# SOME EXPERIMENTAL ASPECTS OF TRANSIENT RELEASES OF PRESSURISED LIQUEFIED GASES

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A number of authors have reported work on two phase discharges from systems in which the entire vessel contents are rapidly expelled. This paper adds to that work by comparing the behaviour of the contents of three vessels which have varying size and discharge geometry. A series of experiments has been carried out using the same material at the same pressurised storage conditions in each of the vessels. Areas available for escape of the material varied from 99% to 1.5% of the original vessel surface. In all cases the time required to depressurise the vessel was less than 800 ms. The internal conditions during depressurisation are compared, and some general conclusions drawn regarding these transient releases.

Key Words: Two phase, transient, release, experimental.

## 1. INTRODUCTION TO EXPERIMENTS

Three different release systems were used which were capable of giving a rapid depressurisation of a storage vessel, together with a rapid discharge of two phase (liquid/vapour) material, undergoing flash evaporation. These release systems encompassed a size range of approximately one order of magnitude, together with a wide range of exit area size relative to the vessels, allowing the effects of constraint by the vessel to be studied.

Thus, these systems simulated the range of vessel failure modes which have been described as 'catastrophic'; from total rupture of a storage tank, through 'end failures' seen in storage bullets, to relatively small but significant tears or holes in a vessel.

The major similarity between these events, and the point in which they differ from the less hazardous 'blow-down' events caused by pipework failures, is that the timescales on which they occur are sufficiently small to prevent equilibrium, or a steady-state, being reached in the flashing process.

The three systems were as follows:

i) 'Glass Sphere' Release.

A 0.4 m diameter, 20 litre glass vessel which could be failed by external impact. The impact induced brittle fracture across the whole of the vessel, giving almost total failure. This provided a large degree of freedom during the early expansion, and approximated most closely to the 'sudden removal of constraint' simplification used in some models.

ii) 'Bursting Disk' Release.

A 0.42 m diameter upright cylinder with a commercial bursting disk forming the upper end. Failure of the bursting disk could be initiated using a cruciform knife pushing up through the vessel along its axis. The bursting disk would then tear apart, opening the full cylinder diameter for the main, two phase release. This provided some constraint from the base and side walls of the vessel, but still with a reasonably large exit area. This system had the largest initial volume of the three.

iii) 'Shock tube' Release.

A system similar to a conventional shock tube, comprising a 50 mm square cross-section tube with a 0.8 m driver section, a fast acting flap valve, and a selection of instrumented expansion sections. This system allowed for the most detailed examination of the release, both within the confines of the original, 'pre-failure' section and in the expanding, flashing release. This system had the smallest volume of the three, and also the smallest relative exit area.

In order to compare the systems most readily, a common release material was chosen, and across most of the experiments a common set of release conditions were selected.

The material selected was Trichlorofluoromethane, Refrigerant-11 which was selected as it has a low toxicity, is non-flammable, chemically stable at temperatures of up to ca.250 °C, and has a boiling point of 22.7 °C. Thus R-11 is liquid at lab temperatures, facilitating handling and storage, but is readily heated to temperatures above its normal boiling point.

For each of the releases the initial pressure was 515 kPa, corresponding to a temperature of ca. 80 °C (a superheat of ca. 57 °C).

In each experiment the internal pressure and temperature inside the vessel were recorded as the vessel failed, and during the subsequent depressurisation.

## 2. RELEASES FROM GLASS SPHERES

The glass sphere releases were carried out in an enclosed room, with a ceiling height of 3.2 m and floor dimensions 9.2m x 7.5 m. The room was of reinforced concrete construction, so that the pressure wave on failure, and the glass fragments, could impact on the structure without risk of damage.

Control and instrumentation connections were run through one wall of the room to a control area in the adjacent room. The test enclosure could be sealed off and the experiment run from the control area. Thus tests could be carried out in a controlled and safe manner.

### 2.1. Release System

The release system was based around a standard Corning QVF 20 litre round bottom flask, as shown in Figure 1. This had an internal radius of 0.185m and a typical wall thickness of ca. 5 mm. The flask was mounted in an inverted position, with the neck facing downwards. The open neck of the flask, which now formed the bottom of the vessel was sealed against a collar and end-plate. The end-plate allowed connections into the flask for filling and for instrumentation. A pair of connections was also provided for a circulation system, allowing the R-11 to be heated using an external heater. This provided a more uniform heating of the fluid than an element or cartridge heater inside the vessel, and the mixing induced by the circulating flow reduced the possibility of stratification within the vessel.

The failure of the vessel was by means of brittle fracture of the glass, induced by an impact. The impact was produced by a pneumatic ram, acting horizontally along a radius of the sphere at a point halfway up the side. The ram held a hardened tungsten tip to provide a single point impact, thus concentrating the stress on the vessel at a small impact point and avoiding any likelihood of not initiating fracture in the glass.

A schematic of the vessel and internal instrumentation is given as Figure 1.

### 2.2. Instrumentation

The mass, pressure and temperature of the R-11 within the vessel were measured.

The mass was obtained from a pair of load cells under a platform which supported the vessel and its stand. The conditioned load cell output, with the tare weight of empty vessel and stand removed, was displayed in the control area.

A pressure transducer connected to the end-plate at the bottom of the vessel was used to monitor the pressure. This was displayed via a digital read-out on the signal conditioner / amplifier in the control area.

A type-E thermocouple was situated in the neck of the flask, 1.5 cm above the end-plate.

