Government of **Western Australia**
Department of **Commerce**
Energy*Safety*

Technical Report

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Investigation into the Effect of Vehicle Fires on the Integrity of LP Gas Containers Installed to AS/NZS 1425:2007

Revision	Description	Date
A	Initial Report	13/01/2010
B	Issued for Internal Review	28/01/2010
C	Issued for Stakeholder Review	29/04/2010

EXECUTIVE SUMMARY

Following several incidents in which the fuel containers of LPG vehicles exploded violently in fires, a review was undertaken by the Energy*Safety* Division of the Western Australian Department of Commerce to establish measures that would reduce the likelihood of such events. Current design standards require containers to be fitted with a Pressure Relief Valve (PRV) which should, under all but the most severe conditions, release the contents in a controlled manner when the container is exposed to fire and prevent an explosion, however, experience has shown that explosions can and do occur.

A survey of the current literature revealed that flame impingement on an uninsulated, thin walled container (even though protected by a PRV) and substantially filled with LPG was very likely to produce a rupture and that this could be instantaneously followed by a Boiling Liquid Expanding Vapour Explosion (BLEVE) and further by a Vapour Cloud Explosion (VCE). BLEVE's generate powerful shock waves that are capable of totally destroying the containment vessel and surrounding structures and usually also gives rise to high velocity projectiles. In the case of LPG containers where a rupture is initiated by fire, it is very likely that the LPG released by the BLEVE will explode in a VCE, in which the entire mass of LPG is burnt almost instantaneously, producing a further blast wave and a fireball.

Given the large number of vehicle fires in Western Australia and the risk that BLEVE's pose to emergency service personnel and bystanders, it was decided to carry out tests that simulated LPG containers caught in vehicle fires as well as actual cases of vehicle fires. Control measures intended to reduce the likelihood of a container rupture occurring in these circumstances were trialled in a series of live tests that were carried out in Hanson Construction Materials' Hearne Hill Quarry. Various levels of protection were applied to the containers to assess their effectiveness. Six of the containers were made by APA Manufacturing Pty Ltd and the other five by Manchester Tank & Equipment Company Australia and in all cases the LPG used was commercial propane.

The major conclusions are as follows:

1. Containers compliant with the current design requirements, filled to near the maximum allowed level, are likely to rupture and produce a BLEVE and VCE in a vehicle fire. The probability of this outcome can be greatly reduced by suitable protective measures.
2. No single control measure was considered likely to be completely effective in eliminating the potential of a container to rupture and BLEVE. However, the test results indicated that a combination of the following would provide a high level of confidence that a BLEVE should be an extremely unlikely outcome:-
   - Insulating the container walls (by sheet steel shielding or intumescent paint), and
   - Replacement of the aluminium and plastic currently used in the fabrication of the container sub-compartment box and vent line with steel equivalents
3. Other possible measures (that were not trialled in these tests) include:
   - Increasing the wall thickness of the steel used in constructing containers to decrease the stress on the vessel walls or the use of more temperature resistant alloys.
   - The installation of a Thermal Safety Element (TSE) on the container that would rapidly vent the container's contents. However, several safety and design qualifications would need to be considered prior to TSE's becoming an option.
   - Design modifications that promote cooling of the internal walls of containers and venting systems that discharge vapour and liquid simultaneously.

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- The use of cylinders made of polymer composites rather than metals.

4. The performance characteristics of the PRV's were found to be a significant factor. In several cases the valve seat failed relatively quickly, possibly contributing to increased relieving rate and venting the container contents rapidly. This, apparently unintended control measure used in isolation does not prevent a BLEVE, as, indicated by Test 11.
5. The PRV's provided with the containers used in these tests had flow capacities that far exceed the minimum specified flow rate under the relevant standard. A minimally compliant PRV would have a lower capacity and use of such a valve would likely increase the potential for and size of a BLEVE.
6. American standard CGA S-1.1 – 2007 "Pressure Relief Device Standards Part 1 - Containers for Compressed Gases", on which the PRV sizing equation in AS 2613 is apparently based, notes that PRV's do not protect the container against possible rupture during the continued application of external heat.
7. AS 4838-2002 "High Pressure Cylinders for CNG as a Fuel for Vehicles" requires the CNG cylinders to be evaluated for their performance in the fire case.

In order to reduce the risk of LPG container failures and BLEVE's the following is recommended:

1. Revise the installation requirements for LPG containers in vehicles to ensure that containers are installed in a manner that makes ruptures and violent explosions an extremely remote possibility. In order to achieve this, a performance based approach is proposed where a proponent would be required to demonstrate, through rigorous testing, the effectiveness of container design and installation practices. In doing so it is advisable to consider the fire case requirements for CNG cylinders and aim to provide some consistency.
2. Review the PRV requirements specified in AS/NZS 1425:2007, in particular for containers constructed to AS/NZS 3509:2009.
3. New materials of container construction, specifically polymer composites, appear promising and should be further investigated.

From the investigations and testing it was found that installations can be made virtually BLEVE proof with reasonable and practical controls. However if it is considered that cost and logistics would make the above recommendations unviable, then a formal Quantitative Risk Assessment should be performed to ascertain the risk to the public and emergency personnel. The results of such an assessment should then form the basis for further action.

It should be noted that such a move will attract a significant responsibility and may have future ramifications for those sanctioning the QRA as opposed to removing the probability of such violent ruptures. Given that the investigations have provided practical outcomes, such an approach cannot be endorsed by Energy*Safety.*

Finally the reader is encouraged to view the DVD accompanying this report which shows testing carried out by Energy*Safety*.

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1 INTRODUCTION

This report details the outcome of investigations carried out by the Energy*Safety* Division of the Western Australian Department of Commerce on vehicle LPG fuel storage containers installed according to AS/NZS 1425:2007. The investigation followed reports of vehicle LPG tanks rupturing, rather than venting in the intended controlled manner, when the vehicle was caught in a fire.

A container rupture is a hazardous event in any circumstance, but in some cases the vessels have exploded violently in a Boiling Liquid Expanding Vapour Explosion (BLEVE), producing a blast wave, flying fragments (of the container and vehicle parts) and a Vapour Cloud Explosion (VCE) from the suddenly released LP Gas. These failures occur with sufficient violence as to become a safety issue for emergency services personnel and any bystanders.

This led to an investigation that raised concerns about the adequacy and appropriateness of the current standards that cover the design, manufacture and installation of LPG vehicle fuel storage containers. Subsequently, a series of practical tests were conducted which included testing containers in an experimental rig intended to simulate the heat of a vehicle fire as well as testing LPG filled containers in vehicles that were set alight. Control measures to reduce the likelihood of containers rupturing in fire situations were also investigated.

Whilst this report and investigation concentrated on the BLEVE potential by testing containers filled to capacity, other explosion sites and vehicles investigated where containers ruptured but did not BLEVE. While the explosion produced by a rupture is of a lesser magnitude than a BLEVE, such events can nevertheless create a hazardous situation and can result in major physical damage.

This report contains the findings of the test program and provides recommendations to improve the safety of LPG fuel storage containers.

The reader is encouraged to view the DVD accompanying this report which shows some of the testing carried out.

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2 BACKGROUND

Energy*Safety* is the technical safety regulatory authority in Western Australia that has jurisdiction over the installation and maintenance aspects of LPG installations used in motor vehicles. The Department of Transport has jurisdiction over all other aspects of motor vehicles.

The LPG storage containers in vehicles are required to comply with certain Australian Standards, which specify, amongst other requirements, that the vessel shall be fitted with an appropriately sized Pressure Relief Valve (PRV). In the event of the fuel container being exposed to fire, the PRV is intended to vent sufficient product so as to avoid excessive pressure developing. However, Energy*Safety* has become aware of a number of instances where a vehicle has caught fire and the LPG storage container has ruptured, sometimes resulting in a BLEVE and the total destruction of the vehicle. These failures occur with sufficient violence as to become a safety issue for emergency services personnel and any bystanders.

In photograph 2.1 below, the vehicle was a late model wagon, fitted with an LPG container in the cargo area. The vehicle was “torched” in Redcliff outside of a child care centre, shown in the background. The container exploded with sufficient force that the roof of the vehicle was torn off and subsequently found approximately 100 metres away in a tree.

Photographs 2.2 and 2.3 show the outcomes of similar incidents.

Photograph 2.1 Incident in Redcliff

Photograph 2.2 Incident in Champion Lakes

Photograph 2.3 Incident involving a van

The frequency of incidents involving ruptured LPG containers under fire conditions is not known. However, it has been deemed to be sufficiently great to conduct an investigation based on the following:

1. Three reports were received by Energy*Safety* within a 13-month period between January 2008 and February 2009.
2. A report written by Stan Ambrose and commissioned by LPG Australia states that within a three year period (1993 to 1996), 40 LPG powered vehicles had exploded in intense fires.
3. FESA advises that, on average, they respond to 1500 vehicles fires in Western Australia annually. Reference 31 indicates that in the financial year 2005/06 the NSW Fire Service responded to approximately 4500 vehicle fires, with a peak in 2001/02 of 5500 vehicle fires.

From the above experience and similar reported incidents it is clearly the case that the fuel tank of an LPG vehicle has the potential to explode violently when exposed to fire, producing a blast, flying debris and a fireball (that can produce a further blast wave and presents a severe risk of burns to anyone in the near vicinity). Incidents of this type have occurred with vehicles where the installation and all components are believed to have complied with all relevant codes and standards, indicating that such compliance does not ensure protection from this type of event. Photographs showing the results of BLEVE's and vehicle fires are presented in Appendices A and B.

Other observations that should be considered are;

1. FESA indicates that there are approximately 1500 vehicle fires in Western Australia and 4500 to 5500 in NSW [31].
2. LPG vehicle conversions and LPG OEM sales have steadily increased in recent years and LPG fuelled vehicles may now represent as many as 10% of the vehicles on the road in Western Australia.

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3 ACRONYMS

ALARP:	As Low As Reasonably Practicable
AS:	Australian Standard
AFL:	Automatic Fill Limit Valve.
AS/NZS:	Australian/New Zealand Standard
BLEVE:	Boiling Liquid Expanding Vapour Explosion
CNG:	Compressed Natural Gas
DFT:	Dry Film Thickness
FESA:	Fire and Emergency Services Authority of WA
LPG:	Liquid Petroleum Gas
OEM:	Original Equipment Manufacturer
PRV:	Pressure Relief Valve
QRA	Quantitative Risk Assessment
SLT:	Superheat Limit Temperature
TSE:	Thermal Safety Element
VCE:	Vapour Cloud Explosion

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4 CURRENT DESIGN REQUIREMENTS

The Australian Standards used in the design of vehicle LPG containers are listed below:-

1. AS/NZS 1425:2007 LP Gas fuel systems for vehicle engines
2. AS/NZS 3509:2009 LP Gas fuel vessels for automotive use
3. AS 1210-1997 Pressure vessels
4. AS 2030.1-2009 Gas cylinders – General requirements
5. AS 2030.5-2009 Gas cylinders – Filling, inspection and testing of refillable cylinders
6. AS 2613-2005 Safety devices for gas cylinders

4.1 Container Design

AS/NZS 1425:2007 Clause 3.2.1 states:

> *A fuel container shall comply with one of the following Australian or Australian/New Zealand standards or in New Zealand, the Traffic Regulations 1976 amendment No. 7, Clause 80B, and shall have a design notified or registered by the appropriate Statutory Authority and subject to requirements in Clause 6.1(c)(ii):*
>
> *(a) AS/NZS 3509*
>
> *(b) AS 1210 (for a design pressure of 2.55 MPa).*
>
> *(c) AS 2030.1 (for propane).*

4.2 Maximum Permitted Fill Level

AS/NZS 1425:2007 Clause 1.5.28 specifies the maximum permitted fill level for LP Gas Containers. In Australia the maximum fill level is 80% of the total available internal volume of the container. In New Zealand, the maximum fill permitted is 85% of the total available internal volume.

4.3 Design Pressure

AS/NZS 1425:2007 Clause 2.1.2 states:

> *The design pressure for a component or any portion of a component that is subject to container pressure shall be 2.55 MPa.*

4.4 Materials

AS/NZS 1425:2007 Clause 2.5 states:

> *Aluminium alloys may be used for other components except piping and pipe fittings. Metallic materials having a melting point lower than 500°C shall not be used in any application where failure could result in gas escape.*

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4.5 Container Wall Thickness

The wall thickness of containers is typically designed to either to AS/NZS 3509:2009 or AS 1210-1997.

AS/NZS 3509:2009 clause 2.1.1 defines a maximum cylindrical stress of 67% of the Specified Minimum Yield Strength and 43% of the Specified Tensile Strength for carbon steels.

AS 1210-1997 clause 3.3 defines a maximum cylindrical stress of 67% of the Specified Minimum Yield Strength and 25% of the Specified Tensile Strength for carbon steel transportable vessels.

Table 2.1 in AS/NZS 3509:2009 Clause 2.1.1 specifies a minimum wall thickness of 1.75 mm (protected) or 2.2 mm (unprotected) for carbon steel containers.

4.6 Pressure Relief Valve

AS/NZS 1425:2007 Clause 3.15.1 Sates:

> *The safety valve shall comply with the following requirements:*
>
> *(a) The safety valve shall be internal.*
>
> *(b) The safety valve shall comply with the requirements appropriate to the type of container to which it is fitted, AS 2613 for a gas container or an automotive fuel container, or AS 1271 for a pressure vessel or be UL listed.*
>
> *(c) The design, manufacture and installation instructions shall comply with an ISO Product Certification Program Level 5 and is installed in accordance with Clause 6.7.*
>
> *(d) The full flow rating pressure shall be 3.3 MPa.*
>
> *NOTE: The start to discharge pressure is expressed as not less than 80% of the full flow rating pressure.*

AS/NZS 1425:2007 Clause 3.16 Sates:

> *(b) The safety valve shall communicate with the vapour space of the container, and no valve shall be installed between the safety valve and the container.*

AS 2613-2005 Clause 2.3 states:

> *The flow-rating pressure of a pressure-relief valve shall be not less than 1.25 times the maximum developed pressure of the contained gas, and shall not exceed the test pressure of the container.*

AS 2613-2005 Clause 2.4 states:

> *The start-to-discharge pressure of a pressure-relief valve shall be not less than 80% of the flow-rating pressure.*

4.6.1 PRV Specified Flow Capacity

There appears to be some variation in the PRV parameters depending on which standard the valve is designed to and some conflicts where multiple standards apply. Specifically, AS 1210 leads to a sizing method for the PRV which is a function of the container's area and the physical properties of the product contained. In contrast AS 2613 sizes the PRV solely on the basis of the container's volume. These formulae can give significantly different results, as shown in Appendix C.

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According to the formula given in AS 2613 Clause 2.2.5 the flow rate of free air for a non-insulated container of 89 litres internal capacity must be at least 8.16 m^3/min of free air. Using the sizing criteria specified in AS 1210-1997, the minimum required flow rate is 15.30 m^3/min of free air (for a vessel of typical area to volume ratio and this capacity containing propane). It is anticipated that the free air flow value would be higher if the vessel contained a mixture of propane and butane rather than commercial grade propane.

4.6.2 PRV Specified Set Pressure

AS/NZS 1425:2007 (Clause 3.15.1 (d)) requires the PRV to have a set pressure of not less than 2640 kPa-gauge, which is 90 kPa greater than the design pressure of the container. In contrast, AS 1210-1997 and AS 2030.5-2009 require the set pressure of the PRV (for a vessel containing LPG) to be 2550 kPa.

4.6.3 PRV Flow Rating Pressure

As stated above AS/NZS 1425:2007 specifies the flow rating pressure as 3300 kPa gauge

According to AS 2030.5-2009 the maximum developed pressure for LPG is 2550 kPa gauge (at 65°C) and therefore, in accordance with AS 2613-2005, 1.25 times the flow pressure rating is 3188 kPa-gauge.

AS 1210-1997 specifies the flow rating pressure as 121% of the set pressure; leading to a value of 3086 kPa gauge.

4.7 Sub-assembly

AS/NZS 1425:2007 Section 3.17.2 states:

> *(e) Materials of construction, including seals and gaskets, shall be such that the enclosure will remain gastight if exposed continuously to a temperature of 100°C.*

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5 THEORY OF BLEVE'S

There several mechanisms by which a vessel containing LPG (or other liquid) can fail if exposed to excessive heating.

Excessive Pressure

Failure of the vessel's PRV can result in pressurisation beyond the design pressure to the point where the vessel ruptures. In this case the failure may result from a vessel becoming liquid full due to the expansion of the contained product with heating and the extremely high pressures that can be expected to develop in these circumstances.

Excessive Temperature

A hot rupture may occur if a vessel is caught in a fire and the steel wall becomes so weakened due to heating that it fails even though the container pressure is within design specifications. If the vessel contains little or no liquid, this will typically result in rupture of the container with the steel showing considerable thinning at the edges of the failure point.

Boiling Liquid Expanding Vapour Explosion

A special case of the above hot rupture is when the vessel still contains a significantly large quantity of liquid and the rupture is sufficiently rapid in its formation that the vapour pressure above the liquid drops almost instantly to atmospheric. In this case, if the liquid is sufficiently hot (above its superheat limit – see Section 5.1 and Appendix D), a BLEVE can be expected to occur. In a BLEVE the superheated liquid vaporises with such rapidity that it produces a shock wave and can totally destroy the containment vessel and surrounding structures. If the liquid is flammable (as is the case with LPG) the escaping product is very likely to ignite and produce a VCE and fireball that further adds to the hazardous situation created by the BLEVE.

