, the fluid inside rises in temperature and pressure, roughly following the saturation curve (although there may be temperature stratification in the liquid and vapour). When the set pressure of the safety relief valve is reached, this valve opens and fluid is vented. If this fluid is flammable it may ignite and form a torch. The pressure inside the tank remains at the controlled pressure of the relief valve if this valve is correctly sized and it is functioning correctly. If the tank tears open the fluid is exposed to atmospheric pressure. The liquid in the tank is at a temperature above its normal boiling point and thus when the tank is opened the liquid is superheated with respect to the new pressure.

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Once the pressure is released the fluid starts to boil. This boiling can be rapid and violent. The tank is torn apart and parts of the tank wall are propelled over considerable distances, up to five hundred metres. If the fluid is flammable, it may ignite and form a fireball. Rail cars which have a lading volume of 128 kilolitres have been known to produce fireballs of hundreds of metres in diameter when they rupture.

Theories on Boiling and BLEVEs

Much research has been conducted on the initiation of boiling. Superheated liquids can exist because nucleation sites are required to initiate boiling. If boiling begins on a liquid-solid interface (as is most often the case), this is referred to as heterogeneous nucleation. Nucleation which begins in the bulk of the fluid is termed homogeneous nucleation. To determine the extent to which a liquid can be superheated, it is necessary to prevent heterogeneous nucleation of the liquid. This is usually done in a bubble column, a column of liquid in which there is a linear temperature gradient between the top and the bottom, with the highest temperature at the top. A droplet of an immiscible liquid is injected at the bottom, and allowed to rise through the column. The temperature at which the liquid changes to vapour is recorded as the superheat temperature limit of that liquid (ref. 2). The locus of these points is called the liquid spinodal. The superheat temperature limit is above the boiling point of that liquid, and is the temperature at which homogeneous nucleation will begin. High superheats are associated with homogeneous nucleation (ref. 3).

When a tank car tears open, the liquid passes through a superheated state. Initially there will be a rarefaction wave with the pressure drop information. This will be followed by a region of superheated liquid, then by an evaporation wave. These rarefaction waves have been measured by Thompson *et al* (ref. 4) in fluids of high heat capacity. In these experiments, a liquid in an expansion tube was suddenly exposed to atmospheric pressure. Records of the pressure at various points along the tube allowed the calculation of the wave velocities and showed that there were two waves - a forerunner rarefaction wave and a following evaporation wave.

Kim-E and Reid (ref. 3) postulated that when a tank containing a pressurized liquid fails and the pressure drops in a very short time frame, there can be a liquid phase at essentially ambient pressure but at a temperature significantly above the equilibrium temperature. This liquid then exists briefly as a metastable superheated liquid. If the thermodynamic state of this metastable liquid is such that the spinodal curve is reached, homogeneous nucleation must occur within the bulk of the liquid, and strong and damaging shock waves can be formed.

If during an isentropic pressure drop the spinodal state results, then homogeneous nucleation must occur. This homogeneous nucleation would then be the cause of an explosion. Therefore, the probability of an explosion is 100% if the fluid is on the spinodal curve. The probability of an explosion is less than 100% if the initial temperature of the liquid is below the superheat temperature limit (ref. 5).

State of Current Research

Research on BLEVEs to date has taken a three - pronged approach. Large scale work is being conducted in Europe with regard to the monitoring of conditions before a tank BLEVEs (refs. 6, 7, 8). Computer models have been developed describing the thermohydraulics inside the tank while it is heated by a fire and also describing the heat transfer between the fire and the outside of the tank. Some of this work has been conducted at the University of New Brunswick (UNB) (ref. 9). The third area, and the topic of this paper, is an attempt to determine what actually causes the pressure waves inside the tank which lead to a BLEVE.

This research has been conducted jointly between UNB and the Atomic Energy of Canada Ltd. (AECL). Two different experiments are reported. In a previous study on BLEVEs, McDevitt *et al* (ref. 10) established a set of criteria with which a BLEVE could be predicted in the specific 1 litre tanks used in their experiments. As a continuation of this work, this paper discusses a study on the initiation of a BLEVE. To this end, rapid boiling and the generation of the pressure waves inside the container were examined using a piezoelectric pressure transducer and spark schlieren photography. Results from this study have provided a new insight into this phenomenon.