Once vessel failure had been initiated, these internal temperature and pressure measuring systems were used to follow the changing conditions inside the vessel. In order to perform the double duty of pre- and post-failure measurements, the instruments were specified as having both stability and a low response time. The pressure transducer/ amplifier system had a frequency response greater than 40 kHz, and a thin-ribbon thermocouple was used which had a response time of better than 18 ms. The instrument amplifier used for the thermocouple had a frequency response of better than 10 kHz, much lower than that of the thermocouple element.

Output from the instruments was brought together at a single place in the control area, conditioned and amplified. This conditioned output was recorded using an instrumentation tape recorder run at a high tape speed, giving a recorded frequency response of ca. 20kHz.

Once an experiment had been recorded, the data was transferred from tape to a Perkin-Elmer 3205 mini-computer. The computer was able to capture this data in real time from the tape, and so no conversion in data rate was necessary.

The tape recorder step was necessary as the experiment was carried out in a special facility remote from the computer, and direct connection was not possible.

For each experiment, the data from the tape were digitised with a sampling rate of 1000 Hz. This was sufficient to follow most of the changes, being greater than the frequency response of most of the instrumentation.

Data processing was carried out using routines from the commercial SPAG system produced by Cranfield Data Systems [1]. Software was developed 'in-house' based on the SPAGS subroutine library in order to process the data most effectively.

### 2.3. Results

A total of six fully instrumented tests were carried out with the glass sphere release system. These were designed to look at the vessel break-up and the influence it has on the subsequent, two phase release. In view of this, some tests were carried out using inert materials, which would not give two phase behaviour. Tests were performed to check the pressure effects, using nitrogen gas to pressurise the sphere without any liquid content. The effect of a partial liquid fill was also tested, using water as the liquid and nitrogen gas to pressurise the system. Finally, tests were carried out using heated R-11 under its own vapour pressure to give a pressurised, initially partially liquid filled, two phase release.

The six tests carried out were as follows:

GS Test 1: Nitrogen gas only, 515 kPa
GS Test 2: as Test 1
GS Test 3: 50% fill with water, nitrogen gas 515 kPa
GS Test 4: 50% fill with R-11, vapour pressure 515 kPa
GS Test 5: as Test 4
GS Test 6: as Test 4

Pressure and temperature histories for tests GS1, GS4, GS5 and GS6 are shown in figures 2 to 5. By plotting the values of temperature against the pressure at the same time, a graph can be produced showing the deviation from the saturation curve during the release. Graphs produced in this way for each of the three R-11 releases are also shown in Figures 3 to 5.

### 2.4. Comments on Results

The measured internal conditions showed significant differences between the gas pressurised releases and the two phase, R-11 releases.

Figure 2 shows the results from test 1. This is typical of all three Nitrogen pressurised tests. The pressure falls from the initial storage pressure to that of the surrounding atmosphere in less that 2 ms. A small drop in temperature is seen, due to the adiabatic cooling of the gas during the rapid expansion.

Figures 3 to 5 show data from each of the three R-11 releases. The pressure drop from storage to atmospheric pressures now takes ca. 80 ms, and takes place in two distinct stages. In the first 2 ms the pressure drops steeply, but then a small rise is followed by a much slower fall to atmospheric. This has been noted in earlier experiments [2] and attributed to a separation of the initial, gas phase expansion causing the first pressure drop, followed by subsequent two phase boiling, giving the pressure rise followed by slower drop as the R-11 boils.

The temperature traces show a two stage process as well. In this case an initial drop in temperature rapidly stabilises, followed by a second rapid fall beginning about half way through the slower second stage depressurisation shown on the pressure traces. This 'knuckle' has not been noted in the earlier studies, where temperature measuring systems with slower response times were employed.

The pressure / temperature plots show, again, that the three R-11 tests, while not identical, have very great similarities. There is a considerable excursion from the equilibrium curve in the early stages of the release, but the equilibrium is quickly re-established (at least at the instrument positions).

## 3. SHOCK TUBE RELEASES

### 3.1. Release System

The 'shock tube' release system was based around a stainless steel tube with a 50 mm square cross section, and is shown in Figure 6. The design is similar to a conventional shock tube, having a 'driver' section and an 'expansion' section separated by a rigid partition. The driver section could be pressurised, and the expansion section was open to the atmosphere at its far end. The partition between the two sections could be 'failed' under controlled conditions, initiating the rapid release of the driver section contents along the expansion section.

The driver section had an internal length of 1.0 m, and was designed to operate up to the homogeneous nucleation limit of R-11, should that have been required. Thus the maximum operating pressure was 34 MPa (500 psi), at a temperature of 250 C. The vessel could be heated using two cartridge heaters inserted in the side walls. A standard feedback control system allowed the vessel to be heated up to, and maintained at, a preset temperature. This also provided a safety cut-out should a preset maximum temperature be exceeded.

The driver section was fitted with a number of threaded ports, to allow for instrumentation. These were positioned on both upper and lower faces of the tube, and consisted of four opposed pairs plus one extra lower face and two extra upper face ports. When any particular port was not in use, it was sealed with a 'blanking' plug.

The failure system used in all the tests consisted of an hydraulically operated 'flap' valve which had an opening time of less than 5 ms.

### 3.2 Instrumentation and Data Logging

The temperature and pressure of the vessel were measured and displayed on read-outs in the control area, adjacent to the main laboratory. Pressure was measured with a transducer connected to the vessel by an inverted 'U'tube from the upper instrument port at the 'open' end of the vessel. This was necessary to allow vapour pressure only to be measured at 100 % fill levels. The 'U'-tube also provided thermal separation from the hot vessel body, which was found necessary in commissioning trials using water at temperatures above 120 C. The system was then used, unchanged, for the R-11 experiments, although these were at a lower temperature.