5.1 BLEVE Mechanism

The BLEVE phenomena is widely known and recognised for the potential hazards it creates [1-16]. It has been described as "... the worst possible outcome of a fire engulfed pressure vessel." [10]. The exact mechanism by which BLEVE's occur is still the subject of considerable debate and is considered in Appendix D.

It is, however, important to distinguish between a BLEVE and a rupture. While a BLEVE represents an extreme case of a rupture and is preceded by a smaller rupture in its development, it is possible for a vessel to rupture without producing a BLEVE. Such a failure as a rupture may occur if the vessel is almost empty by the time the wall temperature reaches the level at which the metal fails. In this case there may still be sufficient vapour (or gas) pressure to produce a sizeable blow out of the vessel but there is insufficient liquid (or none) to produce a BLEVE. A rupture (in the current context) typically results in a large hole in the vessel with considerable metal thinning at the edges. A BLEVE is characterised by the vessel being almost completely flattened or dismembered into several pieces. The edges along failure lines are generally not significantly thinned (except in the region of the precursor rupture), which reflects the extremely rapid propagation of the metal failure and results from the shock wave produced by the BLEVE.

While (non-BLEVE) ruptures have been observed on several occasions, in the present test series, vessels either BLEVE'd or remained fully intact at the completion of the test.

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5.2 Theory on Failure Mechanism with the Current Design

With the current design of containers, the failure theory under fire conditions progresses through the following stages:-

Increase in Temperature and Pressure

A motor vehicle fire can result in a high rate of heat release. Shipp and Spearpoint [17] report a heat the release rate of up to 7.5 MW and temperatures of 1250°C for passenger cars. In tests related to the current project (Section 7.3), vehicles were found to burn fiercely; even without any fuel (petrol or gas) being present and temperatures of over 900°C were recorded. Such conditions could easily provide sufficient heating to initiate venting from the vehicle fuel tank (which, as noted below, can further greatly enhance the fire) and lead to a vessel rupture and possibly a BLEVE. The consequences of such a fire are described immediately below. Photographs of burning motor vehicles are presented in Appendices A and B.

Flame engulfment and impingement causes the temperature of the contained liquid (lading) to rise, which results in its thermal expansion and the vapour pressure to increase. It also causes the temperature of the vessel walls to rise. As noted in Appendix D, this temperature rise is not uniform and wall sections that are “liquid wetted” show a much smaller temperature increase than “vapour wetted” areas, because of the much more efficient heat transfer in the former case [6, 10-12]. A recent report from Manu *et al* [11] shows the respective temperatures to be 130°C and 620-720°C for the liquid and vapour wetted areas.

The increased temperature of the lading causes the vessel to become “liquid full” if the initial fill was near the maximum (80% by volume in Australia) before the vapour pressure becomes sufficiently high to open the PRV (this can occur with propane and even more so with propane/butane blends that have a lower vapour pressure at a given temperature). It follows that if the PRV is defective and does not open, the high pressures developed by the liquid expansion can rupture the tank. Similarly, if the container does not reach liquid full, but the PRV either fails to open or does so but in a manner that vents at an insufficient rate, high internal pressures can build due to the greatly increased vapour pressure at elevated temperatures. This, combined with metal weakening caused by flame impingement, may lead to a rupture.

However, a more likely scenario of vessel rupture (and possibly a BLEVE) is that the PRV operates sufficiently well to maintain the pressure within specification limits and the vessel ruptures (and BLEVE’s) due to the weakening of the steel which results from the high wall temperature in the “vapour wetted” area. This type of failure was observed in the test series reported herein. Manu *et al* [11] show that increase wall temperature greatly reduces the time to failure. Time to failure is an important parameter, as if it is sufficiently long the PRV will have vented the majority (and perhaps virtually all) of the product before failure occurs, which would produce a weaker BLEVE if one occurred at all.

It may also be noted that even if, for instance, two different types of PRV both maintain the container pressure within acceptable pressure limits in a fire situation, it may not be the case that they will be equally effective in preventing BLEVE’s. This is considered immediately below.

Pressure Relief Valve Actuation

As the pressure within a fire engulfed container increases beyond the setting of a (functional) PRV, the valve will commence to discharge vapour and/or liquid. If the container does not become liquid full, the vapour pressure will reach the PRV set pressure at approximately 65°C, the exact figure depending on the composition of the LPG.

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If sized adequately, the PRV will control the pressure to within the required limits, less than 125% of the maximum developed pressure, or 3188 kPa-gauge in this case (the maximum developed pressure of propane being 2550 kPa-gauge). Valves usually cycle as a result of the closing pressure being lower than the opening pressure (blowdown). Also, when venting vapour the liquid is cooled by evaporative cooling, that is, the "refrigeration effect" of the required latent heat of vaporisation being withdrawn from the liquid. This in turn reduces the vapour pressure which may fall below the PRV's closing pressure. If the vessel remains exposed to the heat source the liquid temperature and consequent vapour pressure rises again and the cycle repeats. The frequency of cycling varies widely [5, 10, 12, 15, 18] and cases have been observed where the PRV did not cycle at all, but vented continuously [6]. It has been noted that PRV's that are ostensibly similar vary considerably in their performance characteristics [14]. However, in the present work, all PRV's maintained the vessel pressures below the specified container test pressure (3300 kPa-gauge) and also below 3188 kPa-gauge, being 125% of the maximum developed pressure, although, in some cases, they did not "pop" until pressures significantly higher than the "set pressure" of 2550 kPa-gauge was reached. Heating of the PRV as a result of flame engulfment or impingement typically results in more rapid venting through softening of the spring materials [10, 14] and, in some cases, the melting of plastic seats. PRV performance is considered in detail in Section 8 and Appendix C.

In a standard vehicle configuration, the propane tank's PRV vents into an aluminium sub-compartment and from there the vented LPG is intended to be carried to the outside via a plastic discharge duct. The sub-compartment typically also has plastic clips on the valve. In the event of fire engulfment, the plastic components (and subsequently the aluminium components) melt, which results in the discharge of LPG directly into the compartment housing the tank. This greatly enhances the already powerful flames burning the vehicle upholstery and other combustibles within the vehicle and may be expected to make a container rupture or BLEVE very likely.

Ambrose [15], while recognising that a non-metallic vent tube in this situation would melt and that the vented propane would add to the intensity of the fire near the container, nevertheless concluded, on the basis of prior testing, that this would not increase the risk of a BLEVE. In contrast, in the present work, it was found that unprotected containers that were filled to 80%, both in vehicles and when tested on the burner rig, BLEVE'd under these conditions in all cases tested while an unprotected container filled to 20% did not rupture. It is understood that in the work referenced by Ambrose the initial container fill was 60% (compared to the maximum permitted fill capacity of 80%, as was used in this investigation), something which is very likely to be the key to the different outcomes.

As noted earlier, PRV's with greater blowdown values have been found to delay vessel failure and so reduce the severity of a BLEVE incident [10, 14]. Similarly, Birk and Cunningham [3] report that "…it was also clear that BLEVE's were much more likely in tanks with higher PRV set pressures than those with lower set pressures." They also observe that "…if the PRV is set near or above the SLT, then the boiling response will push the event into a long-duration BLEVE…" for the containers considered in this report this is certainly the case. The PRV's nominal set pressure was 2550 kPa-gauge. For pure propane this corresponds to a temperature of approximately 71°C; well in excess of the atmospheric SLT for propane of 53°C [1, 3]. As noted earlier and may be seen in Section 8, the PRV's tested did not start to discharge significantly ("pop") until the indicated pressure has substantially exceeded 2550 kPa-gauge.

Also, two phase flow may occur through a PRV. This type of flow is complex [19] and may arise when the PRV inlet is in contact with the liquid. During such flow the mass discharge rate may be higher (giving rise to an increase in the fire intensity and radiance) and it also detracts from the evaporative cooling of the liquid inside the container, as the liquid droplets that are not vaporised within the vessel do not contribute to the loss of latent heat from the liquid.

In addition, with either liquid or two phase flow, there will be a lower exit velocity than with gaseous discharge. This will result in greater heat flux in the immediate vicinity of the container as shown in the accompanying video.

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Increase in Material Temperature on Top of Vessel

As noted above [6,10-12], the temperature around the "twelve o'clock" position of a fire engulfed vessel (which is largely, but not completely filled with liquid) quickly becomes much hotter than the liquid wetted area, this is due to the much more efficient heat transfer at the liquid/metal interface than at the corresponding vapour/metal boundary. At sufficiently high temperatures the metal will lose its integrity, even at internal pressures consistent with a properly functioning PRV. Such a failure constitutes a rupture and may be a precursor to a strong BLEVE. While data on the performance of steels in the relevant temperature range is difficult to find (due to their not being suitable for service under such conditions), Figure 5.1 shows typical deterioration of metal strength in the temperature range of 400 to 700˚C and is consistent with the trend reported by Birk and VanderSteen [18], as seen immediately below.

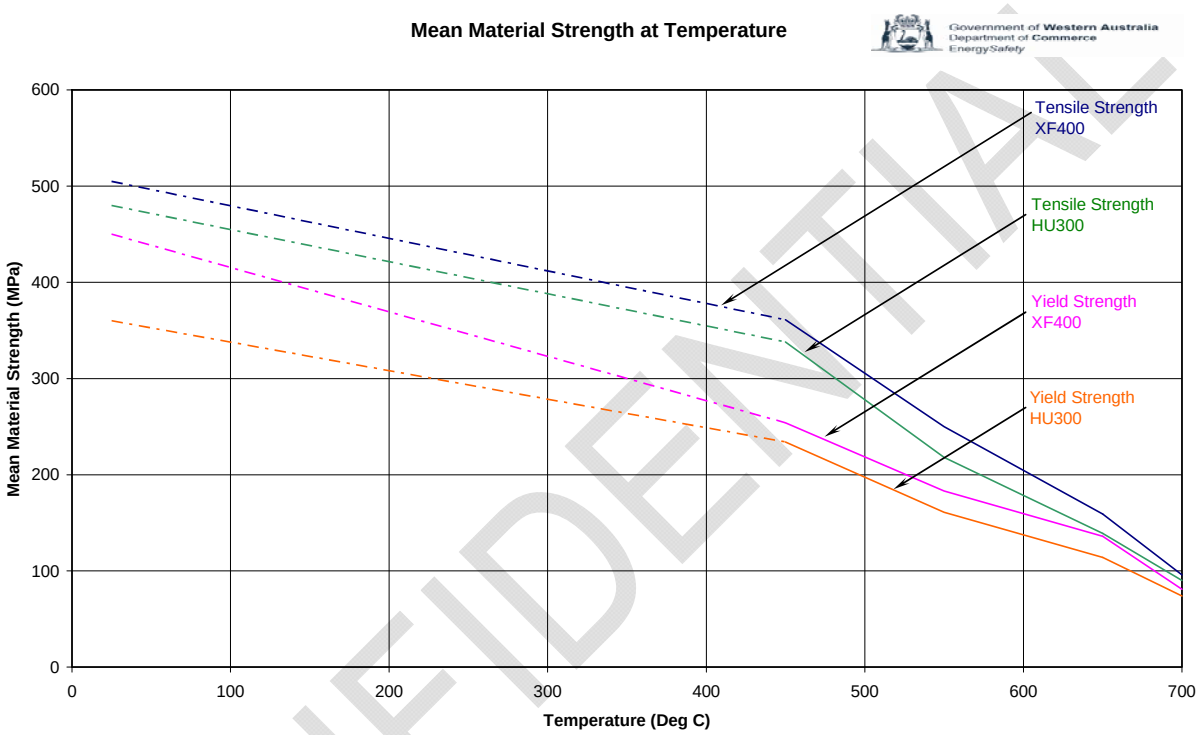

Figure 5.1 – Strength deterioration with increasing temperature of two steels

Material Stress beyond the Strength Limits

The decrease in material strength resulting from high temperature, in combination with the stress due to the internal vapour pressure of the contained liquid may cause a ductile failure of the container wall at pressures much lower than the container design and test pressures. The ductile, shear failure may be the result of a stress rupture where the tensile strength of the material is exceeded.

In a study centring on the survivability of 33.5 pound (15 kg) propane containers, Birk and VanderSteen [18] showed that the steel used in the container construction ("1025 steel", which is basically similar to steels used for this purpose in Australia) lost little of its ultimate tensile strength (UTS) when the temperature was raised from ambient (at which it was 380 MPa) to approximately 300°C. However, beyond that temperature the UTS falls off rapidly with rising temperature and is reduced to only half its ambient value at 600°C. They calculated that hoop stress in the containers (305 mm in diameter and 2.0 mm wall thickness) was 198 MPa at internal pressure 2600 kPa. At temperature 580°C the steel's UTS had fallen to this value (198 MPa). Manu *et al* [11] report in detail on the effects of high temperatures on steel properties and the relationship between temperature and time to vessel failure. Likewise, Susan *et al* [4] and Ambrose [15] also consider the loss of the steels strength at temperatures relevant to fire engulfment.

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It is notable that it is stated in the Handbook of Compressed Gases (Reference C8 in Appendix C) that *"Pressure relief valves are designed to maintain the pressure in the container at a level determined by the spring force. Therefore such devices do not protect the container against possible rupture when continued application of external heat or direct flame weakens the container wall to the point where its rupture pressure is less than the operating pressure of the relief valve."* The standard CGA S-1.1 – 2007 "Pressure Relief Device Standards Part 1-Containers for Compressed Gases" (Reference C6 in Appendix C) gives a similar warning in its Section 5.1 "General Requirements", and it is apparent that the flow rating requirements for PRV's (for use with liquefied gases, such as LPG) specified in AS 2613 are based on the CGA S-1.1 requirements.

The theoretical failure curves (Figure 5.2) show the plastic limit, where the stress exceeds the mean yield stress, and the stress rupture curve, where the stress exceeds the mean tensile strength of the material. These aspects are considered further in a metallurgical report provided by Altrum and presented in Appendix E.

Figure 5.2 – Container strength limits

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6 POSSIBLE CONTAINER PROTECTION METHODS

Possible methods to prevent container ruptures and BLEVE's are presented below. Not all of these protection methods were fully investigated as some were considered non-preferred due to their perceived impracticality.

6.1 Maximum Fill Level

Reducing the maximum fill level of the container reduces the possibility of a BLEVE. With a lower fill limit the container will hold less potential energy, discharge less fuel and de-pressurise more quickly. Also the discharge during the initial stage of the fire will tend to be of higher velocity vapour, rather than liquid or a two phase mixture of liquid and vapour. A two phase discharge produces a much more intense and radiant flame when ignited than is the case with an equivalent single phase vapour discharge. In tests reported below, a container filled to only 20% (Test 1) did not BLEVE while one filled to 80% (Test 2) in an equivalent test did BLEVE and also produce a VCE (photographs of these may be seen in Appendix A).

Reducing the allowable fill level was not further investigated as a protection method as it is not considered practical or likely to be acceptable.

6.2 Container Wall Thickness

Increasing the wall thickness will decrease the stress in the metal under otherwise equivalent conditions. This implies a higher failure temperature and therefore reduces the likelihood of vessel rupture.

This protection method was not fully investigated.

6.3 Container Construction Material

Construction materials that are less susceptible to tensile strength degradation when exposed to elevated temperatures could be considered. This solution would imply a higher failure temperature and therefore reduces the likelihood of vessel rupture at temperatures experienced during a fire. This protection method would involve the use of highly alloyed steels in place of the currently used steel. It was not further investigated because it was considered a non-preferred solution that would likely increase the cost of the containers for a number of reasons and still be only a marginal solution.

On the other hand, LPG cylinders made of composite material have come to prominence as an alternative to metal containers, and it is claimed [21-23] that it is highly unlikely if not impossible for such vessels to suffer a fire induced BLEVE.

6.4 Pressure Relief Valve Design

As noted in Section 5.2, decreasing the opening pressure of a PRV reduces the likelihood of a rupture or BLEVE and reduces the intensity of a BLEVE if one should occur. However, setting PRV's to lower opening pressure was considered impractical, as it would give rise to excessive venting on days when the ambient temperature was high.

Another possibility is to increase the size of the PRV to expedite the emptying of a vessel caught in a fire. This would require changes to existing standards and the increased venting rate may be expected to contribute to the fire which would intensify radiation heating the wall and increase the possibility of a rupture or BLEVE. This effect would be mitigated to a large extent by the employment of non-destructible components in the venting line, as noted in Section 6.6. The question of PRV requirements is considered in detail in Appendix C.

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An additional concern is that increasing PRV sizing beyond certain limits may, under some conditions, cause such rapid depressurisation that it contributes to, rather than prevents, a BLEVE.

These considerations also apply to Thermal Safety Elements (Section 6.8).

6.5 Pressure Relief Valve Vapour Pickup Tube

With the current 80% fill limit, heating of the product (as can happen on a hot day and much more so in the event of a vehicle fire) may cause the liquid to thermally expand so that it submerges the PRV intake. This will cause the PRV to vent liquid and/or a two phase mixture in the event of it activating. As discussed above, this may contribute to the an increase in fire intensity, reduce the "refrigeration" effects of flashing liquid within the vessel and the discharge of fluid at a low velocity, further increasing the heat flux on the container. All of these consequences can contribute to conditions that may lead to a rupture or BLEVE.

A vapour pick-up tube would largely overcome the two phase flow phenomenon noted above and promote the transfer of single phase vapour to the valve. However, testing described below indicated that it was unlikely to make a significant contribution to averting a BLEVE, if it were the only control applied.