BLEVE EXPERIMENTAL APPARATUS AND PROCEDURE

To measure the pressures generated during a BLEVE, one litre commercially available propane tanks were filled with a liquefied gas, heated, and burst with a rifle bullet. Since a BLEVE is an explosion due to rapid boiling, there is no ignition or chemical reaction involved. Tests were done with both R12 and R22, non-flammable gases. R12 had been shown to BLEVE by McDevitt *et al* (ref. 10).

The apparatus for the BLEVE experiments consisted of a series of 1 litre propane cylinders, of the type normally used for soldering. These tanks are 26 cm long and have a diameter of 7.5 cm with a thickness of 0.635 mm. The relief valves were removed and a group of three type K thermocouples inserted in this hole. The top was drilled and tapped to allow the insertion of a pressure transducer. The tank is sketched in Figure 1, with the instrumentation as indicated. Once the instrumentation was installed the required weight of R12 or R22 pumped into the tank.

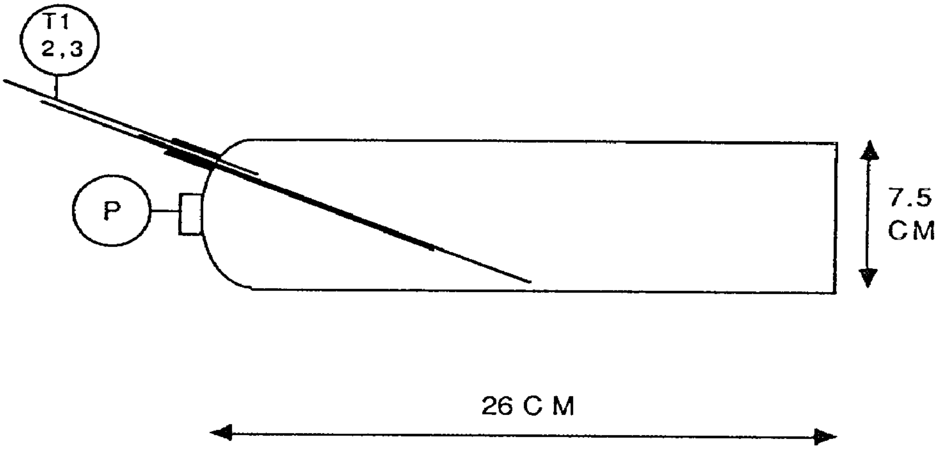


Figure 1: Tank and Instrumentation for BLEVE Experiments

The tank was supported horizontally by a coupling welded to a blast-protecting shield. This coupling not only serves as a support, but as a protector for the transducer. A fence enclosure served to contain the flying tank pieces. Thermocouples were connected to a local display and the transducer to two oscilloscopes. Power was supplied by a portable generator.

An area 50 metres to the East of the tank was designated by Protective Services personnel as a "safe" area, the location from which a rifle shot would be fired. The equipment was set up in the field and all personnel cleared to the "safe" area. A propane torch was placed under the cylinder as a source of heat. When the internal temperature of the tank reached the test temperature, the tank was ruptured with a .3006 full metal jacketed rifle bullet. The pressure traces on the oscilloscopes were photographed, along with the tank fragments from the experiment.

TANK BLEVE RESULTS

These experiments repeated those done by McDevitt *et al* (ref. 10) with the addition of the dynamic response pressure transducer. Consequently, the outcome was predictable. This allowed collection of pressure data under conditions where in which a BLEVE was assured.

The temperatures at which the tanks were punctured were somewhat inaccurate due to the nature of the test. It was not possible to have a temperature indication at a remote location, so it was necessary for someone to remain near the tank (but behind the blast wall) to read the temperature. Once the desired temperature was reached, that person moved to a "safe" area. The Protective Services person then fired into the tank. Due to the time between the last temperature reading and the rupture of the tank, the exact temperature at the time of rupture is estimated.

Figure 2 shows the pressure-time history as recorded by the transducer at the end of the tank. The fluid inside the tank was 879 g (88 v%) or R22, which was heated to approximately 65 C. The pressure inside the tank at this temperature would be 2700 kPa. As can be seen from the figure, the pressure dropped slightly, then rose to a maximum of 3500 kPa. This result shows that the high pressure which tears the tank occurs after the tank has ruptured, and after the pressure has dropped slightly. This suggests that the BLEVE occurs after the