A type-K sheathed thermocouple, placed in the centre of the tube cross section, was used to measure the temperature of the vessel contents. A second type-K thermocouple was used to measure the laboratory temperature. Neither of these thermocouples was connected to the data logging system.

Within the driver section, the piezo resistive pressure transducer used to monitor the vessel pressure was also used to follow the depressurisation at the 'open' end of the section. A piezo electric transducer was placed in the upper port closest to the 'closed' end of the driver section, in order to study variations in pressure histories across the vessel.

The temperature in the vessel was measured using a thermocouple placed at half height in the tube cross section close to the 'closed' end of the driver section. This was a 0.25 mm diameter, sheathed type-K device, with a response time of better than 3 ms.

In order to provide sufficient rigidity to avoid the thermocouple being damaged or moved out of position during the release, the 0.25 mm diameter sheathing was passed through an hypodermic needle. Approximately 4 mm of the end of the sheathing (including the sensitive tip containing the junction) protruded from the end of the needle, and the thermocouple was sealed in place using an epoxy resin adhesive. The complete thermocouple / hypodermic unit was then mounted in a carrier to fit the threaded instrumentation ports, again being sealed with epoxy resin adhesive.

The instrumentation output that was recorded during a release was logged directly onto the Perkin-Elmer 3205 mini-computer, as this was sited in a nearby building. A bank of 'anti-aliasing' filters was used to allow the fastest data rates to be used without causing signal interpretation errors. The thermocouple outputs were all amplified using differential instrument amplifiers prior to logging, to give a signal that could be measured readily. No 'cold junction' compensation was performed before logging, in order to minimise the response time of the thermocouple systems. The laboratory temperature, as displayed in the control room, was measured at a connector board where the thermocouple junctions were made.

The captured data was stored in a format that made it compatible with the 'timebase offset', thermocouple correction and instrumentation correction routines developed for use with the other experimental systems.

### 3.3 Results

In the test series, four fully instrumented R-11 runs were carried out at the 515 kPa initial pressure.

ST Test 1 ... 2 kg R-11, 515 kPa
ST Test 2 ... 1 kg R-11, 515 kPa
ST Test 3 ... 1 kg R-11, 515 kPa
ST Test 4 ... 1 kg R-11, 515 kPa

Pressure and temperature histories for each test are presented in Figures 7 to 10. Plotting the values of 'open end' temperature against 'open end' pressure at the same time produced the graphs of deviation from the saturation curve also shown on the same figures.

### 3.4. Comments On Results

The 515 kPa, R-11 releases show that the depressurisation time (i.e. the time taken for the internal pressure of the vessel to drop to that of the atmosphere) is dependent on the amount of material in the vessel. The cases where 1 kg of R-11 is released at 5 bar have depressurisation times of 250 to 300 ms (Figures 8, 9, 10), whereas the 2 kg release requires 500 ms (Figure 7). The difference in times occurs in the second part of the pressure drop, the initial drop being similar in magnitude and duration.

It can also be seen that the return towards the saturation curve as equilibrium is restored occurs more quickly for the 1.kg releases. While the data from each test show some differences, the 1.kg releases show significant similarity from test to test.

The 'knuckle' on the temperature curve noted in the glass sphere results is more pronounced in the shock tube R-11 tests, being seen as a definite increase in temperature in some tests, most notably test ST4 (Figure 10). This is also associated with a second departure from the saturation curve, which can be seen in all the results but again most noticeably in Figure 10.

## 4. BURSTING DISK RELEASES

### 4.1. Release System

The release system was based around a 0.42 m diameter upright cylindrical vessel fashioned from a 0.55 m length of mild steel pipe, and is shown in Figure 11. The bottom end of the pipe section was fastened to a supporting framework and a stainless steel base plate. A neoprene gasket was used to form the bottom seal, held by a standard (nominal 16 inch) flange. A similar flange at the top of the pipe section was used to support a commercial 0.42 m (16 inch) diameter bursting disk. This was sealed using a steel clamping ring and a fibre composite gasket. The bursting disks used in the experiments were commercially supplied nickel disks, which had a rated burst pressure of 8 bar.g. All of the experiments were made at the 'standard' release pressure of 515 kPa. This meant that the bursting disk was at approximately 65% of its nominal burst pressure when the vessel was at release conditions.

Connections for filling, venting, a circulation system and various instrumentation were made through the plate at the bottom of the vessel. In many respects this was similar to the system used in the releases from glass spheres. An external circulation loop with a heater in was used to increase the R-11 temperature and pressure once the system was closed. Failure of the bursting disk was induced using a cruciform cutter mounted on the end of a pneumatic ram. This operated vertically upwards, along the axis of the cylindrical vessel, and as the ram extended the cutter blades were forced through the bursting disk. The placement of the ram axially, inside the vessel was chosen to minimise the effects of its presence on the expanding cloud.

### 4.2. Instrumentation

The vessel conditions were monitored using a pressure transducer at the base plate, measuring the liquid pressure at the bottom of the vessel, and also a type-K sheathed thermocouple in the liquid 30 mm above the bottom of the vessel, shown in Figure 11. Both these instruments were connected to digital displays in the control area.

Once the release had been initiated, the changing conditions in the vessel were followed using two pressure transducers and a single thermocouple. The thermocouple was a type-E, thin ribbon device with a response time of better than 18 ms. This was mounted through the base plate of the vessel, with the measuring point 15 mm above the bottom. Two similar pressure transducers were used in the vessel, each one having a response rate of better than 40 kHz. One of these transducers was the one used to monitor conditions before release, and was connected to the base plate, measuring the pressure at the bottom of the vessel. The second transducer was connected to a rigid tube protruding through the base plate to a point close to the top of the vessel. In this way it was possible to measure the vapour space pressure.