6.6 Sub-compartment and Duct Manufacture

The current materials of construction of the sub-compartment cover and ducting are, respectively, aluminium and plastic. These materials readily melt at the heat generated by a vehicle fire. This results in the venting of LPG in the direct proximity of the container and the consequent compounding of the heat load on the container – a condition that promotes a rupture or BLEVE.

Changing the material of construction of these components to steel would allow the vented LPG to be conducted away from the vessel and so reduce the effect of the burning LPG discharge on the vessel's heat flux. This measure is considered very beneficial when used in conjunction with other control measures, as discussed in Section 8.4.

6.7 Container Insulation

Increasing the thermal resistance of the vessel's walls is recognised as a highly effective way of reducing the possibility of a BLEVE or its severity should a BLEVE occur [14-16, 24]. The function of the insulation is to maintain the vessel's wall temperature at a lower value than would be the case in its absence. Thermal insulation can be achieved through several methods, as described immediately below.

6.7.1 Shielding

A steel shield will reduce heat transfer onto the container wall and therefore the metal temperature. This method was demonstrated in preliminary tests with vessels containing water and subsequently proved effective in preventing BLEVE's in "live" Tests 8 and 12 (Section 7.2.4, 8.5.1 and Appendix A).

6.7.2 Intumescent Paint

Intumescent paint (once activated by exposure to sufficiently intense heating) is also effective in reducing heat transfer onto the container wall. This method was demonstrated in preliminary tests with vessels containing water and subsequently proved effective in preventing BLEVE's in "live" tests No's 4, 5, 6, 7 and 9 (Section 7.2.4, 8.5.2 and Appendix A).

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6.7.3 Fire Blanket

A fire blanket with a low heat transfer coefficient will act as an insulation barrier. The method was not further evaluated in the present work, but may be an avenue for manufacturers to achieve improved rupture/BLEVE protection.

6.8 Thermal Safety Elements

A fusible plug, in addition to a PRV, would rapidly reduce the pressure in the container by activating once its pre-determined temperature was reached. However, such rapid de-pressurisation may cause, rather than prevent, a BLEVE. Further, the large quantity of rapidly released LPG would, as a minimum, create a conflagration and possibly a vapour cloud explosion. Further, a scenario in which the discharged LPG failed to immediately catch alight would be potentially even more hazardous than one in which it did instantly catch fire, as the latter situation would be likely to involve a widespread inferno if and when the (denser than air) vapour ignited (as it likely would).

It is clear that before thermal safety elements could be implemented further consideration would need to be given to the set temperature and orifice sizing as well as the numerous issues noted here.

Further disadvantages of the Thermal Safety Elements are:

1) They add to the number of openings in the container and thus leak points.
2) They are subjected to high summer temperatures that are potentially close to the trigger temperatures.

6.9 Other Possible Design Features

Fauske [25] has pointed to the possibility of constructing tanks with an inner, incomplete, thin shell annuli to ensure that, in the event of fire exposure the vessel's outer shell is internally liquid wetted (and so kept relatively cool) by the circulation created between the annuli and the outer wall. This is not seen as a viable approach for relatively small vessels such as vehicle fuel containers.

Fauske has also suggested combined vapour/liquid venting valves [26] as a measure to largely eliminate the possibility of a BLEVE occurring. This would involve the simultaneous discharging of vapour from one valve and liquid from another port, resulting in more rapid emptying of the container. The implementation of this design would inevitably involve greater complexity and cost and, as with 6.8 immediately above, would result in an intense conflagration as the discharging liquid burnt.

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7 DESCRIPTION OF TEST METHOD

The test methods and outcomes are described below; these include preliminary heat transfer tests to evaluate the effect of shielding and intumescent paint, burning of motor vehicles without fuel being preset (either petrol or LPG), and "live" testing of containers containing propane under both simulated and actual vehicle fire conditions.

7.1 Initial Heat Transfer Determination

Prior to carrying out the "live" tests (that is, with propane filled vessels) tests were conducted to test the effect of shielding and intumescent paint in reducing the heat transfer into a partially flame engulfed vessel (which was constructed to be of similar dimensions and to simulate an LPG vehicle fuel container). Comparisons of heat absorption rates were made at different firing rates with the simulated containers unprotected, shielded with a mild steel cover and painted with intumescent paint. In order to perform these tests an experimental burner rig was constructed. A strengthened version of this rig was used subsequently in the live testing.

7.1.1 Heat Transfer Test Rig

The test rig consisted of a metal table on which two rows of three sets of propane fired duck bill burners were set. Each burner consisted of 18 individual "duck bills". See the photograph at the end of this Section. In these tests, water was flowed through the containers at a known rate and the inlet and outlet temperatures were recorded. The propane (used to fire the burners) was supplied from a bank of four 45 kg cylinders and metered through a suitably sized (100 litre/revolution) test meter. Gas pressures (electronic and "U" gauge manometers) and temperatures (various thermocouples and thermometers) were recorded to establish the gas rate. The water flow rate was measured using a previously calibrated variable flow meter, (rotameter) and this reading was checked against a domestic water meter. The above procedures were carried out in a similar principle to that detailed in Australian Standard AS 4552-2005 "Water Heaters". However, the instruments were not calibrated to the level required in such standards or by the National Association of Testing Authorities (NATA), for accreditation and reliance was placed on flow meters for the determination quantity of water passed. A high level of accuracy was not required in determining the gas flow rate here or in the work described in Section 7.2 below.

In these tests, comparisons were made where two heat input rates were used: initially approximately 400 MJ/h (110 kW) subsequently this was increased to approximately1150 MJ/h (320 kW). The simulating containers were constructed of mild steel (3 mm thickness) and of approximate dimensions 375 mm diameter by 800 mm long. The combinations were:

1. unprotected,
2. protected by a 1.5 mm mild steel shield set approximately 15 mm from the container that covered the entire flame impinged area and
3. painted with Contego intumescent paint (in accordance with the maker's recommendations for structural steel [27]). Water flowed through the simulated container at a known steady rate during the test, and the inlet and outlet temperatures were recorded using K type thermocouples inserted into the stream through glands.

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In conducting the tests it was found that the intumescent paint did not become sufficiently hot to activate (intumesce) with the low heat rate. This is attributed to the low temperature gradient through the steel wall resulting in the paint surface remaining relatively cool despite the impingement of flame gases. It suggests that there must be a large temperature gradient in the boundary gas layer close to the surface of the painted steel. In this inactivated condition, the paint had little effect on the heat absorption rate. In order to overcome this, the water was removed from the simulating container and the burners fired. This caused the paint to activate, and the simulated container was used in this condition in subsequent tests at low and high heat rates.

The photographs below show a low thermal input test with the steel shield in place, and a painted container in its pre-test condition.

Photograph 7.1 - Heat transfer test with shield (left) and cylinder painted with intumescent paint (right)

7.1.2 Heat Transfer Results

The results obtained in terms of heat absorption are given in Table 7.1 below:

Table 7.1 – Percentage of Heat Absorbed

Protection	Low Heat Rate (400 MJ/hr)	High Heat Rate (1150 MJ/h)
None	10.8%	
Steel Shield	4.3%	
Inactivated Paint	11.9%	
Activated Paint	5.0%	3.1%

The results, which are averages of tests conducted at different water flow rates, show that both shielding and (activated) intumescent paint substantially reduced the rate of heat absorption.

However, subsequent “live” testing indicated that caution should be exercised in extrapolating these results to actual vehicle fires, especially when LPG is vented from the container’s PRV and starts to burn. In such cases, the heat generation, the thermal radiation and level of flame engulfment of the container is much greater than in the rig tests.

7.2 Live Testing

Following the heat transfer tests, live testing was carried out using vehicle containers from two manufacturers (APA Manufacturing Pty Ltd and Manchester Tank & Equipment Company Australia) containing commercial propane LPG, which is suitable as “autogas” used for fuelling vehicles. Eleven live tests of containers were carried out, comprising six in a burner rig (a modified version of the one described in Section 7.1 above) and five vehicle fires. As such tests are hazardous with the likelihood of BLEVE’s and Vapour Cloud Explosions (VCE’s) it was necessary to carry them out in a remote location with safety provisions for personnel. The test conditions and results are detailed in Section 8 and further described with photographs in Appendix A.

7.2.1 Location and Safety

The tests were carried out between mid September 2009 and early November 2009 in a disused site in Hanson Construction Materials’ Hearne Hill Quarry, off Toodyay Road, Red Hill, Western Australia. Photograph 7.2 shows the location from above and at ground level. The tests consisted of placing the container under tests on a burner rig (described below) set inside a disused and modified sea container (the Test Container) with multiple (100 x 100 mm) holes cut in the sides and top to allow for aeration, escape of heat and explosion venting. The photograph below shows the Test Container being moved into place. Viewing was from another sea container (the Observation Container) some 100 metres away, which was equipped with 32 mm polycarbonate viewing ports (see photograph below). Members of the Fire and Emergency Service (FESA) attended each test and were equipped with fire fighting appliances.

Photograph 7.2 - Views of the test site and the Test and Observation Containers.

7.2.2 Test Rig and Instrumentation

A test rig very similar to the one described in Section 7.1.1 above was used. It differed only in that it was of heavier construction and included uprights to allow the placement of a cover over the container under test to ensure more complete flame engulfment than might otherwise occur. Photographs in Appendix A show typical test rig arrangements. In all cases the burners were operated at approximately 1200 MJ/h (333 kW), which is similar to the "high heat" tests of Section 7.1. The propane gas was fed to the burners from a bank of four 45 kg LPG cylinders located on the far side of the Observation Container via a 40 mm PVC line. The metering and pressure measurement arrangements were similar to those described in Section 7.1. Ambient temperature, the accuracy of which was not critical, was measured by various thermometers.

The rig's heat output was intended to produce an incident heat flux of approximately 250 kW/m^2 on the container under test. This is lower than some reported values for vehicle fires in the literature (over 400 kW/m^2 [28]) and suggests that the rate of heating of a container may be higher in a car fire than was the case in the rig. Nevertheless, once the PRV opens the heat flux generated by the burning propane that is discharged far exceeds that of the initiating fires. This is particularly the case when liquid and/or two phase discharge occurs.

The burner rig had the advantage of greater control (fewer variables) than a vehicle fire as demonstrated in the consistent pressure increase slope and hence heating rate of the LPG contained in the container under test (Figures 8.1 and 8.2). A distinct disadvantage of the rig was the high cost and time delay of rebuilding it in the cases when a BLEVE occurred (and completely destroyed the burners and related equipment).

The rig was equipped with a pilot burner, and an ON/OFF solenoid permitted the main gas to be switched from the Observation Container. Numerous trials were carried out to ensure that the main burner could be safely lit and remotely operated before live testing commenced. This ensured that all personnel were safely located before the main burners came on and applied heat to the container under test.

In the vehicle fire tests FESA personnel used a small quantity (in the order of two litres) of an accelerant (a mixture of petrol and diesel fuel) to start the fire. They then quickly retreated to the Observation Container. In some cases additional fuel load (not exceeding 50 kg) was added to the vehicle in the form of paper, cardboard and/or wood. The vehicles' petrol tanks had been emptied prior to delivery to the site. Descriptions of the tests and photographs are given in Appendix A.

Monitoring instrumentation consisted of recording the container internal pressure (using a Gems 4-20 mA pressure transducer and Fourier DAQPro digital data logger) and, in some cases, vapour wetted metal temperature (type K thermocouples welded or held by strong magnets to the container wall). Unfortunately, for various reasons, these instruments did not function reliably in all cases. The tests were recorded with video cameras at various locations, viewed through a mirror in order to protect the camera from flying debris. In Test 2 a high speed camera (300 frames per second) was available and successfully captured the developing bulge on the container top that preceded its rupture and BLEVE. A photograph of this is given under Test 2, Appendix A.

Furthermore, temperature measurements represent only one point on the metal surface. It might be expected that the inevitably chaotic behaviour of the flames surrounding and impinging on the vessel would create spatial non-uniformities in surface temperatures at any given instant.

7.2.3 Container Fill Levels

With the sole exception of Test 1, all containers were with a mass of commercial propane that would occupy 80% of their internal volume (water capacity) at temperature 5°C. As the temperature was invariably considerably higher than 5°C, the actual volume occupied by the liquid at the commencement of testing would be somewhat greater than 80% of the internal volume. In the case of Test 1 the fill was to 20%.

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7.2.4 Container Protection Methods Trialled

The following container protections were trialled in various combinations. Note that Test 10 does not appear in the summary or descriptions, as it was test of a domestic 45 kg container and the results are reported elsewhere [29]. The details of the containers are summarised in Section 7.2.5.

No protection

In this case the container was tested as it would currently be installed in a vehicle. The containers' sub-compartment cover was made of aluminium and the vent line was plastic (or, in one case, not used at all, as it is was known from a previous test that these melt early in a fire). The consequences of this configuration are that the aluminium cover and plastic vent fail and the burning, vented LPG greatly adds to the intensity of the fire. Similarly, there was no thermal insulation barrier or internal pick-up tube in these tests. This was the case in Tests 1, 2 and 11.

Steel Sub-compartment Cover and Ducting

In Tests (3, 4, 5, 8, 9, 12) the aluminium sub-compartment cover was replaced with one made of 3.0 mm thick steel and the plastic vent duct was replaced with one of equivalent size (approximately 50 mm internal diameter) but made of corrugated stainless steel hose. These tests were intended to determine if replacing the original sub-compartment and vent with non-destructible versions provided some advantage. This technique was used in Test 3 and in other tests in combination with other protection measures.

Steel Shield

Enclosing the container within a steel shield of 1.6 mm thickness and extending from the floor of the compartment towards the vehicle roof extending about 200 mm above the container but not covering the top of the container (Tests 8 and 12). Photographs showing various aspects the shields (and stainless steel ducting) are presented in Appendix A.

Intumescent Paint

Contego Intumescent paint was applied as a measure to prevent container ruptures. The required thickness for structural steel is 1.8 mm dry [27]. However, in Tests 4 and 5 on 16-10-09 the paint was incorrectly applied and the thickness is estimated to have been only in the order of 0.5 mm. In the other tests where it was used (Tests 6, 7 and 9) it was correctly applied.

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7.2.5 Container Construction Details

The containers provided by Manchester Tank and APA Manufacturing were constructed to the parameters given in Table 7.2:

Table 7.2 – Container Construction Details

Parameter	Manchester Tank	APA Manufacturing
Design Standard	AS/NZS 3509	AS/NZS 3509
Shell Thickness	2.7mm	2.8mm
Shell Material	AS 1594 XF400	AS 1594 XF400
Specified Yield Strength	380MPa	380MPa
Specified Tensile Strength	460MPa	460MPa
Hoop Stress (at 2550kPa)	176MPa	169MPa
Outside Diameter	375mm	375mm
Internal Volume	89 litres	89 litres

A drawing of the Manchester container is provided in Appendix F

7.2.6 Relief Valve Design

The PRV's provided with the Manchester Tank and APA Manufacturing containers had the parameters shown in Table 7.3:

Table 7.3 – PRV Design Details

Parameter	Manchester Tank	APA Manufacturing
Manufacturer	SCG Thailand	SVM Thailand
Model	7545K	SVM 635
Set Pressure	2550kPa	375psi (2586kPa)
Flow Capacity	13.6m^3/min (air)	12.4m^3/min (air)
Pressure at Flow Capacity	3300kPa	460psi (3172kPa)

It should be noted that these were the types of valves supplied and fitted in the containers on this occasion. It is understood to be the case that different makes of PRV's may be fitted by either manufacturer.

Drawings of the PRV's are given in Appendix F.

7.3 Vehicle Burning Tests

Two vehicles were set alight at the FESA Forrestfield test centre. The purpose of these tests was for Energy*Safety* personnel to gain an appreciation of the intensity of a vehicle fire. A thermocouple was set in the proximity of where the gas tank would be located in an LPG vehicle and measurements of up to 925°C were recorded. However, this recording is only approximate as the thermocouple was not certified nor was it radiation shielded.

The cars were set alight by FESA personnel using 2 to 3 litres of accelerant, as described above. In both cases the petrol tanks had been emptied prior to testing and the fires were therefore fuelled by the vehicles' interior, body parts and tyres. Photographs of the cars are given in Appendix B.

8 TEST FINDINGS

A total of 11 automotive containers where tested from the 21st September to the 5th November 2009 and the results are summarised in Table 8.1. Pressure and temperature profiles of the containers (where valid data was obtained) are also given, as is a description of the various BLEVE mitigation techniques. It may be noted that the results from Test 7 have not been included as the pressure instrument line burst and the electrical connections to the recording equipment melted, giving spurious results. Test 10 has been omitted from the results below as it was a residential 45 kg upright container and is therefore outside the scope of this report.

In these tests, where vehicles were burnt, their petrol tanks had been fully drained prior to the testing

Table 8.1 below summarises the results and a description of the tests by container, with photographs in some cases given in Appendix A. Figures 8.1 and 8.2 show the pressure profiles on a long and reduced time scale, while Figure 8.3 shows the temperature profiles. Figure 8.4 shows the pressure – temperature profile and material strength limits, from which it is theoretically possible to predict whether a rupture will occur. It is seen that the profile of container 11 crossed the “failure boundary” and did, in fact, suffer a BLEVE approximately 64 seconds later.