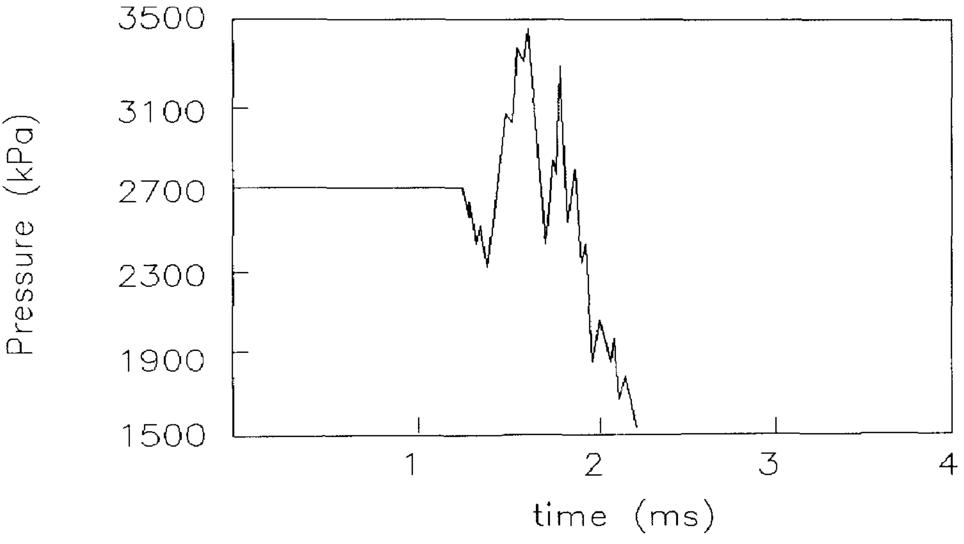


Figure 2: Pressure Response during a BLEVE of R22 in a 1 Litre Tank

initial depressurization and is a result of a rapid vapour generation caused by boiling. It has been demonstrated by Frost (ref. 11) that unstable boiling of a superheated liquid can create huge pressure waves. If the tank cannot withstand these pressure waves, then it will tear, and a BLEVE will be the result. While these experiments document the fact that the pressure inside a tank during a BLEVE initially drops and then rises above the initial pressure, they do not reveal the nature of the initiation of the explosion. Experiments were designed to be conducted in a steel channel equipped with windows to study the events which occur when a heated tank filled with liquid is ruptured.

SHOCK TUBE EXPERIMENTS

High speed photographs taken during the BLEVEs of the 1 litre tanks indicate that the event occurs in less than 2 ms. This short time frame, along with the fact that pressure travels in waves, points to a shock - related event. Experiments were performed to obtain direct evidence of the existence of shock waves, and to attempt to measure their destructive capability.

The conditions under which the R12 tanks would BLEVE were known (it should be noted that these conditions are specific to the tank geometry and thickness), and BLEVEs in these specific tanks could be predicted. It was decided to conduct a similar test in a shock tube which would be able to withstand the pressures generated by the sudden depressurization. Under these more rigid conditions, the dynamic pressures could be monitored, the burst area and location could be varied, and data could be recorded in the microsecond time scale.

The shock tube has inside dimensions of 91.4 cm x 2.5 cm x 3.8 cm, (36" x 1" x 1.5"). The volume is 0.868 litre. Since it was necessary to burst a hole in the shock tube to initiate the event, one of the plugs was removed from the bottom of the tank and replaced by an 0.005 cm (0.002" thick) stainless steel disk. Below this was a four - pronged arrowhead attached to a piston. The piston was driven by 482.5 kPag (70 psig) helium, which was controlled by a solenoid.

The R12 vented to a blowdown tank which was then slowly discharged through a vacuum pump. This same pump was used to evacuate the test chamber prior to filling. The overall set-up is sketched in Figure 3.

For instrumentation there were 3 type K thermocouples. These were placed with one near the bottom of the shock tube, one about 1 cm above the bottom of the shock tube and the third about 1.5 cm from the top of the shock tube. The thermocouple readouts were 3 LED displays. Pressure transducers were PCB dynamic piezoelectric transducers which have a rise time of 1 microsecond. One