Data processing was carried out using the techniques and computer programs used with the releases from glass spheres.

### 4.3. Results

Six fully instrumented experiments were carried out with the bursting disk release system. These tests were designed to compare the effect of releases at different initial fill levels.

The six test were as follows:

BD Test 1: 25% fill R-11, vapour pressure, 515 kPa
BD Test 2: repeat of test 1
BD Test 3: repeat of test 1
BD Test 4: repeat of test 1
BD Test 5: 50% fill R-11, vapour pressure, 515 kPa
BD Test 6: repeat of test 5

The internal conditions measured in the releases from the bursting disks were pressure and temperature at the bottom of the vessel, and pressure at the top of the vessel, above the initial liquid level.

In each test but one the instruments worked correctly, and a full set of results is available. In test 3 the signal conditioner for the pressure transducer below the initial liquid level failed immediately prior to the release, and no data were obtained from the instrument.

'Vapour space' pressure, 'liquid' pressure (apart from that for test 3) and temperature histories for the tests are presented in Figures 12 to 17. Graphs showing pressure against temperature during five of these R-11 releases are also shown in Figures 12, 13 and 15 to 17.

### 4.4. Comments on Results

The pressure and temperature histories from the 6 tests show similar profiles to each other. The two 50% full tests are distinguishable by a longer time required for the pressure to fall to atmospheric.

The 'vapour' space pressure (denoted by (a) in the Figures) falls to a value close to that of the atmosphere in ca. 20 ms. Some of this time will be due to the depressurisation of the 'vent' line leading up from the transducer below the vessel into the vapour space, so the fall time in the body of the vessel may be much less than this.

The initial fall is followed by a similarly steep rise in pressure, but to a value much less than the initial storage pressure. This then falls more slowly to reach atmospheric pressure again after ca. 200 ms. In the 50% full tests (figures 16(a) and 17(a)) the results differ in that the intermediate pressure is maintained for a longer period of time, however the time required to fall to atmospheric is similar.

The 'liquid' pressure ( (b) in the figures ) falls to an intermediate pressure in ca. 6 ms, this pressure being similar to that of the second maximum for the vapour space pressure. This is maintained for ca. 50 ms, then falls relatively slowly towards atmospheric for a further 50 ms. There is then a second intermediate peak, rising in ca. 50 ms and then falling to atmospheric after a further 50 ms. Thus the total depressurisation time is ca. 200 ms, as for the 'vapour space'.

The temperature traces show a two stage behaviour. The initial fall in temperature is very steep but slows down after ca. 20 ms. This is in the same order as the response time of the thermocouple, and probably reflects the instrument response to a faster temperature change. The slope of the cooling curve then becomes less steep; indeed in tests BD1 and BD6 there is a slight increase in temperature, followed by a shallower cooling curve. The temperature reaches a steady value, at the atmospheric pressure boiling point of R-11, after ca. 150 ms for the 25% full tests and ca. 200 ms for the 50% full tests.

The pressure / temperature traces for all but test BD3, where 'liquid' pressure data were not available, show a considerable deviation from the equilibrium curve during the first few milliseconds of the event, with a subsequent return towards an equilibrium value.

## 5. COMPARISON OF RESULTS FROM ALL THREE SYSTEMS

It is in the initial depressurisation that the identification of common characteristics and of differences are most important, as the different geometries will, per se, have a dominant influence on the subsequent cloud expansion. It is the geometrical factors which will change in hazard assessment problems.

Similar data are available for internal conditions in each experimental geometry; the pressure and liquid temperature. Also, because of the dovetailing of the experimental programmes, a common set of release conditions has been used across the tests.

## 5.1. Similarities Between Cases

Initial comparison of the temperature and pressure plots reveals marked similarities in the overall history. The pressure falls rapidly towards that of the surroundings, then builds up again, though to a lower value, before finally dropping much more slowly to the ambient. The temperature shows a similar rapid fall, followed by a period at a constant or near constant value, followed in turn by a slower fall to the boiling point at ambient pressure.

The 'knuckle' on the temperature curve corresponds to the build up of the intermediate pressure peak, and it is during this period that the thermodynamic equilibrium is being approached.

## 5.2. Differences between Cases

It can be seen that, despite the similarities in overall shape of the curves, there are differences in the time required for depressurisation. The glass sphere system shows a drop to atmospheric pressure in ca. 130 ms. With the bursting disk system this depressurisation time is increased to ca. 200 ms. The shock tube times are greater still, at ca. 270 ms.

As the initial conditions are the same, the changes must be due to mass or geometry, which vary between the systems. As the shock tube releases the smallest mass and the bursting disk the largest the time differences are not mass related. The relative size of the available exit area is the most obvious remaining geometrical factor after the size and relative fill are discounted. This can be done as the fill levels are comparable and the mass of material, which is then directly related to the size, has been shown to be unrelated to the differences in pressure and temperature histories.

The three systems have widely varying exit areas. These are compared in Figure 18. The glass spheres have a ratio of exit area to total area of 0.994. The bursting disk exit area ratio is 0.167, while the shock tube exit area ratio is 0.015. These are in the correct sequence relative to the timescales for depressurisation, but no simple relationship is apparent between the magnitudes of the exit area ratio and the timescale.

It can also be seen that the pressure traces show some detailed differences between the systems. The glass sphere tests show a rapid fall followed by a single secondary peak. The bursting disk tests show two secondary peaks and the shock tube tests have a single, but much extended peak.