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Table 8.1 – Summary of Test Results

Test	Date	Fill %	Heat Input	Manufacturer	Sub-Compartment	Duct Construction	Pickup Tube	Intumescent Paint	Shielding	BLEVE
1	21/09/09	20%	1200 MJ/hr	APA	Aluminium	Plastic	No	No	No	No
2	21/09/09	80%	1200 MJ/hr	APA	Aluminium	Plastic	No	No	No	Yes
3	01/10/09	80%	1200 MJ/hr	APA	Manufactured Steel	Stainless Steel	No	No	No	Yes
4	16/10/09	80%	1200 MJ/hr	Manchester	Manufactured Steel	Stainless Steel	Yes	Yes*	No	No
5	16/10/09	80%	1200 MJ/hr	Manchester	Manufactured Steel	Stainless Steel	No	Yes*	No	No
6	26/10/09	80%	1200 MJ/hr	APA	Aluminium	Not Fitted	No	Yes	No	No
7	26/10/09	80%	Vehicle Fire	APA	Aluminium	Not Fitted	No	Yes	No	No**
8	26/10/09	80%	Vehicle Fire	Manchester	Manufactured Steel	Stainless Steel	Yes	No	Yes	No
9	04/11/09	80%	Vehicle Fire	Manchester	Manufactured Steel	Stainless Steel	No	Yes	No	No
11	04/11/09	80%	Vehicle Fire	Manchester	Not Fitted	Not Fitted	No	No	No	Yes
12	05/11/09	80%	Vehicle Fire	APA	Manufactured Steel	Stainless Steel	No	No	Yes	No

* On containers 4 and 5 the intumescent paint was not applied to the full specified thickness.

** The pressure sensing line burst on container 7 rapidly decreasing the internal pressure.

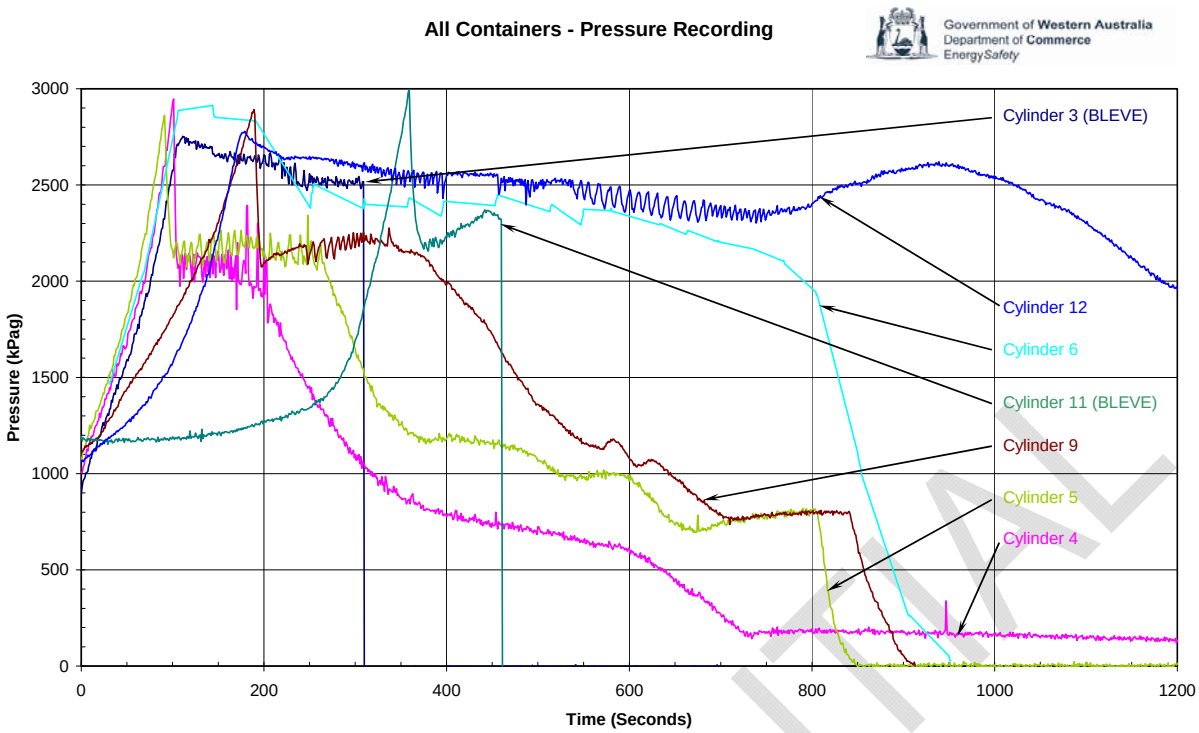

Figure 8.1 – Pressure profile over 1200 seconds

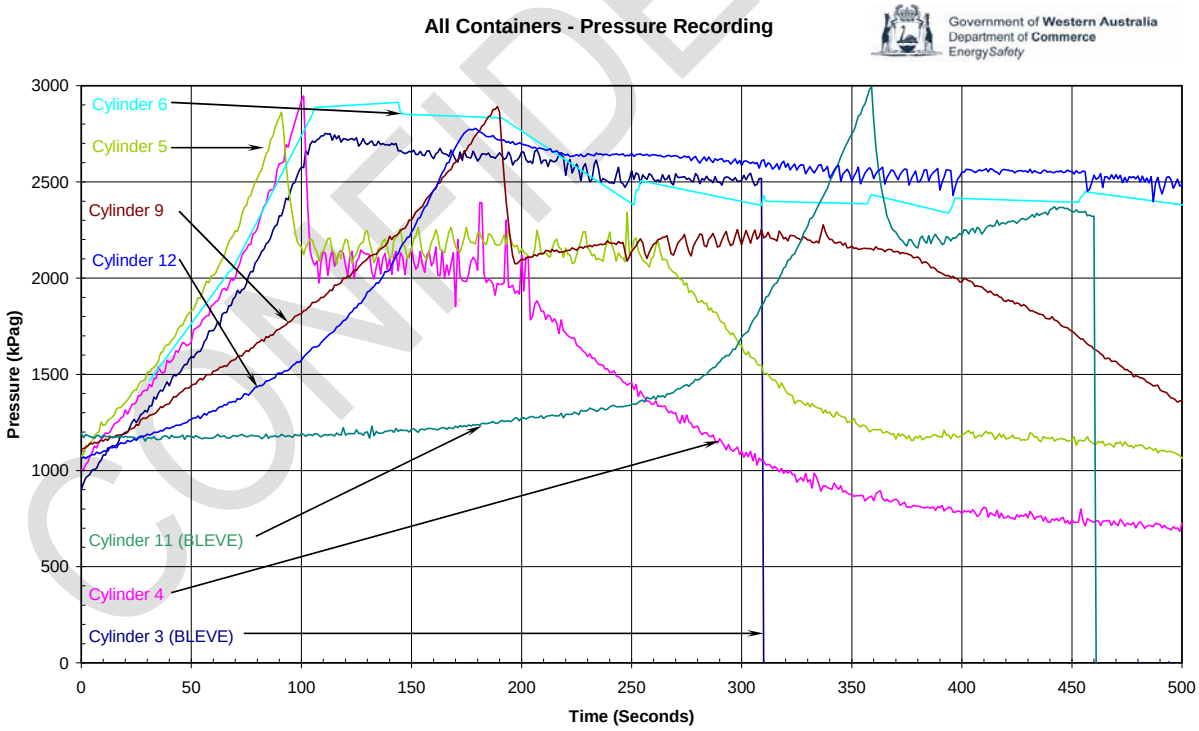

Figure 8.2 – Pressure profile over 500 seconds

Note: The Design Pressure of the containers and the Set Pressure of the PRV's is 2550 kPa-gauge.

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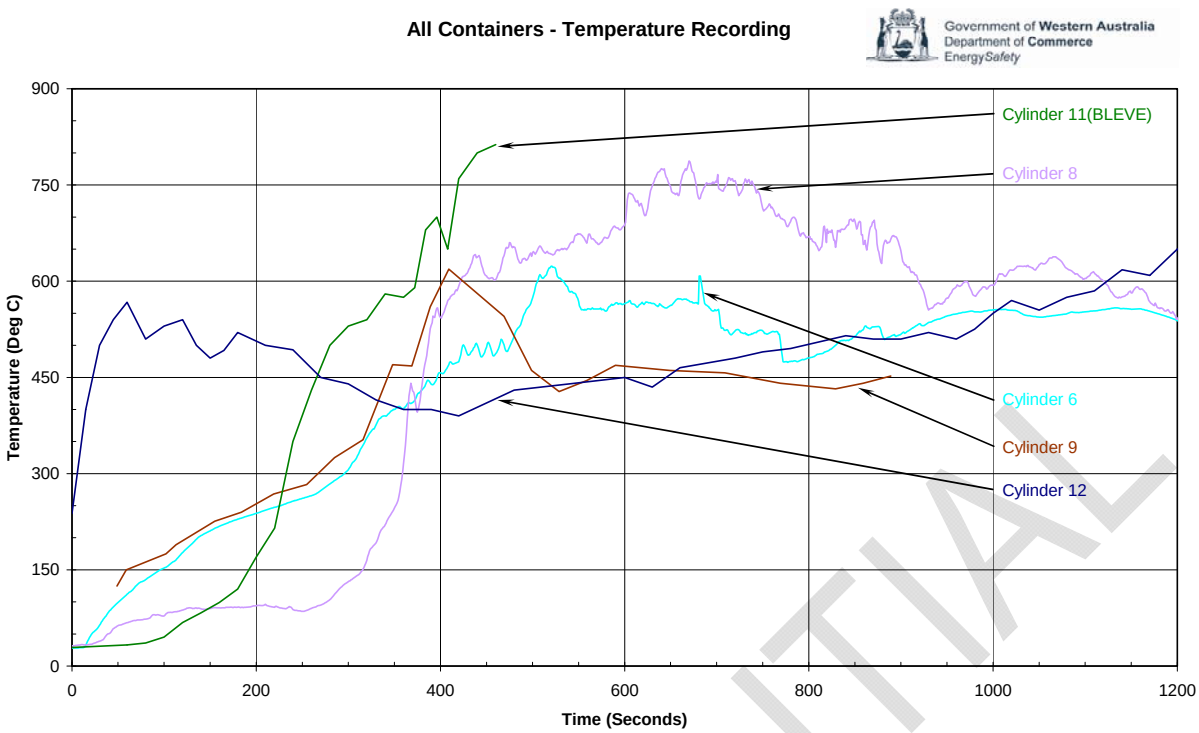

Figure 8.3 – Temperature profile over 1200 seconds

Note: If the container held an internal pressure of 2550 kPa-gauge, the mean tensile strength of the material will be exceeded if the temperature reaches 630^{0}C.

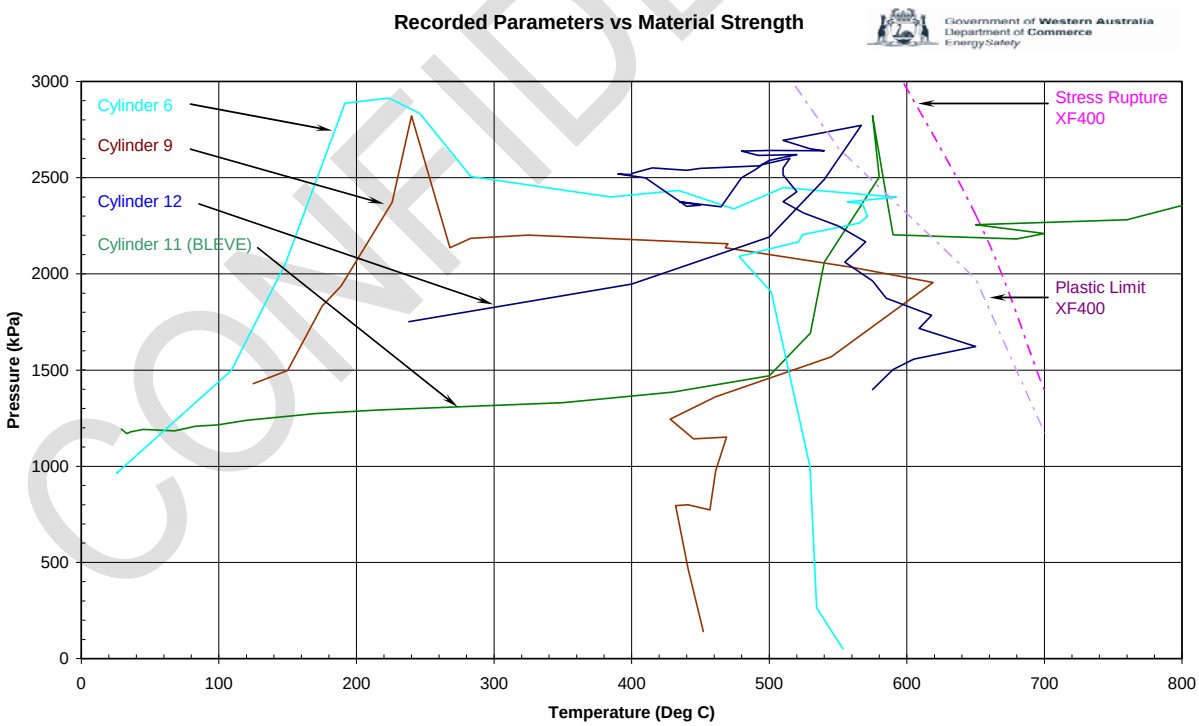

Figure 8.4 – Pressure – temperature profile and material strength limits

Note: Container 11 failed approximately 64 seconds after exceeding the material tensile strength.

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8.1 Fill Level

Test 1, in which the container was filled to 20%, with no other controls did not rupture, nor show any signs of distortion. Container 2, tested under the same conditions and heat rate with an 80% fill level ruptured and created a BLEVE.

Further testing to determine the threshold value for a fill level which will produce a BLEVE was not conducted. It is estimated that fill levels between 60 and 80% are required to lead to ruptures and BLEVE's

8.2 Pressure Relief Valve Design

The two types of containers tested (APA and Manchester) were fitted with different makes of PRV. In the tests these valves proved to have different characteristics (as well as some commonality) as can be seen below:

1. Inspection of figures showing pressure profiles (Figure 8.1, 8.2 or 8.5) indicate that both designs of PRV began to relieve (popped) at 2750 to 3000 kPa-gauge. This is higher than the designated set pressures (of 2550 and 2586 kPa-gauge respectively for the Manchester and APA PRV), as shown in Table 7.3.
2. Both designs had sufficient capacity to relieve pressure under the test condition.
3. With the exception of early "spikes", the PRV used on the Manchester container generally controlled the pressure on average at 2100 to 2300 kPa-gauge during the active phase – that is before it commenced a sustained fall in pressure.
4. The PRV used on the APA containers controlled the corresponding pressure at a somewhat higher level (average at 2400 to 2600 kPa-gauge).
5. The Manchester PRV cycled for 100 to 200 seconds before a significant drop in container pressure.
6. The APA PRV cycled for 500 to 800 seconds before a significant drop in container pressure

Figure 8.5 shows the pressure profiles in terms of the PRV's used in the two makes of containers tested.

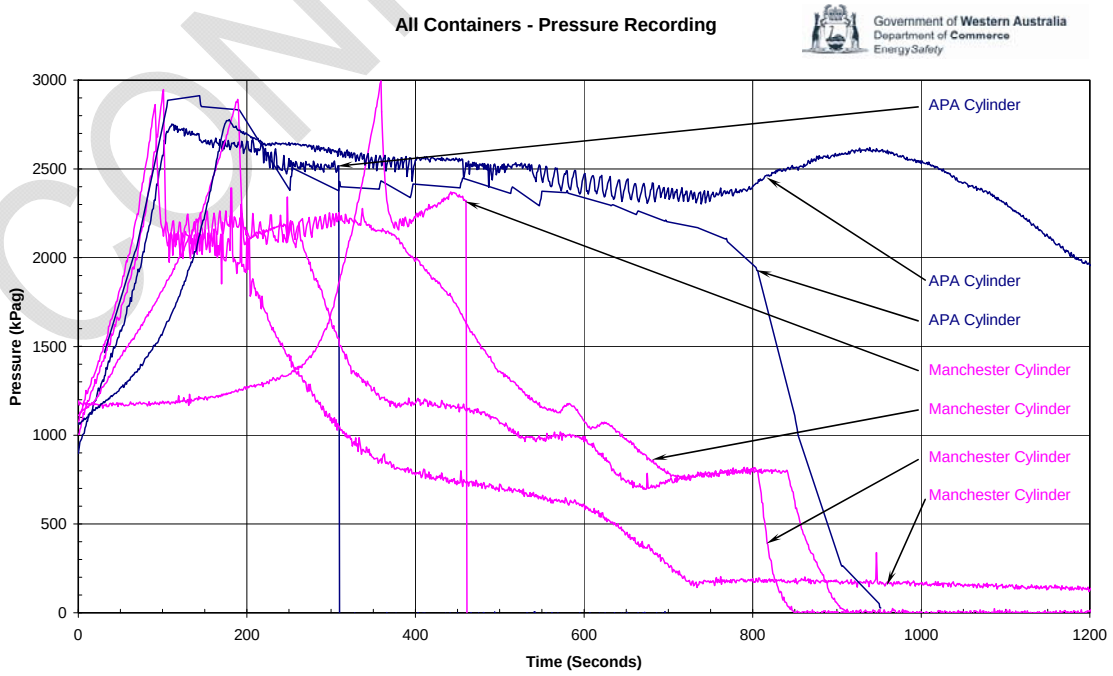

Figure 8.5 – Pressure profile relating to PRV design

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8.3 Pressure Relief Valve Vapour Pickup Tube

In Tests 4 and 8 the containers were tested with vapour pick-up tubes on the inlet to the PRV. The intention of these was to limit the intake of liquid and/or two phase "liquid swell". Tests with containers 4 and 5 provided a direct comparison between the presence and absence of a pick-up tube. However, in neither case did the container BLEVE. It is to be noted that the containers were painted with intumescent paint in both cases (though, not to the specified thickness, as stated in Sections 7.2.4. and 8.5.2.