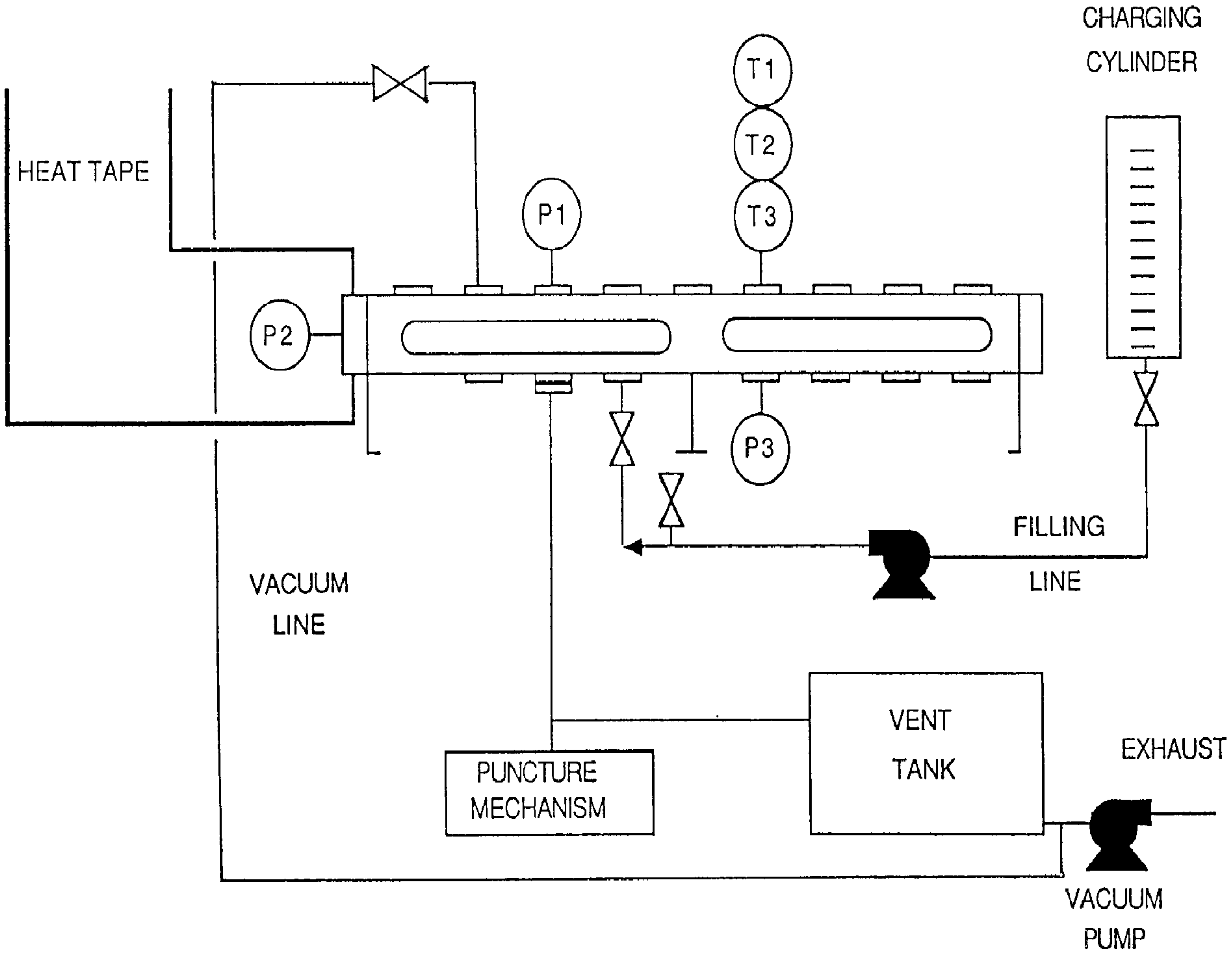


Figure 3: Schematic of Shock Tube and Associated Equipment

was located in the vapour space directly above the burst disk (TRANS 1), the second was in the end of the tank, 25 cm from the burst disk (TRANS 2), and the third was 30 cm from the disk, in the liquid (TRANS 3).

The stainless steel burst disk was installed and the arrowhead mechanism tightened down, then R12 was pumped into the tank from a charging cylinder. The shock tube was purged with R12, then a vacuum was drawn on the system. Once the tank was under vacuum, the vacuum line was valved off and the desired weight of R12 pumped from the charging cylinder into the tank. The steam tracing and electrical heat were then turned on.

Once the fluid was at the test temperature and the oscilloscope set up to record the pressure data, the helium was turned on and the temperature and static pressure recorded. With the immediate area clear of personnel, the solenoid was triggered which pushed the arrowhead into the burst disk and initiated the event. There was usually a loud bang. Data were recorded from the oscilloscopes and the pressure traces photographed. The heat was turned off and the tank allowed to cool somewhat before the next experiment.