## REFERENCES

[1] Cranfield Data Systems, Bedford, 1984."Data Collection System for Health and Safety Executive".

[2] Bettis, R.J., Nolan, P.F. & Moodie, K., 1987, IChemE Symposium Series No.102, pp.247-263.

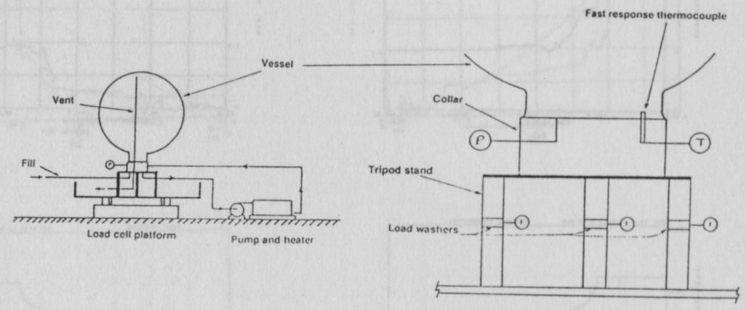

Figure 1: "Glass Sphere" Release System

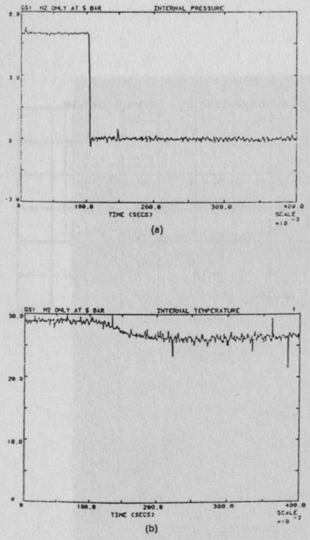

Figure 2: GS Test 1, Internal Conditions

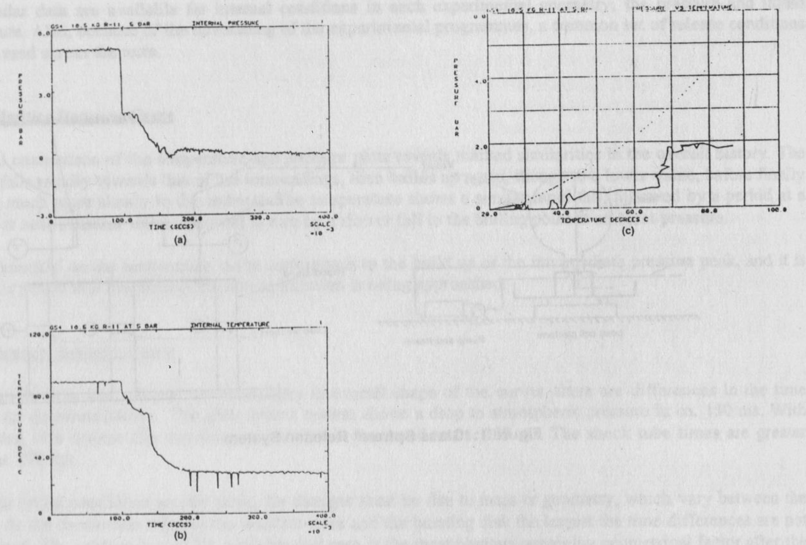

Figure 3: GS Test 4, Internal Conditions