There did appear to be some difference in the internal pressure profiles between the containers in Tests 4 and 5, shown below, suggesting that the effect of the pick-up tube was essentially beneficial, though not by itself capable of preventing a BLEVE. Figure 8.6 shows the pressure profiles in terms of the presence or absence of a pick-up, with all other variables constant.

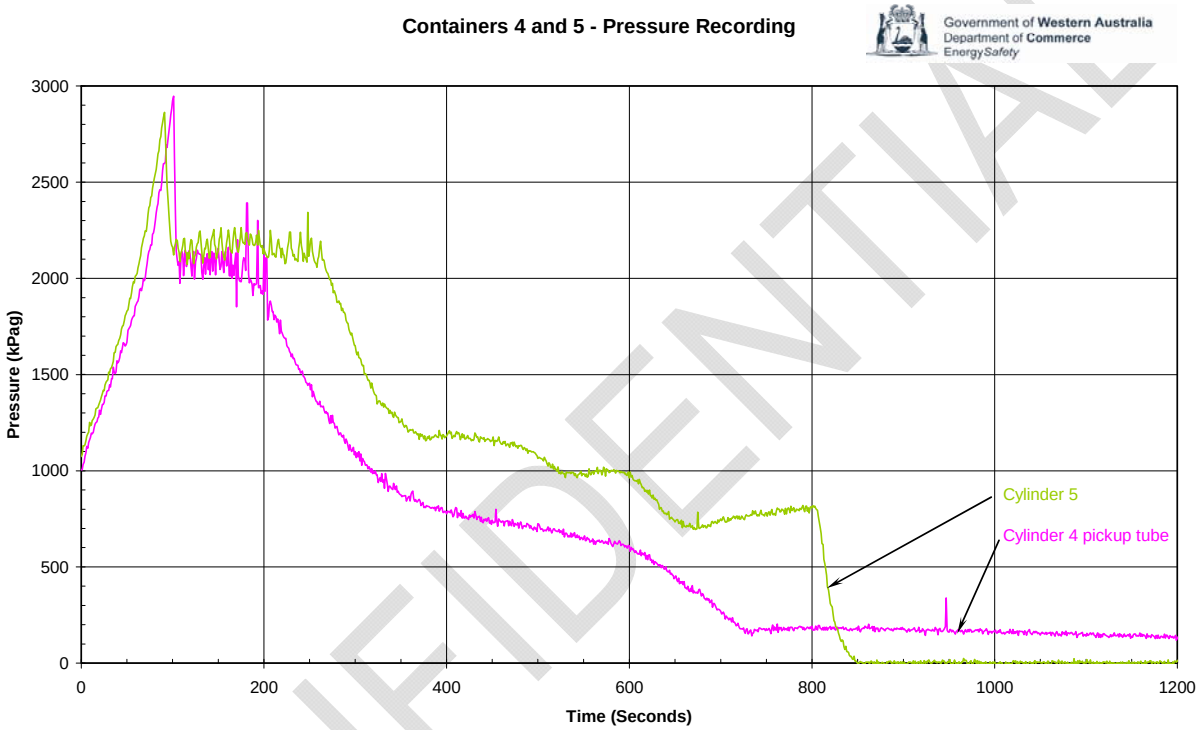

Figure 8.6 – Pressure profile with the variable of a pick-up tube

It was noted that the PRV, when discharging liquid or a two phase mixture of vapour and liquid, produced a distinctly different noise compared to the sound from discharging single phase vapour. The two phase flow was characterised by a definite "whine" that was not present with single phase discharge. Also, the PRV cycling tended to be more rapid when the discharge was single phase vapour, with the most probable cause of this being the reduced rate of heat exposure (of the container) from the escaping, burning, vapour compared with the case of two phase discharge that greatly adds to the heat flux experienced by the container.

When a container PRV vented liquid or a two phase mixture (vapour and liquid) the mass ejection rate was greater, though the exit velocity lower. When alight, this resulted in powerful and highly radiating flames that greatly contributed to the increased temperature of the container wall and, in some cases, its subsequent failure. This can be seen in the photographs of Tests 7 and 8 in Appendix A and the accompanying video.

The fitment of a pick-up tube, intended to limit the entry of liquid or two phase mixture into the PRV, appeared to give rise to a less intense and radiant flame when the discharged LPG was on fire. However, in contrasting tests (pick-up tube present and not present) the outcome was the same: a BLEVE did not occur. In both cases the containers had the confounding effect that they were painted with intumescent paint, and that is considered the primary reason that failures did not occur.

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8.4 Sub-compartment and Duct Manufacture

In Tests 3, 4, 5, 8, 9 and 12 the containers were tested using a fabricated steel valve box with a bolted lid in place of the aluminium sub-compartment cover. Also corrugated (flexible) stainless steel ducting was substituted for the plastic vent hose. The stainless steel vent line was of approximately the same internal diameter (50 mm) as the plastic one it replaced. The purpose was to make the sub-compartment cover and vent pipe capable of withstanding the heat generated in a vehicle fire.

Tests 2 and 3 were intended to provide a direct comparison between the standard aluminium sub-compartment and plastic vent with the upgraded version (steel sub-compartment and a stainless steel vent) on the burner rig. In the standard configuration (Test 2) a BLEVE occurred, but there was some expectation that the modifications would prevent a repetition in Test 3. However this proved not to be the case and the container in Test 3 also BLEVE'd. Nevertheless, as seen below, in vehicle fires these modifications were considered to be highly advantageous. In Test 6, where a standard aluminium sub-compartment cover was used, the cover melted (as expected) and the venting high velocity vapour and/or two phase discharge from the PRV removed the protective intumescent paint in the vicinity of the PRV at the top of the container. However, in this case the container did not BLEVE, which appears to attest to the effectiveness of the intumescent paint, even when partially blasted off by the jetting action of the gas escaping from rubber seals that became defective (see photograph in Appendix A, Test 6). In tests where the containers had standard aluminium sub-compartment covers, video recordings show much increased heat from burning of the vapour/liquid discharged from the PRV. Where steel fabricated sub-compartments and stainless steel vent lines were substituted for the standard (destructible) versions, the steel maintained its integrity and the LPG was discharged to the outside of the burning vehicle, thereby greatly reducing the heat flux on the container.

Photographs in Appendix A Test 8 show the ducting in combination with shielding in a vehicle.

8.5 Container Insulation Techniques

In all six cases where the containers were insulated from the heat flux they did not rupture or show signs of mechanical distortion. Note that, as stated above, Test 7 is discounted due the failure of the pressure sense line and electrical connections.

Intumescent paint was effective in preventing ruptures and BLEVE's in all cases where it was tested. This is despite the fact that high container wall temperatures were recorded in some cases (though even higher temperatures were recorded with unprotected containers).

Metal shielding was also effective in preventing ruptures or BLEVE's of containers in vehicles, though, as with intumescent painted containers, relatively high wall temperatures were still recorded. The measured pressure and temperature values during Test 12 indicate that the container came close to the theoretical failure curves.

Anything that provides a substantial insulating barrier between the flames and the container wall and so reduces the rate at which the metal temperature rises should be effective in reducing the likelihood of a BLEVE. Techniques such as wrapping containers in suitably rated fire blankets were not trialled in this test series, but may nevertheless be viable.

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8.5.1 Shielding

Containers in Tests 8 and 12 were tested using shields to isolate the container from the heat of the vehicle fire. Both of these containers also had a fabricated steel valve sub-compartment and stainless steel duct.

The recorded temperature for the container in Test 8 was relatively high, showing almost 800°C, well above the anticipated 630°C limit given as the design internal pressure, close to the value recorded in Test 11 just prior to a BLEVE occurring. The difference in outcomes may be attributable to the fact that in Test 8 it took approximately 250 seconds for the container temperature to rise from 500 to 800°C, whereas in Test 11 the same increase was observed in container temperature in approximately 150 seconds. This time delay provided additional time for the relief valve to decrease the internal pressure of the container.

The recorded temperature for Test 12 was lower than Tests 8 and 11, mentioned immediately above. However, as can be seen from Figure 8.4, the container came close to exceeding the theoretical failure curves, though it did not fail.

Photographs showing the shielding as implemented appear in Appendix A, Test 8 and 12.

8.5.2 Intumescent Paint

In Tests 4, 5, 6 and 9 the containers were tested after being painted with Contego intumescent paint. It is significant that the thickness of the paint on containers used in Tests 4 and 5 was much thinner (estimated at 0.5 mm) than the manufacturer specifies for structural steel, which is 1.8 mm when dry (DFT) [27].

In Test 6, the intumescent paint was the only additional control measure when compared to test 2. In Test 6 the container did not rupture, while in Test 2 there was a powerful BLEVE. The temperature at the top of the container in Test 6 reached 600°C, some 500 seconds after commencement of the test. In comparison the Test 2 container 2 ruptured after 310 seconds. From this it appears evident that the intumescent paint reduced the heat transfer rate sufficiently to prevent a rupture. It is, of course, the case that delaying the metal temperature reaching its failure temperature will reduce the power of a BLEVE as a minimum and may prevent a BLEVE or even a rupture by allowing sufficient time for the container to be largely emptied of its contents.

Both in Test 6 and 9 the containers' pressure and temperature were recorded. In both cases the containers were at their highest pressure when the temperature was only 200 to 250°C. Both containers also came close to the theoretical failure curve when at about 600°C. Photographs in Appendix A, tests 4 and 6 show the activated intumescent paint.

In Test 7 the container was also painted with intumescent paint and did not rupture. However, as noted earlier, this test is discounted because the pressure sense line ruptured and acted as an unintended relief device.

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9 RISK ASSOCIATED WITH VEHICLE LPG CONTAINERS

It is an irrefutable and widely acknowledged fact that LPG containers have the potential to explode powerfully when the vehicle is caught in a fire. This makes LPG vehicles inherently more hazardous than their CNG, diesel or even petrol fuelled counterparts. This situation, which arises from the fundamental fact that LPG is stored as a pressurised liquid, makes it incumbent on those involved in the industry to seek measures to greatly reduce, if not completely eliminate, the possibility of such events.

Although the quantity of LPG involved in a motor vehicle container is small compared to large storage tanks and similar vessels that have been involved in devastating BLEVE's and VCE's, the explosion of a vehicle container can present a significant hazard also due to close proximity of people and other vehicles. It therefore follows that measures to minimise, if not completely eliminate, the possibility of such events are warranted. This was the rationale for the present test series. It follows that the onus is heavily on any individual or group advocating against the adoption of protective measures, such as detailed herein, to justify their position.

During the course of the investigations a number of papers, documents and video images were studied and, as can be seen in the references cited, these have centred on large vessels. However it is also apparent that there have been previous studies of the behaviour of containers in the case of vehicle fires. Unfortunately, to date, despite a number of recommendations, the salient issues have not been addressed, much less resolved. It is understood to be the case that there are no recorded injuries or fatalities in Australia that have resulted from ruptures and/or BLEVE's of vehicle LPG containers. It is the view of Energy*Safety* that this good fortune should not become a pretext for failure to take action on what is clearly a potential hazard.

The Ambrose report [15] details a semi-quantitative Risk Assessment undertaken and estimated a risk of 0.4×10^{-6} fatalities per LPG fuelled vehicle per annum. At the time, this could be converted to approximately 0.2 fatalities per year. There does not appear to be any further records of authorities carrying out a Risk Assessment.

In engineering it is established practice that if a risk can be eliminated or significantly reduced by using controls, that such processes will be applied in particular if the hazard has the potential to involve fatalities and severe injury. In this case, total elimination may be impossible but, on the other hand, applying engineering controls to minimise and all but eliminate such risks are very feasible.

9.1 Consequence

Due to the thermal energy released and the occurrence of high velocity of projectiles, it is considered a significant possibility that a vehicle container BLEVE could cause serious and possibly fatal injuries to persons within less than 50 metres of the event. At greater distances the probability of serious injury is reduced.

Emergency services personnel attending a vehicle fire will be equipped with high quality protective equipment and can be assumed to be in good health. However, if attempting to extinguish the fire or cool the surrounding environment they may be within metres of the vehicle at the instant that it suffers a BLEVE. In this case such personnel could be expected to experience severe consequences from the blast, projectiles and thermal effects generated by a BLEVE and VCE. Photograph A.11 (Test 11) in Appendix A convincingly shows how a vehicle was totally destroyed by a BLEVE, while the extent of a likely VCE may be seen in Photograph A.2.4 (Test 2) also in Appendix A.

Bystanders from the general public will be further from the vehicle than emergency personnel, but ill equipped to withstand the radiant heat exposure of the VCE and may also be sufficiently unfortunate to be impacted by hot shrapnel.

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9.2 Probability

The present tests have shown that the potential of a BLEVE is real and present with the current design requirements, with all unprotected containers that were filled to 80% rupturing and producing a BLEVE and VCE.

Reference is often made to a test series entitled “The Ultimate Test” conducted in NSW during the late nineteen eighties when six early model LPG/dual fuelled Ford Falcons were set alight and none of the containers suffered a BLEVE failure [15, 20]. In terms of the LPG container behaviour in a vehicle fire, the outcomes of these earlier tests are not considered indicative of the worst credible outcome for the following reasons:

1. Containers were not filled to 80% at 5°C equivalent (container fill level at the time of fire has a major influence on the rupture potential).
2. The vehicle fires prior to the release of the fuel through the PRV were less intense than fires occurring in modern vehicles due to the much increased use of plastics, linings and other combustibles in modern vehicles (according to reference 30, the “Combustible plastics and composites in cars have increased from 9 kg in 1960, to 91 kg in 1996 and 136 kg in 2007”)
3. Only Sedans were used and the aeration available to a fire in a station wagon or van would be much greater, resulting in a far more intense fire both prior to and during venting of fuel from the container’s PRV.
4. The NSW tests were designed to evaluate “pipe-away” versus plastic ducting for venting LPG and therefore the variables of the experiments are not suitable to represent the potential for a container rupture or BLEVE.

Other observations that should be considered are;

1. The testing showed that the rupture/BLEVE potential was highest when containers were filled to the maximum allowed level of 80% of the internal volume.
2. Given that filling a motor vehicle with LPG is inherently less convenient than petrol, motorists are therefore likely to fill the container to the maximum, AFL controlled quantity.
3. FESA indicates that there are approximately 1500 vehicle fires in Western Australia and 4500 to 5500 in NSW [31].
4. LPG vehicle conversions and LPG OEM sales have steadily increased in recent years and LPG fuelled vehicles may now represent as many as 10% of the vehicles on the road in Western Australia.

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9.3 Acceptance Criteria

Reference to what criteria are used that defines an acceptable risk in relation to LPG storage in vehicles could not be found. For comparison, with comparable industries, the following two acceptance criteria are presented.

9.3.1 Quantitative Acceptance Criteria

For a hazardous industrial plant, reference is made to the published guidelines on Risk Management from the Environmental Protection Agency of WA. These Guidelines specify an acceptable risk in a residential area of 1×10^{-6} fatalities per year.

It should also be noted that the LP fuelled vehicle industry has not been in existence long enough to establish sufficient empirical data to prove that the risk is at or below this acceptance criteria.

9.3.2 Qualitative Acceptance Criteria

AS/NZS 4645.1:2008 Gas Distribution Networks includes a Qualitative Risk Matrix and acceptance criteria. With this matrix a risk of High is considered unacceptable, Intermediate can be considered acceptable only where the risk is demonstrated as ALARP (As Low As Reasonably Practicable) and Low is acceptable provided the hazard is managed and controlled.

ALARP can only be demonstrated where the cost to implement a control measure is considered grossly disproportionate to the reduction in risk. It should be noted that practical and cost effective controls were successfully trialled, as detailed herein.

The risk matrix from AS/NZS 4645.1:2008 has been included in Appendix G.

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10 CONCLUSIONS

Tests were carried out to establish the susceptibility of motor vehicle LPG storage containers to rupture and explode violently (BLEVE) when the vehicle is caught in a fire. The tests included preliminary work to establish the effect of heat barriers (both metallic shields and intumescent paint), burning of vehicles without the presence of any fuel (petrol or LPG) and conducting live tests. The live tests consisted of heating containers on a rig fired with propane burners and setting alight vehicles that were fitted with LPG containers. With only one exception, in both the burner and vehicle tests the containers were filled to 80% capacity with LPG (commercial propane).

Whilst this report and investigation concentrated on the BLEVE potential by testing containers filled to capacity, other explosion sites and vehicles investigated where containers ruptured but did not BLEVE. While the explosion produced by a rupture is of a lesser magnitude than a BLEVE, such events can nevertheless create a hazardous situation and can result in major physical damage.

The following conclusions are made:-

10.1 Potential for LPG Containers to BLEVE

Containers in standard configuration with no protective measures that are filled to near the maximum containment level (80%) and are caught in a vehicle fire will likely rupture producing a Boiling Liquid Expanding Vapour Explosion (BLEVE) and a Vapour Cloud Explosion (VCE).