RESULTS OF SHOCK TUBE TESTS

Figure 4 (a) shows a typical pressure trace from the transducer directly above the burst disk. This experiment had 808 g (94 v%) of R12 at 90 C. When the disk ruptures, the pressure in the vapour space initially falls, then suddenly rises to a peak, and then drops again. This pressure peak is important in that it shows that there is a pressure rise within the tank after it has been ruptured.

Figure 4 (b) is a pressure trace from the same experiment. The top trace is from TRANS 1, and shows the same response as Figure 4 (a) with a much compressed time scale. The lower trace is TRANS 2, the transducer located in the end of the tank. The pressure initially rises, then drops slightly, rises higher then drops. This oscillation continues but dampens out. The pressure trace for TRANS 3, the transducer in the liquid further along the tank, is the same as that for TRANS 2.

The oscilloscope recording the pressure data was triggered by the change in pressure recorded by TRANS 1, and the breaking of the diaphragm is estimated to have occurred about 260 μs before the drop in pressure recorded in Figure 4 (a).

The pressure peak in Figure 4 is not as large as that observed in Figure 2, but the similarity of the pressure responses suggests that rapid evaporation has caused a pressure increase shortly after the depressurization of the liquid.

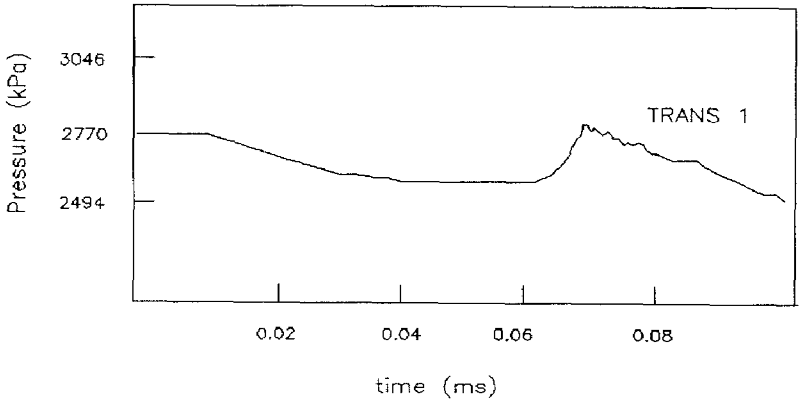


Figure 4(a): Response of TRANS 1 during Shock Tube Experiments

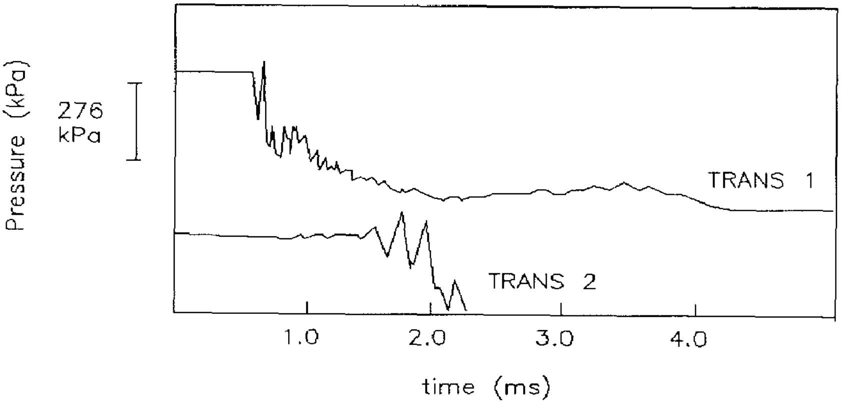
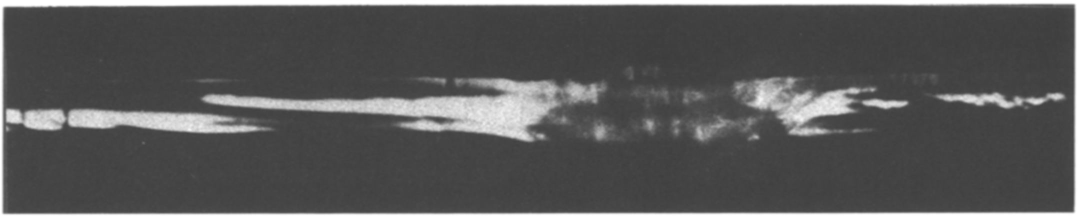