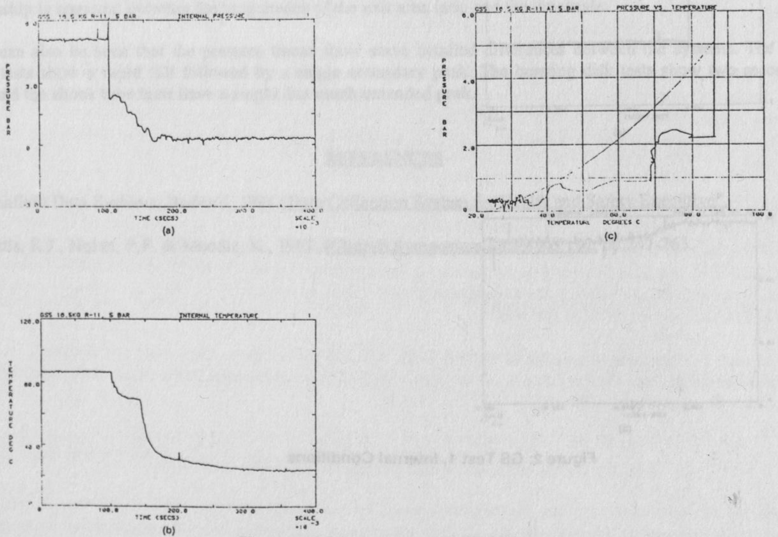

Figure 4: GS Test 5, Internal Conditions

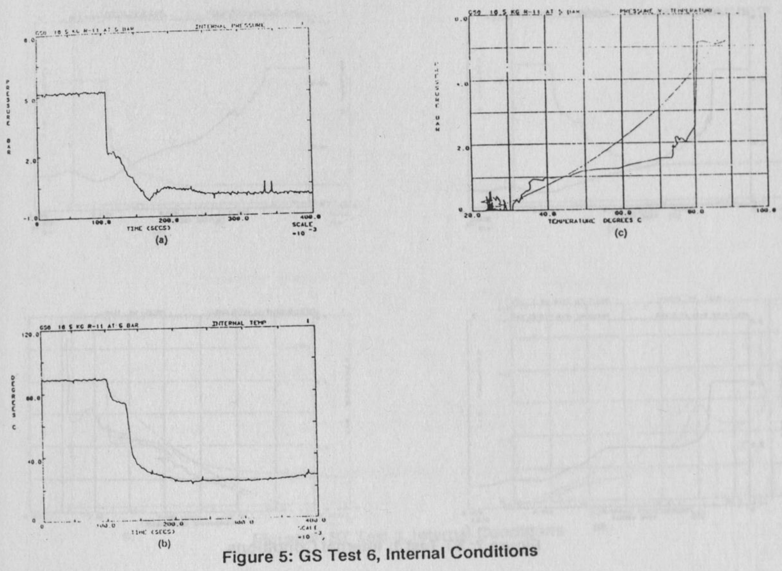

Figure 5: GS Test 6, Internal Conditions

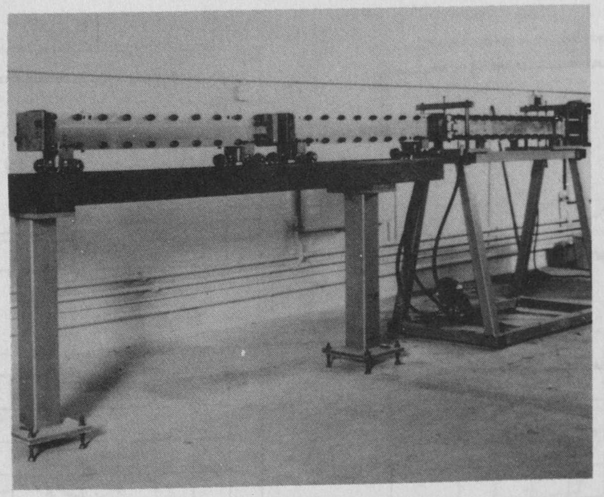

Figure 6: "Shock Tube" Release System

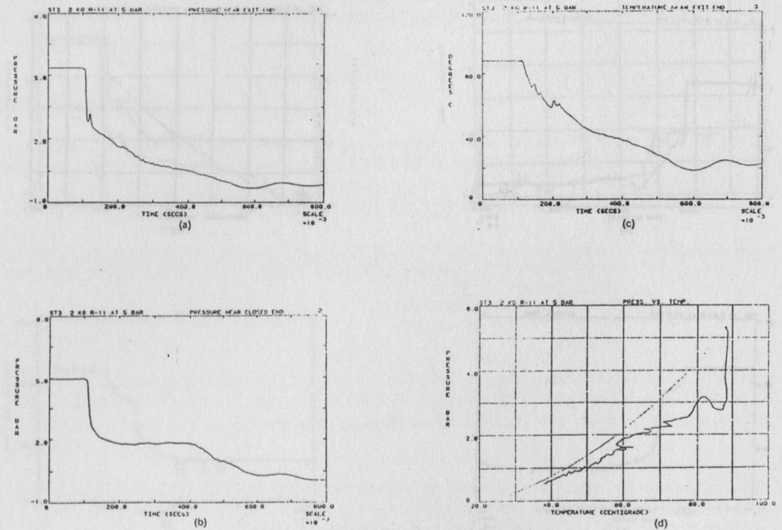

Figure 7: ST Test 1, Internal Conditions

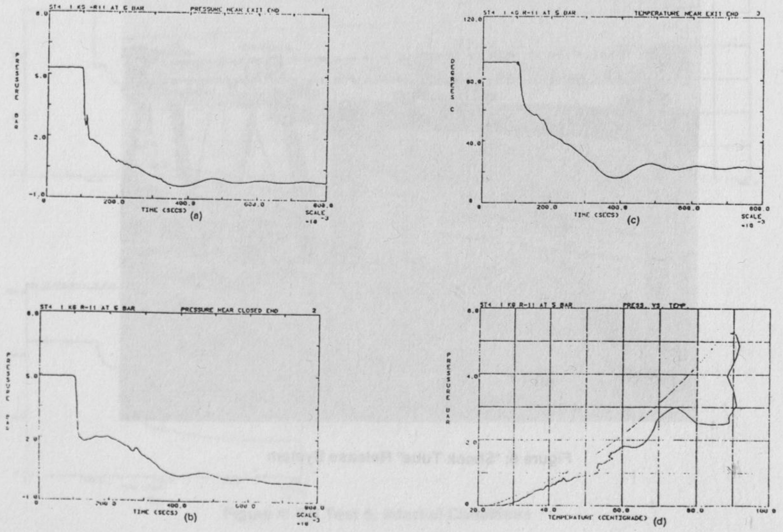

Figure 8: ST Test 2, Internal Conditions

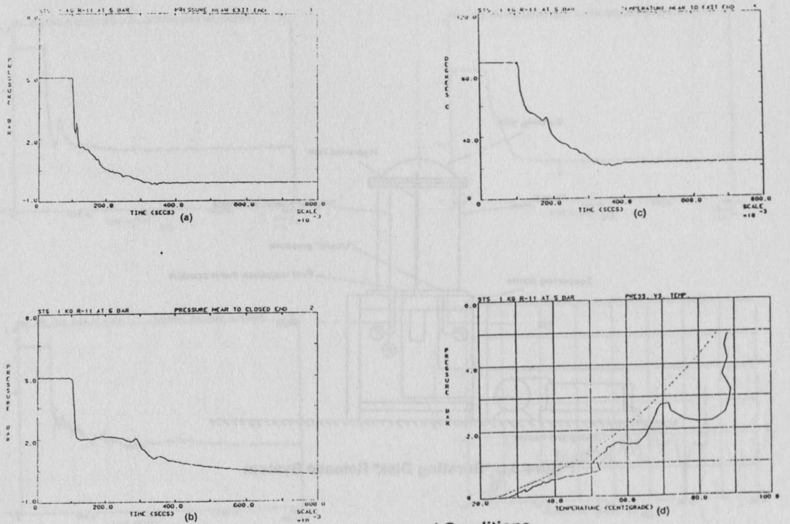

Figure 9: ST Test 3, Internal Conditions