This contrasts with tests carried out in the late 1980's [20] and the difference is attributed to:

1. Fill level used: 80% in the containers that BLEVE'd in these tests and only 60% in the tests shown in Reference 20.
2. Greater access of air to the fires in the station wagons of the present tests compared to the sedans of the earlier tests [20] was an important factor.
3. Modern vehicles have a greater load of combustibles than their earlier counterparts.

Despite the obvious risk and strong likelihood for catastrophic failures to occur, no evidence could be found to show that the situation is being addressed.

10.2 Failure Mechanism

The mechanism for a rupture and subsequent BLEVE to occur is for the wall temperature of the vapour wetted area to exceed approximately 650°C and the internal pressure of the container to be close to or greater than the design pressure. Under these conditions the stress applied to the container walls exceeds the tensile strength of the material at such temperature.

With unprotected containers there is sufficient heat flux from material and vented LPG to increase the material wall temperature beyond 800°C. This gives rise to a precursor rupture which leads to a BLEVE and VCE. A failure of this type can occur even if the PRV is operating satisfactorily and venting at a rate close to double the minimum requirements set out in the relevant standards.

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10.3 Effectiveness of Protective Measures

No single control measure was considered likely to be completely effective in eliminating the potential of a container to rupture and BLEVE. However, the test results indicated that a combination of the following would provide a high level of confidence that a BLEVE should be an extremely unlikely outcome:-

1. Insulating the container walls (by sheet steel shielding or intumescent paint), and
2. Replacement of the aluminium and plastic currently used in the fabrication of the container sub-compartment box and vent line with steel equivalents

10.4 Other Possible Protective Measures

Other protective measures, such as constructing containers of thicker steel, highly alloyed steels or other suitable materials may also be effective. Similarly other techniques of insulation, such as steel shielding or intumescent paint, may be effective.

The installation of a Thermal Safety Element (TSE) on the container in order to rapidly vent the container's contents. However, several safety and design qualifications would need to be considered prior to TSE's becoming an option.

Design modifications that promote cooling of the internal walls of containers and venting systems that discharge vapour and liquid simultaneously. These protection measures, such as the construction of inner annuli, may be viable with large tanks but seem unlikely to be applicable to vehicle containers.

It is known that aluminium containers are much more prone to rupturing than ones made of steel [18]. This conclusion can be generalised to any metallic material that is less resistant than steel to temperatures in the relevant range.

An alternative approach that appears promising is the use of composite cylinders, as they are generally reported to be effectively BLEVE proof. However, currently, their availability appears to be restricted to domestic applications and fork lifts.

In all cases, before any such measure is adopted its efficacy must be rigorously proven.

10.5 Relief Valve Performance Characteristics

The performance characteristics of the PRV's were found to be a significant factor. In several cases the valve seat failed relatively quickly, possibly contributing to increased relieving rate and venting the container contents rapidly. This, apparently unintended control measure used in isolation does not prevent a BLEVE, as, indicated by Test 11.

It was also noted that the PRV's from different manufacturers behaved differently under the fire conditions

10.6 Relief Valve Specifications

As seen in Section 4.1 and Appendix C, AS/NZS 1425:2007 Clause 3.2.1 allows three options for the design of containers (according to AS/NZS 3509, AS 2030 or AS 1210). These lead to different design requirements in some areas (PRV capacities and material stress levels in particular).

AS 2613 specifies a calculation procedure for the valve capacity in a different manner and has different requirements to that used for Pressure Equipment (AS 1210). This results in a PRV that has a considerably lower capacity requirement than an equivalent pressure vessel.

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This may be significant as the PRV's installed during the testing had capacities that exceeded the AS 2613 specification and were close to the AS 1210 requirement. If the capacity of the PRV was reduced to the AS 2613 minimum specification, this could have resulted in higher pressures than those recorded, with corresponding higher liquid temperatures and an increase in the fire exposure duration at pressure. Consequently if the PRV's used were of only the minimum required capacity (under AS 2613) it is a significant possibility that a greater number of ruptures and accompanying BLEVE's/VCE's could have resulted in these tests. These aspects are detailed in Appendix C.

10.7 Limitations on PRV's in Preventing BLEVE's

Following Section 10.6, it may be noted that the American standard CGA S-1.1 – 2007 "Pressure Relief Device Standards Part 1 - Containers for Compressed Gases", on which the PRV sizing equation in AS 2613 is apparently based, notes that PRV's do not protect the container against possible rupture when continued application of external heat or direct flame weakens the container wall to the point where its rupture pressure is less than the operating pressure of the relief valve. Given this statement from the CGA, it is evident that additional protection measures, as outlined in this report, are required to give a high level of assurance that a container rupture/BLEVE/VCE will not occur when a container is caught in a vehicle fire.

10.8 CNG Comparison

A test procedure for a fire case is described in AS 4838-2002 High Pressure Cylinders for CNG as a Fuel for Vehicles. The hazards for pressurised hydro-carbons are clearly at the foundation of this standard. As noted earlier in this report, pressurised liquids (such as LPG) provide a mechanism for the occurrence of a BLEVE and VCE. This is not possible with cylinders containing on single phase gas (such as CNG). This is not to suggest that a situation in which a CNG cylinder is exposed to fire does not present a major hazard. However, it is clearly reasonable that LPG containers, which are used in far greater numbers should be tested with at least the same degree of rigour and stringency as is applied to CNG cylinders.

10.9 Qualification

Finally it must be recognised that the high cost and logistic considerations strictly limited the number of tests that could be conducted. Therefore no attempt could be made to infer the level of repeatability or reproducibility of results obtained and the possibility that a retest under a given set of conditions would produce a different outcome cannot be completely discounted.

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11 RECOMMENDATIONS

Considering the findings of these tests, it must be accepted that LPG fuelled vehicles are inherently more hazardous than their diesel or petrol fuelled counterparts. Energy*Safety's* view is that the potential of a container rupture and BLEVE/VCE creates a significant risk to emergency services personnel, bystanders and the public. This situation makes it incumbent on those involved in the industry to seek measures to greatly reduce, if not completely eliminate, the possibility of such events as container ruptures, BLEVE's and VCE's. In order to achieve this, the following recommendations are made:-

11.1 Revise Installation Requirements

The installation requirements should be revised so that the containers are installed in a manner that ruptures and violent explosions are an extremely remote possibility. In doing so it is advisable to consider the fire case requirements for CNG cylinders and aim to provide some consistency for pressurised fuel containers.

Possible methods of achieving this have been considered above. Container insulation and modifications to prevent vented LPG from contributing to the heat flux on the container are prominent possible solutions. Increased container wall thickness and material of construction may also warrant further consideration.

In order to implement, a rigorous test procedure will need to be formulated to test the effectiveness of measures intended to minimise the risk of a rupture/BLEVE/VCE occurring in LPG fuelled vehicles. It is envisaged that such a test would involve practical trials with modern wagons fitted with LPG tanks filled to the allowed limit and with the addition of combustible material. That is to say a situation representative of a worst case scenario. It is recognised that the detailed aspects of such a test would be subject inputs from many stakeholders and interested parties, as well as others with expertise in the field.

Some of the salient aspects for inclusion in a test procedure are presented in Appendix H. Testing as described in Appendix H is designed to prove that the selected method of BLEVE mitigation can provide a margin of at least 25% to the tensile strength of the material.

11.2 Review AS/NZS 1425 and AS/NZS 1425 Reference Standards

The current version of this standard AS/NZS 1425:2007 Clause 3.2.1 allows three options for the design of containers (according to AS/NZS 3509, AS 2030 or AS 1210). These lead to different and sometimes conflicting design requirements in some areas. In particular, this relates to PRV capacities. AS/NZS 1425 Clause 3.15.1 requires "automotive fuel containers" to be fitted with a "safety valve" compliant with AS 2613. The adequacy of the AS 2613 requirement in this case should be reviewed.

The use of increased PRV capacity (beyond that obtained using a calculation based on AS 1210) and/or Thermal Safety Elements may be considered, but should be approached with caution for reasons specified in Sections 6.4 and 6.8, as such attempts may actually lead to BLEVE conditions.

11.3 Consider Evolving Technologies

New materials of container construction, specifically polymer composites, appear promising and should be further investigated.

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12 ALTERNATE GUIDANCE

From the investigations and testing it was found that installations can be made virtually BLEVE proof with reasonable and practical controls. However if it is considered that cost and logistics would make the above recommendations unviable, then a formal Quantitative Risk Assessment should be performed to ascertain the risk to the public and emergency personnel. The results of such an assessment should then form the basis for further action.

It should be noted that such a move will attract a significant responsibility and may have future ramifications for those sanctioning the QRA as opposed to removing the probability of such violent ruptures. Given that the investigations have provided practical outcomes, such an approach cannot be endorsed by Energy*Safety.*

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(LISTING SUBJECT TO BOARD APPROVAL XXX)
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31. S Ransom, A profile of motor vehicle theft related arson in New South Wales and South Australia, Comprehensive Auto-theft Research System, (2007)

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Appendix A – Results by Container

Test 1 (21-9-09)

In this test an APA container was filled to 20% volume and placed on the rig without any protection. Some 5 minutes after the burners were turned on, the relief valve began to intermittently operate. The venting continued until the container emptied in an orderly manner without a BLEVE or other incident. A photograph of the pose test container is attached. From this test it was concluded that containers filled to 20% do not present an explosion hazard and in all future tests the fill level was 80%.

Photographs A.1.1- Pre test photographs, showing the initial setup.

Photographs A.1.2- Post test photographs, showing the container survived.

Test 2 (21-9-09)

Test 2 was similar to Test 1 in all respects, except that it was filled to 80%. In this test venting began soon after the rig burners were turned on, and a BLEVE and VCE took place at about 8 minutes. Noting the PRV when relieving and the nature of the flames indicated that two phase flow was occurring. Photographs immediately below attest to the power of the BLEVE and VCE.

Photographs A.2.1- These photographs show the remains of the burner apparatus and container post BLEVE

Photographs A.2.2 - Damage to the test container roof and support beam

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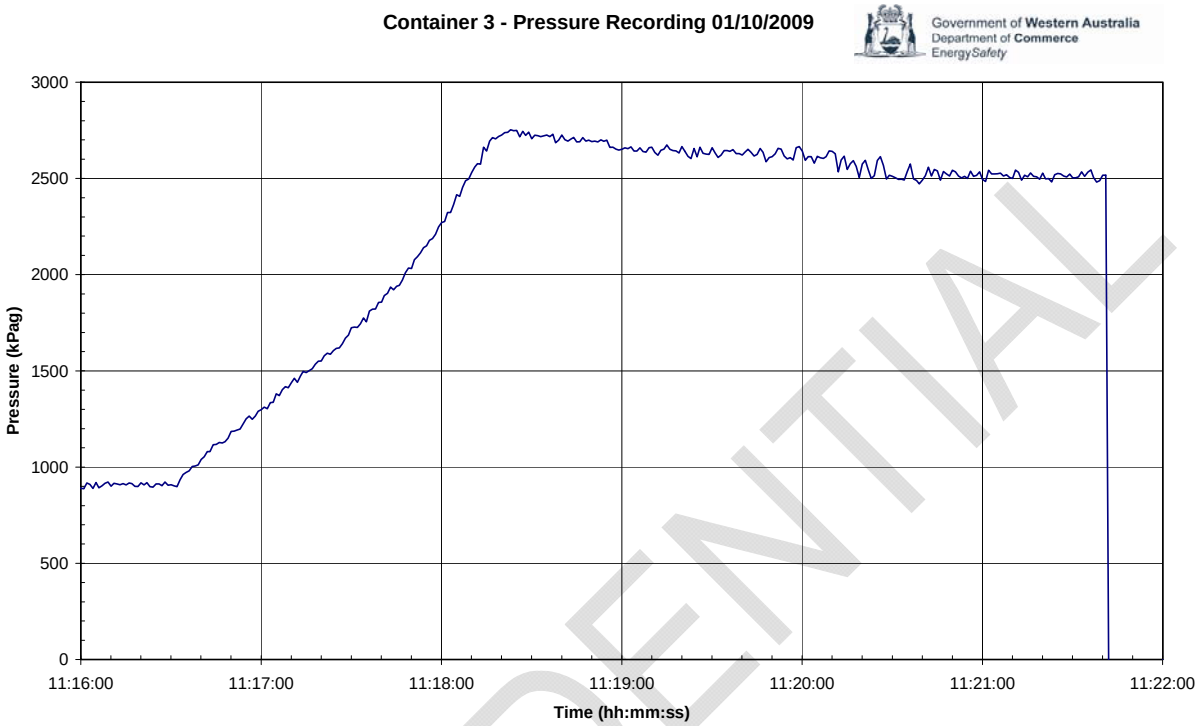
Photograph A.2.3 - High speed camera shows bulge on top left of container. In the next frame, 3.3 milliseconds later, the container ruptured.

Photograph A.2.4 - Vapour cloud explosion

Test 3 (1-10-09)

In Test 3 an APA container was used. However, the aluminium sub-compartment cover was replaced with one of steel and the plastic vent pipe was replaced with a flexible stainless steel pipe of approximately the same diameter. The objective was to limit the level of flame engulfment and in doing so reduce the likelihood of a BLEVE. However, these measures were unsuccessful and a BLEVE and VCE occurred in less than 5 minutes.



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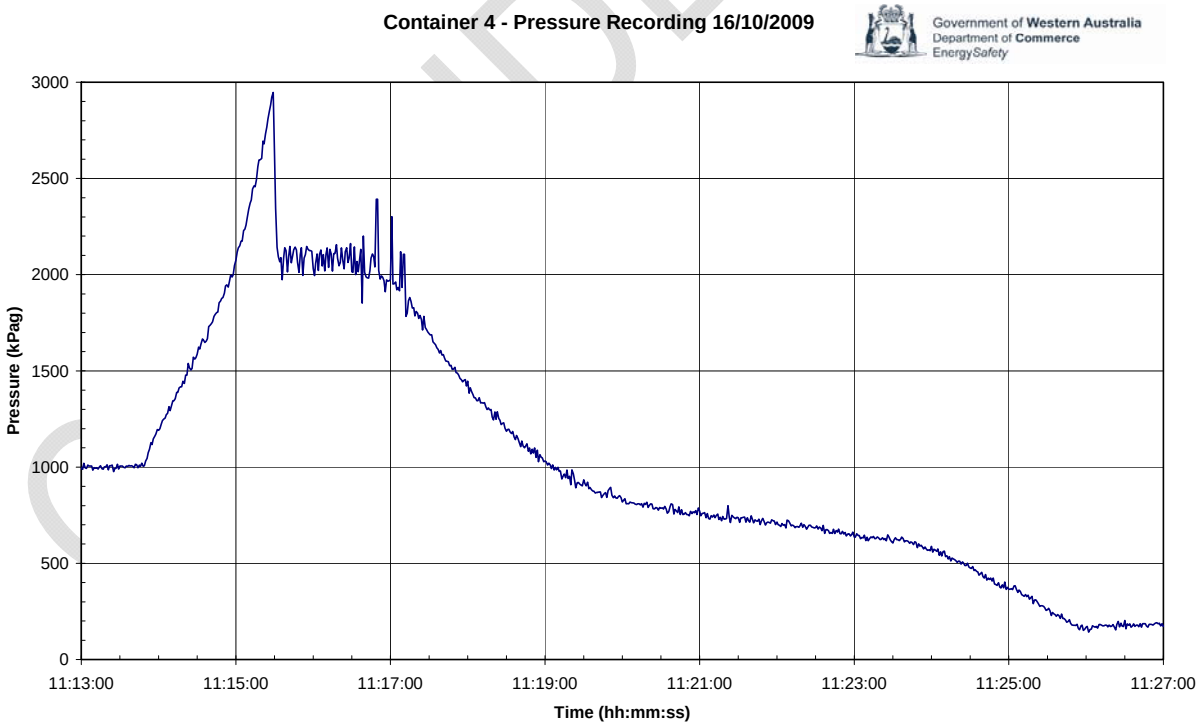
TEST 4 (16-10-09)

A Manchester tank fitted with steel sub-compartment and stainless steel vent tube with the addition of a “pick-up tube” (to limit liquid and two phase flow occurring through the relief valve, as described in Section 6.5) was tested on the burner rig. In this case there was also the further measure that the container was painted with Contego intumescent paint. However, due to a misunderstanding the paint was applied at a thickness of only about 0.5 mm, instead of the required 1.8 mm (dry) [27]. The container did not BLEVE, despite the thinner than required application the intumescent paint. It was noted that noise produced during two phase flow was different (in that it contained a distinct “whine”) from that of single phase flow. The photographs below show the pre and post fire condition of the intumescent paint.