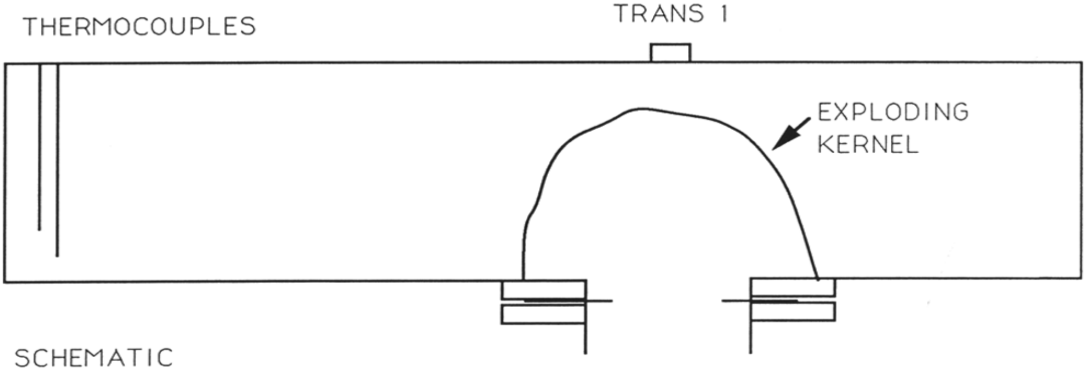
Figure 4(b): Response of TRANS 2 during Shock Tube Experiments

The pressure rises shown in Figure 4 are lower than those recorded during actual tank BLEVEs, shown in Figure 2. The experiment was designed so that pressure rises in the shock tube were not high enough to damage the windows of the shock tube. In these experiments, the size of the hole in the vessel is limited to a 2.5 cm diameter hole. Experiments with restricted hole diameters showed that the peak pressure increased with increasing hole size. It is estimated that a larger hole size would increase the pressure peak.

In order to confirm that the pressure increase was related to the boiling of the fluid, a spark schlieren photograph was taken 40 µs after the triggering of the oscilloscope, slightly before the pressure peak recorded on TRANS 1. This photograph is shown in Figure 5. It was not possible to achieve a proper seal around the windows of the shock tube for this experiment and thus experiments were conducted before the fluid had reached thermal equilibrium. As a result shear in the fluid due to convective movement can be seen as dark bands in Figure 5. Nevertheless, an explosion kernel originating near the rupture location in the tank is clearly visible. This photograph supports the suggestion of the pressure trace that an explosion has occurred after the initial depressurization and is caused by the boiling of the superheated liquid. Once the explosion occurs, a blast wave is formed and eventually overtakes the expansion waves. This accounts for the fact that the pressure transducers TRANS 2 and TRANS 3 initially indicate a pressure rise.



SCHLIEREN PHOTOGRAPH



SCHEMATIC

Figure 5: Schlieren Photograph showing Boiling in the Vicinity of the Rupture

Only the liquid in the vicinity of the break experiences the pressure drop. Once the rarefaction wave has travelled a finite distance, the superheated liquid behind this wave will homogeneously nucleate and cause a pressure wave. This pressure wave (explosion) then overtakes the rarefaction wave, and the fluid in the ends of the tank experience a pressure wave. Therefore, the volume of the exploding fluid, and thus the size of the explosion kernel, depends on the size of the break (the rate of depressurization). This will affect the magnitude of the pressure peak, which determines whether or not the tank explodes. The tank and the fluid properties should also have an effect on the strength of the explosion kernel, and on whether the tank can withstand the internal pressure wave.

As seen in Figure 5, the boiling of the fluid around the hole is homogeneous. It in not possible to say that this photograph proves the theory that the pressure rise in a BLEVE is necessarily associated with the pressure rise known to result during homogeneous nucleation. Homogeneous nucleation produces a large vapour volume, and the inertial considerations of escaping fluids may also play a role in the pressure wave formation.

SUMMARY

This study shows that a BLEVE is an explosion which can be initiated by the depressurization of a pressure-liquefied gas through a break. This depressurization causes the fluid near the break to be in a superheated state. There is a local explosion caused by a rapid, homogeneous boiling of this superheated fluid. Pressure records indicate that the local explosion near the break in the tank occurs before the expansion wave has propagated far from the break. The blast wave from the explosion eventually stops any further boiling. The volume of the fluid involved in the initial explosion determines the magnitude of the blast (pressure) wave. The blast wave is the cause for the catastrophic failure of the container as observed in many accidents.

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