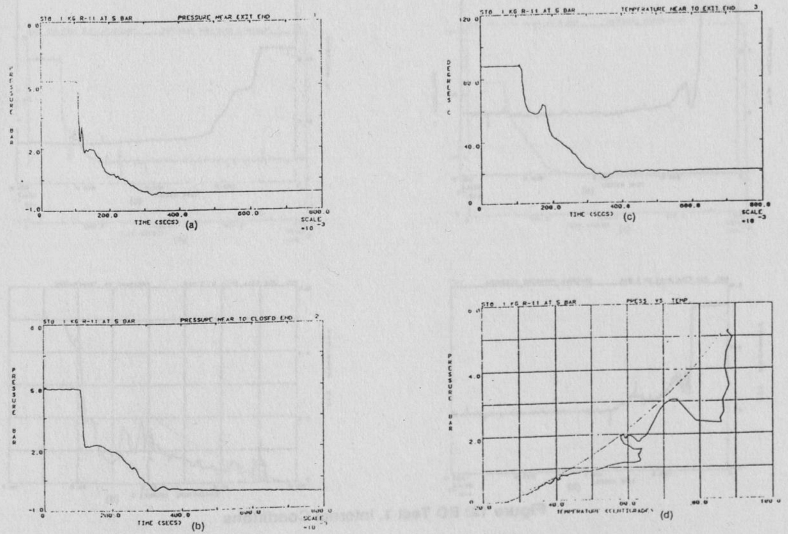

Figure 10: ST Test 4, Internal Conditions

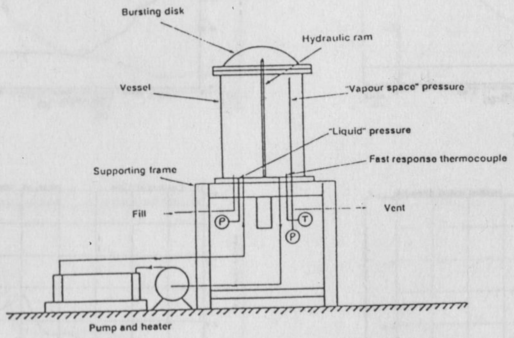

Figure 11: "Bursting Disk" Release System

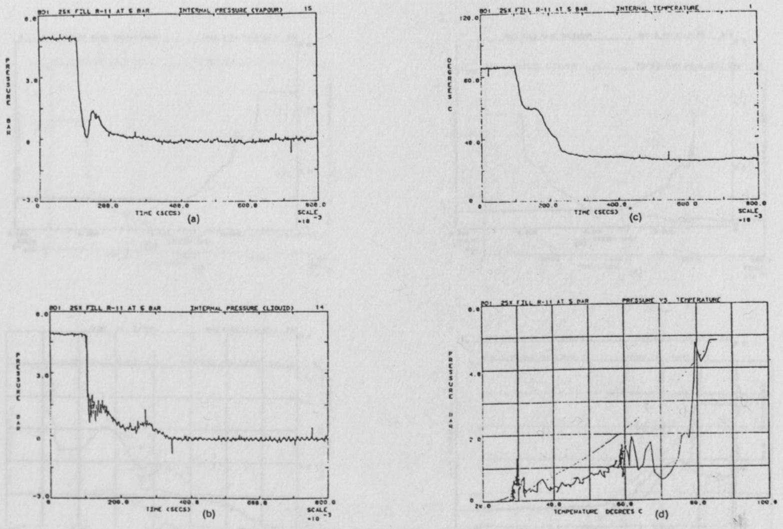

Figure 12: BD Test 1, Internal Conditions

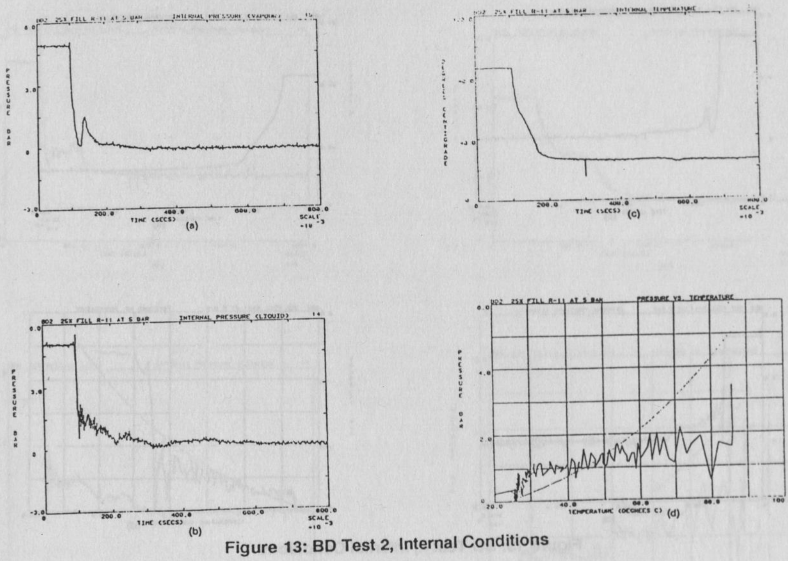

Figure 13: BD Test 2, Internal Conditions

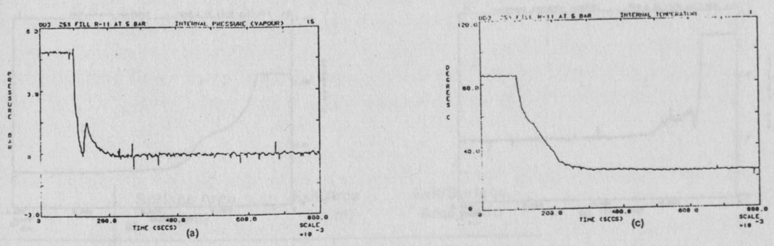

Figure 14: BD Test 3, Internal Conditions

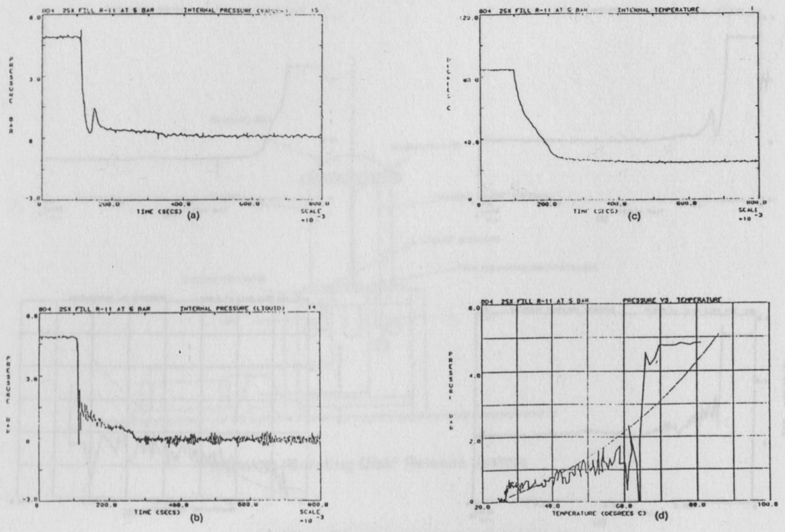