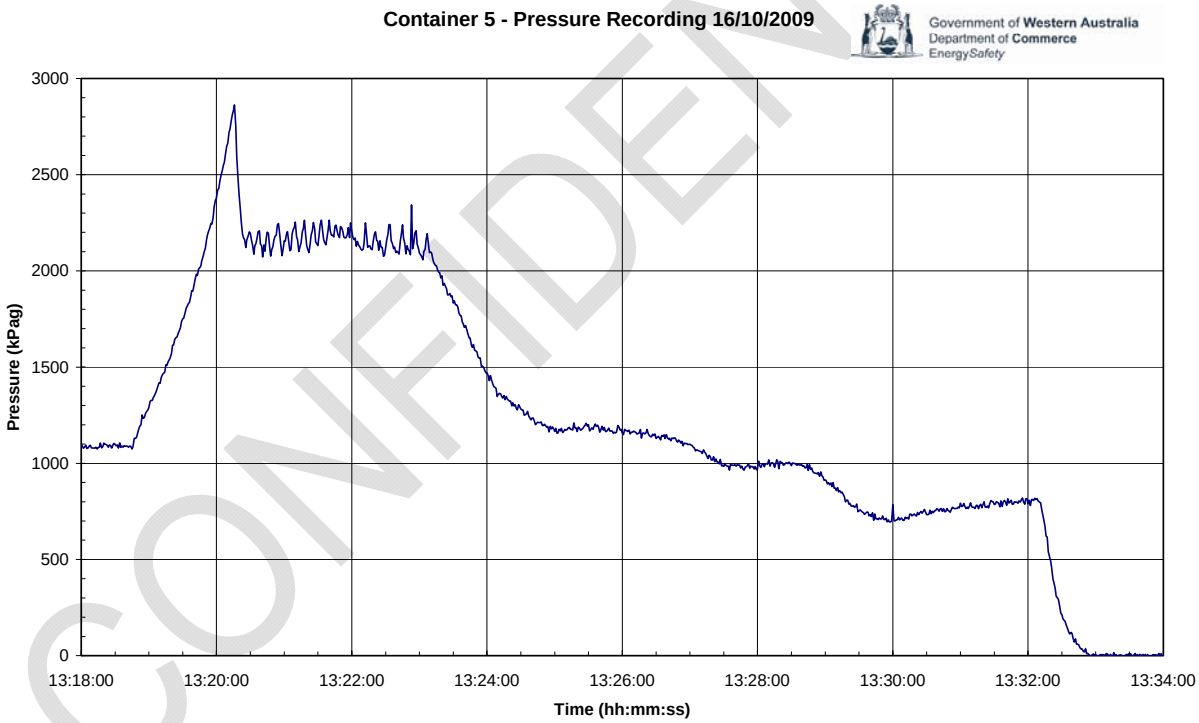
Photographs A.4- View of intumescent paint applied to container before and after exposure to flames.



Test 5 (16-10-09)

This test was a repeat of Test 4 with the exception that the container was not equipped with a pick-up tube. As in Test 4 the intumescent paint was only about 0.5 mm thickness. However, also as in Test 4, the container did not BLEVE.

Photographs A.5- View of intumescent paint applied to container before and after exposure to flames.



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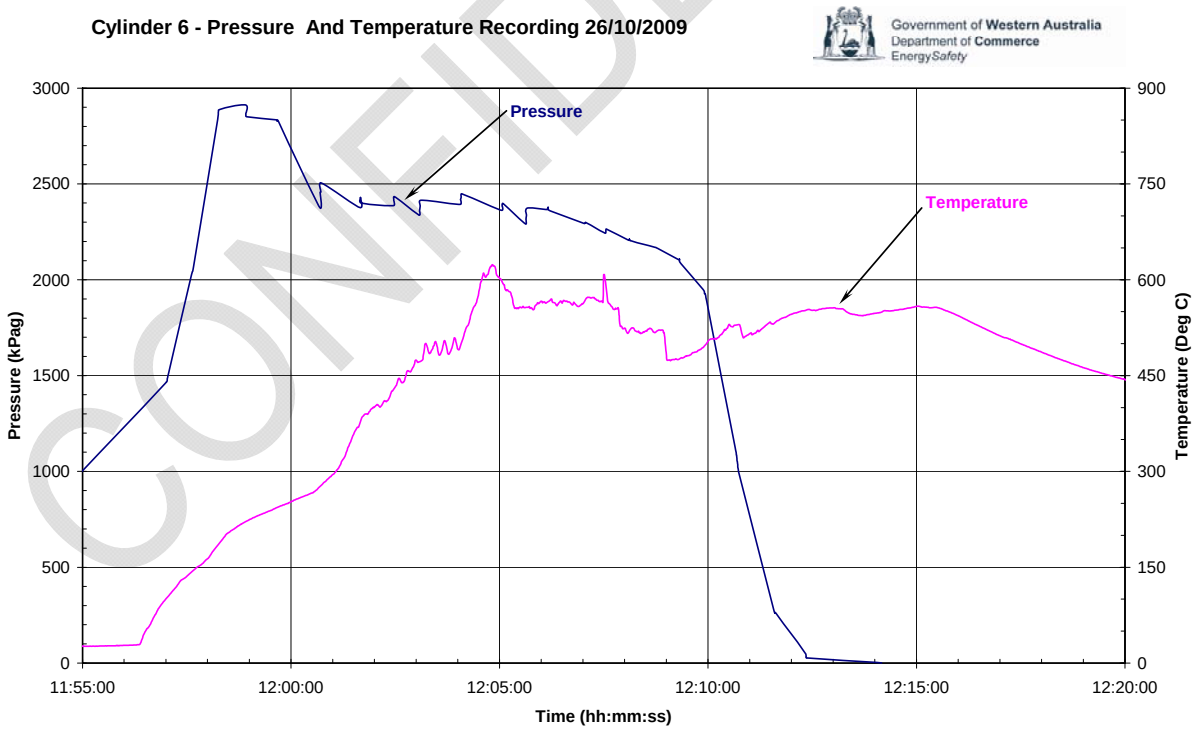
Test 6 (26-10-09)

An APA container was tested on the burner rig. The container was painted with Contego intumescent paint in accordance with the manufacturer's instruction (1.8 mm thickness when dry). Apart from the paint no other protections were employed. The container did not BLEVE. The photographs below show the pre and post condition of the paint. It is apparent that the high velocity venting vapour and/or two phase flow from the PRV blew away some of the intumesced paint. Despite this, the container survived.

Photographs A.6 - The painted vessel before and after the test.
The right photo shows where the activated intumescent paint was blown away by the venting stream from the PRV.



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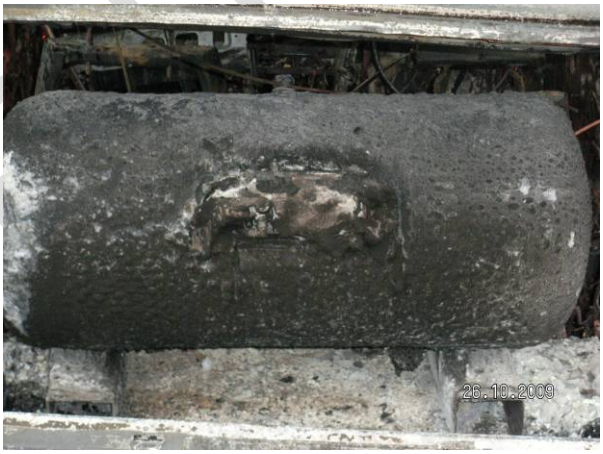
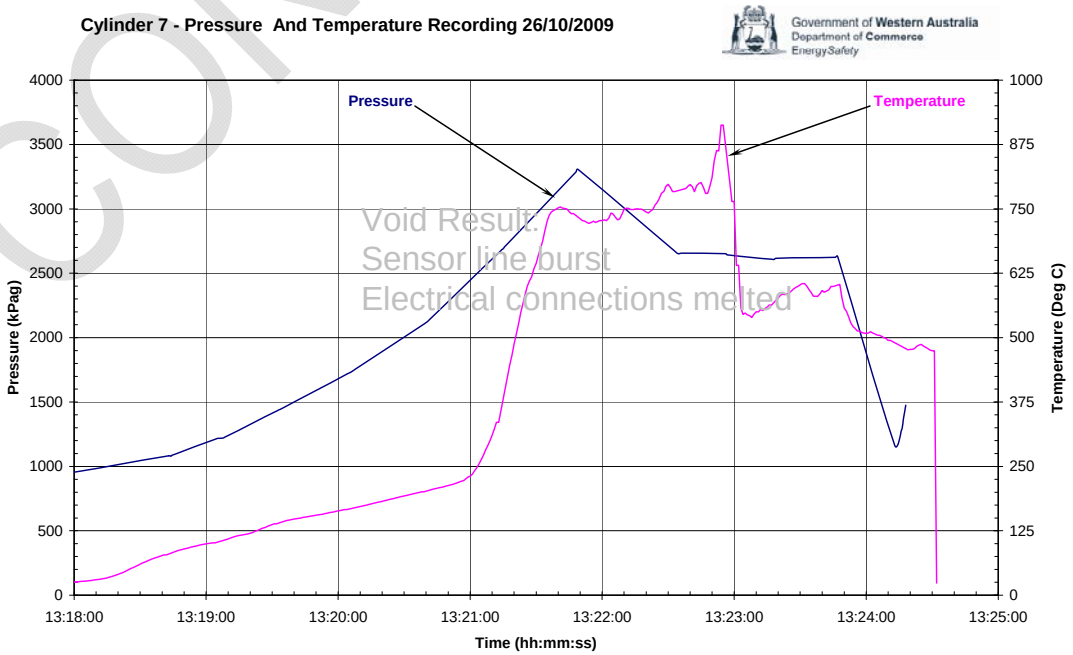
Test 7 (26-10-09)

An APA container with no protections other than intumescent paint (as in Test 6) was tested in a vehicle fire (Nissan Pintara). In this test the pressure sensing line ruptured and the temperature recording cables melted, largely invalidating the test. The container did not BLEVE.

Photographs A.7.1 – Vehicle before and during testing.



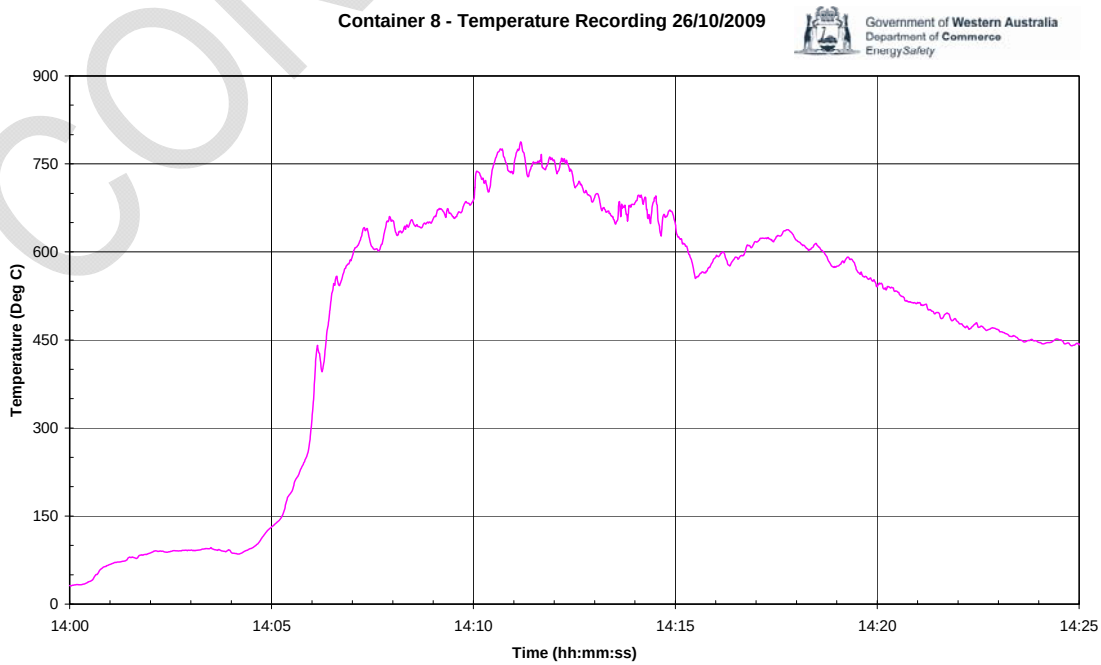
Photographs A.7.2 – Vehicle and container after testing.



Test 8 (26-10-09)

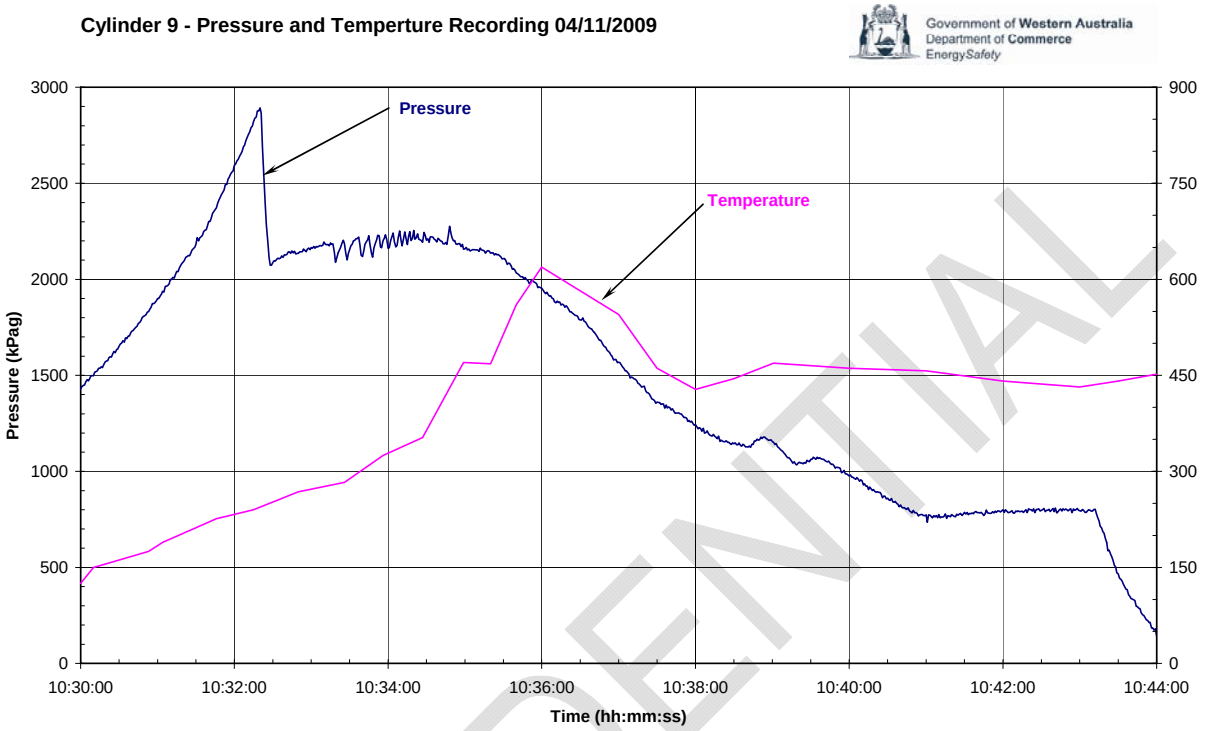
A Manchester container was tested in a vehicle fire (Ford Futura). The container was equipped with a pick-up tube and protected with a steel shield of thickness 1.6 mm. A stainless steel vent was also provided. The container did not BLEVE. The photographs below show the placement of the shield and the vehicle on fire. Also shown is the additional fuel (in the form of cardboard and wood that was included to intensity the fire).

Photographs A.8 - Stages of shield placement (with vent pipe) and car alight. As in Test 7 the venting LPG greatly adds to the fire.



Test 9 (4-11-09)

A Manchester container was tested in a vehicle fire (grey Holden Commodore, shown on the left in the photograph in Section A.11 below). The protections comprised of a stainless steel vent and intumescent paint. The container did not BLEVE.



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Test 10 (4-11-09)

Tests 10 and 13 were included in the program to validate observations made as a result of the Victorian bush fires of February 2009. The outcomes of these tests will be reported in a separate report. This was a test of an upright Rheem 45 kg LPG container used in domestic situations, rather than a motor vehicle container, and the results are reported elsewhere [28]. It may be noted, however that it did not BLEVE.

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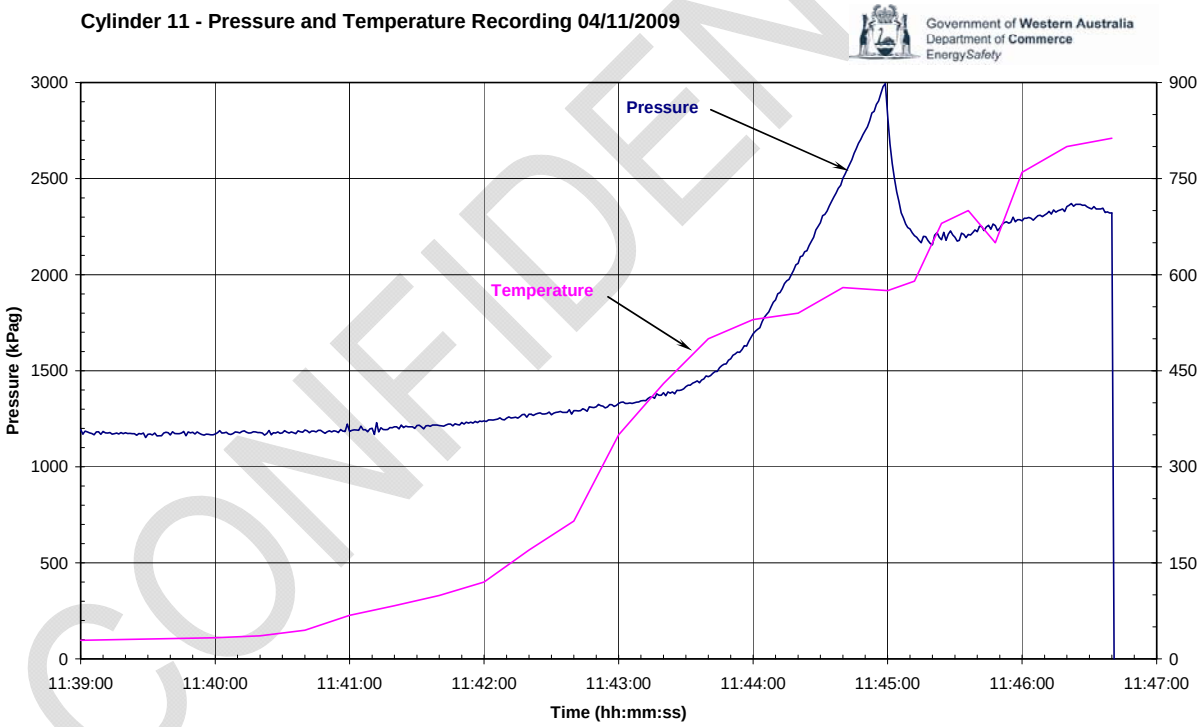
Test 11 (4-11-09)

A Manchester container with no protection was tested in a vehicle fire (Ford Escort, centre in the left side photograph below). The container BLEVE'd with sufficient force to destroy the vehicle beyond recognition, as shown in the right side photograph.