Figure 15: BD Test 4, Internal Conditions

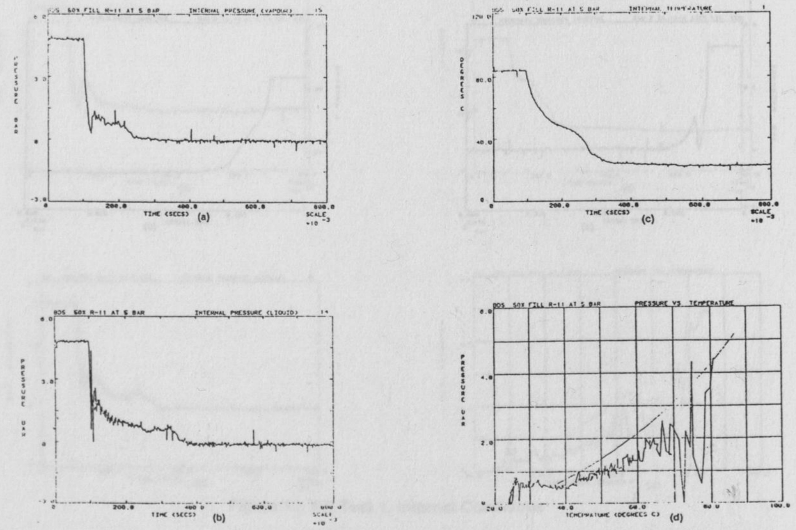

Figure 16: BD Test 5, Internal Conditions

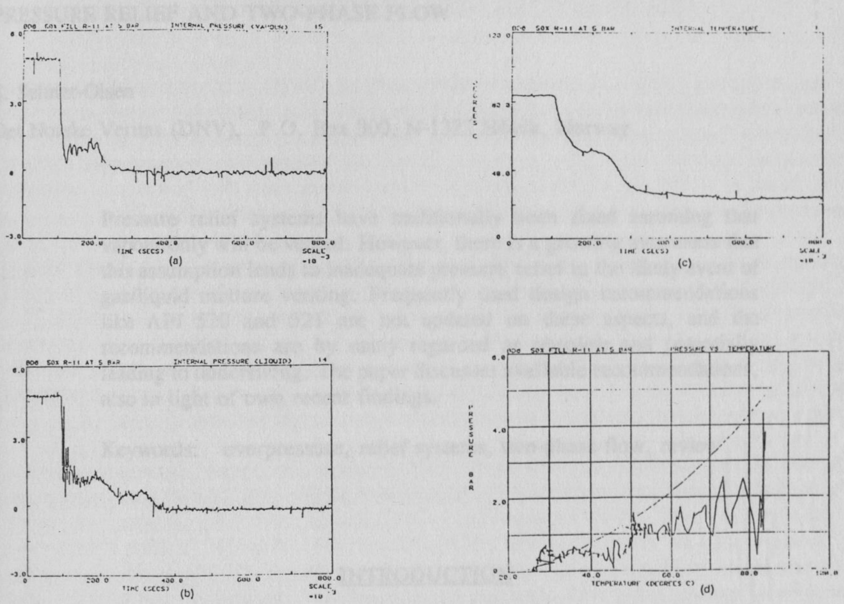

Figure 17: BD Test 6, Internal Conditions

| | Surface Area (sq.m) | Exit Area (sq.m) | Exit/Surface Area Ratio |
|---|---|---|---|
| Glass Sphere | 0.356 | 0.354 | 0.994 |
| Bursting Disk | 0.755 | 0.126 | 0.167 |
| Shock Tube | 0.167 | 0.0025 | 0.015 |

Figure 18: Exit Areas Comparison