Photographs A.11-Vehicles delivered for test and the remains of the Ford Escort.



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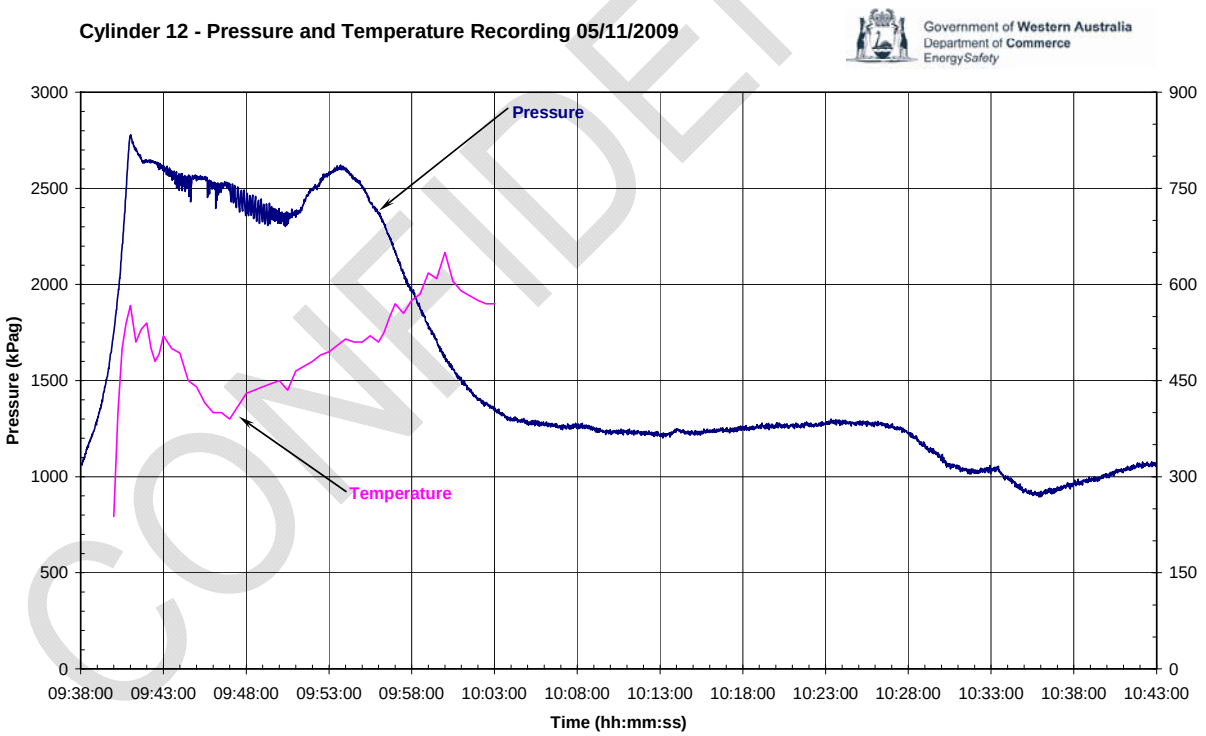
Test 12 (5-11-09)

An APA container with steel shielding and a stainless steel vent (but no other protection) was tested in a vehicle fire (red Holden Commodore). This test was similar to the one described in Test 8 except that an APA container was substituted for the Manchester container used in Test 8. The container did not BLEVE. The photographs below show the vehicle and the final placement of the steel shield, with additional fuel.

Photographs A.12 -The vehicle set up showing the shield and additional fuel.



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Test 13 (5-11-09)

Like test number 10, this was a test of a Rheem 45 kg LPG container used in domestic situations but in the lying down position. The results are reported elsewhere [Reference 29, report proper]. It may be noted, however that the container BLEVE'd, with even greater force than the vehicle containers and also produced a spectacular vapour cloud explosion.

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Appendix B – Vehicle Burn Tests

Vehicle burn tests at FESA's Forrestfield Test Centre 12-10-09

The photographs below show two various stages of tests in which two cars were burnt as described in Section 7.3

Photographs B.1 - Various stages of the burn test of two vehicles at FESA's test centre.

Appendix C – PRV Sizing

Apparent anomalies in the relevant standards are noted below:-

(This Appendix should be read in conjunction with the relevant clauses of the standards cited.)

C.1 Clause 3.2.1 of AS/NZS 1425 Interpretation

Clause 3.2.1 of AS/NZS 1425:2007 states:

> *A fuel container shall comply with one of the following Australian or Australian/New Zealand standards or in New Zealand, the Traffic Regulations 1976 amendment No. 7, Clause 80B, and shall have a design notified or registered by the appropriate Statutory Authority and subject to requirements in Clause 6.1(c)(ii):*
>
> *(a) AS/NZS 3509*
>
> *(b) AS 1210 (for a design pressure of 2.55 MPa).*
>
> *(c) AS 2030.1 (for propane).*

This appears to offer three design options for the fuel containment vessel and, as shown below, these can lead to differing requirements for the PRV.

C.2 Flow Rating Pressure and Other Issues in the Relevant Standards

As noted earlier, there appears to be numerous ambiguities in the relevant (LPG related) standards. Some of these are listed below:-

1. Apparent ambiguity in AS/NZS 1425 Clause 3.2.1, in which standards apply to the fuel container (AS/NZS 3509, AS 1210 or AS 2030) as described in the preceding section.
2. AS/NZS 1425 Clause 3.15.1 (b) states: “The safety valve shall comply with the requirements appropriate to the type of container to which it is fitted, AS 2613 for a gas container or an automotive fuel container, or AS 1271 for a pressure vessel or be UL listed.” However, as above, AS/NZS 1425 Clause 3.2.1 also allows containers constructed to AS 1210, which has a different PRV requirement to that of AS 2613
3. AS/NZS 1425 Clause 3.15.1 (d) states that the “The full flow rating pressure shall be 3.3 MPa.” In contrast, AS 2613 Clause 2.3 states “The flow-rating pressure of a pressure-relief valve shall be not less than 1.25 times the maximum developed pressure of the contained gas, and shall not exceed the test pressure of the container.” In the case of LPG “the maximum developed pressure” (according to AS 2030.5-2009) is 2550 kPa-gauge and 1.25 times 2550 is 3188 kPa-gauge or 3289 kPa-abs (the formula for calculating the required free air flow rate of a PRV in AS 2613 specifies the absolute pressure). This therefore poses the question of whether the flow rating pressure in a PRV test for a container of design pressure 2550 kPa-gauge should be 3188 or 3300 kPa-gauge. Also notable is the use of the factor 1.25 in AS 2613. Other standards such as AS 1210 and API 520 set the relieving condition at 1.21 times the design pressure.
4. AS/NZS 1425 Clause 3.15.1 (d) also adds the note “NOTE: The start to discharge pressure is expressed as not less than 80% of the full flow rating pressure.” Given that AS 1425 specifies the “full flow rating pressure” as 3300 kPa-gauge (and 80% of this pressure is 2640 kPa-gauge), this indicates that the PRV should not open until the vessel’s pressure has reached 2640 kPa-gauge, which is 90 kPa higher than the design pressure. AS 2613 in Clause 2.4 also specifies the 80% figure, but is consistent with the “1.25 times the maximum developed pressure” requirement.

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5. AS 1425 Clause 3.16 states "The safety valve shall communicate with the vapour space of the container, and no valve shall be installed between the safety valve and the container". As noted elsewhere in this report, a container filled to 80% with propane under ambient temperature conditions will come close to liquid full before the propane vapour pressure reaches the PRV lifting threshold pressure of 2550 kPa-gauge. In the case of mixtures containing significant levels of butane this is much more so the case, due to their lower vapour pressures. According to correlations in reference C1, the density of propane at temperature 15°C is 0.500 kg/L and at 71.2°C is 0.393 kg/L (71.2°C is the temperature at which propane's vapour pressure reaches 2550 kPa-gauge) and from these densities it is seen that a vessel filled to 80% at 15°C would be liquid full at 71.2°C. It is the case that these calculations would be tempered to some degree by stratification of the contained liquid, where higher temperature product rises to the top and sets the vapour pressure. It is nevertheless the case that the requirement that "The safety valve shall communicate with the vapour space of the container…." is not likely to be met in practice.
6. AS 1210 Clause 8.6.2.2 specifies a calculation procedure for the required minimum flow rate of free air (Qa at 15°C and 101.5 kPa) for PRV's. However, it does not explicitly state the applied (flow rating) pressure at which this minimum flow must occur. This omission should be rectified.
7. The values of "G" (the coefficient used in AS/NZS 1596:2008) is derived from formulae given in Clause 8.6.2.3 of AS 1210 and relates to a design pressure of 1750 kPa-gauge, rather than 2550 kPa-gauge relevant to automotive LPG tanks. Therefore, it is not appropriate for use in automotive tank applications.
8. As described in Section C3 below, the calculation procedures for PRV sizing in AS 2613 and AS 1210 are different and lead to very different results. The AS 1210 calculation procedure produces a flow rating requirement that depends on the vessel's area and the physical properties of the fluid contained, whereas the AS 2613 calculation is a function of the vessel's internal volume. In the cases considered, the AS 1210 method resulted in a much greater required flow (see Section C3 immediately below).

C.3 PRV Sizing Conflict

AS/NZS 1425, on the one hand in clause 3.2.1(b), states that AS 1210 applies for 2.55 MPa containers, then, on the other hand, in clause 3.15.1 clearly states that "... (b) The safety valve shall comply with the requirements appropriate to the type of container to which it is fitted, AS 2613 for a gas container or an automotive fuel container, or AS 1271 for a pressure vessel or be UL listed." The difficulty is that the procedures for determining PRV capacity in AS 1210 and AS 2613 are quite different (the calculation in AS 1210 is based on the vessel's surface area and the physical properties of the contained product, while the calculation in AS 2613 depends only on the vessel's internal volume) and these methods can give quite different results, as shown below. Therefore, it seems there is an apparent conflict in AS/NZS 1425, on the one hand referencing AS 1210 as applying to "2.55 MPa" containers, yet specifying a PRV sizing procedure that differs from that in AS 1210.

As above, in AS/NZS 1425 Clause 3.2.1 (c) cites AS 2030.1 for "propane" containers, AS 2030.5 in clause 5.3.1 is clear: "Safety devices shall comply with AS 2613". This, again, would seem to put AS/NZS 1425 in the position of specifying two possible and quite different sizing methods for PRV's to be used with vehicle containers. In the example below, it can be seen that, in the case considered, the sizing calculation method of AS 1210 produces double the required air flow (15.30 m^3/min) for a PRV to that of AS 2613 (8.16 m^3/min).

It is also significant that the above calculation refers to pure propane, and calculated rates higher than 15.30 m^3/min would generally apply to other autogas mixtures.

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Example of PRV Sizing

The following shows different requirement obtained using AS 1210 and AS 2613 methods.

Assume a horizontal tank with ellipsoidal ends of dimensions given below initially filled with propane to maximum limit (80%) and engulfed in a fire. Calculation of the required relieving rate by AS 1210 and AS 2613 produces different requirements as below.

1. Cylindrical container 2:1 semi-ellipsoidal ends
2. Content pure propane initially filled to 80% at room temperature
3. Overall length: 892 mm
4. Outside diameter: 375 mm
5. Wall thickness: 2.7 mm
6. Internal capacity: 89.0 litres
7. External area: 1.135 m^2
8. Design pressure of vessel: 2550 kPa-gauge (approx 2650 kPa-abs)
9. Relieving Pressure: 3086 kPa-gauge (approx 3187 kPa-abs). This follows AS 1210 in taking the relieving pressure as 1.21 times the vessel's design pressure
10. Temperature (T): 81°C, or approximately 354 K (the temperature at which propane vapour pressure equals 3187 kPa-abs [C1]. Note also that the vapour pressure equals 2650 kPa-abs, the vessel design pressure, at 71.2°C
11. Latent heat propane (L) at 81°C: 186.0 kJ/kg [C1]
12. Liquid density at 15°C: 0.500 kg/L and at 81°C: 0.363 kg/L [C1], therefore vessel approximately liquid full and wetted area is total area. This conclusion also applies at temperature 71.2°C, when the liquid density is 0.393 kg/L.
13. Compressibility factor (Z) of vapour at relieving condition: 0.569 by Soave Redlich Kwong equation of state [C2]. A similar result for Z is obtained from Figure G1 of AS 1271-2003.
14. Isentropic exponent (k) for propane: the ideal value on the basis of published heat capacities [C3] is 1.13. A "real gas" correction [C4] gives a value of approximately 1.11, which is used in the calculation below. However, the calculated required air flow rate for the PRV (Qa), using the AS 1210 formulae is only a weak function of k.

AS 1210 Calculation

Applying equations given in AS 1210 -1997 Clause 8.6.2 "Aggregate capacity for fire conditions" gives a free air relieving rate (Qa) of 15.30 m^3/minute. As above, it may be noted that AS 1210 does not state explicitly what is the required pressure to be applied (flow rating pressure) in obtaining the flow rate Qa. It may be implied that it is 121% of the design pressure, as this criterion is used elsewhere in the standard. In contrast, in AS/NZS 1596:2008, Appendix H "Discharge Capacity of Safety Valves" specifies that test pressure shall be 120% of the PRV's set pressure. The formula used in AS/NZS 1596 is a special case of the AS 1210 equation.

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AS 2613 Calculation

In comparison, using the equation AS 2613-2005 Clause 2.2.5 "Pressure relief valve for use with a liquefied gas" and taking the "flow rating pressure" to be 3289 kPa-abs (i.e. 1.25*2550+101), gives a free air relieving rate of only 8.16 m^3/minute

Note also that there is some apparent inconsistency in the definition of "flow pressure rating". According to AS 2613 Clause 2.3, it is, as above, 1.25 times the maximum developed pressure of the contained gas, but shall not exceed the test pressure. In contrast AS/NZS 1425, Clause 3.15.1 "General" states: "full flow rating pressure" shall be 3.3 MPa-gauge (it does not state, whether gauge or absolute). Furthermore, the factor of 1.25 seems somewhat curious, and 1.21 might be expected by analogy with the AS 1210 requirement noted above.

C4 Adequacy of AS 2613 Sizing Formula

From Table 7.3, reproduced here for convenience, both of the PRV's used tested at much higher flow capacities than would be the case of PRV that was minimum compliant to AS 2613. The latter valve would have a (free air) capacity of 8.16 m^3/min at flow rating pressure 3289 kPa-abs. Using formulae such as those given in Appendix F of AS 1271, the Crosby Engineering Handbook or from fundamental fluid mechanics, it is possible to calculate the effective area of the PRV from the flow rates and pressures. The results from AS 1271 (which are very similar to the other approaches mentioned) are: SCG (Manchester) 34.27 mm^2, SVM (APA) 32.46 mm^2 and AS 2613 minimum 21.26 mm^2. These figures refer to the flow rating condition and, depending on valve construction and internal geometry, may be significantly dependent on the inlet pressure during operation (as would be the case with a "proportional" valve)

It may also be noted that the flow (8.16 m^3/min) calculated according to AS 2613 is lower than would be obtained for from the equation given in Clause 5.7.2.5 of NFPA 58 [C5]. The latter equation applied to the container specified in Section C3 above would be 11.8 m^3/min of air. The NFPA equation is stated as referring to "*The minimum rate of discharge of pressure relief valves installed in ASME containers …*"

While the origins of the AS 2613 PRV flow equation (Clause 2.2.5) are not cited in the standard, it seems likely to have been taken from the Compressed Gas Association publication CGA S-1.1, Thirteenth Edition [C6], Clause 5.7 of which leads to the same PRV sizing result as is obtained using AS 2613 (for liquefied gases). It is notable that Clause 5.7 of CGA S-1.1 [6], which applies to "liquefied gas", does not include an equation for the flow calculation but simply requires a doubling of the value obtained from the formula given in Clause 5.6, which is for "non-liquefied gases". The concept of simply doubling the required flow rate in this manner appears somewhat arbitrary and questionable on three grounds:

(a) the quantity of material held in a vessel containing pressurised liquid would usually be far more than double that of vessel of the same capacity filled with pressurised gas,

(b) the pressure in a cylinder containing only gas falls as the gas is vented, however, if liquid is present the pressure will, to a first approximation, be maintained at the equilibrium vapour pressure of the hottest liquid, and

(c) a vessel filled with gas or vapour, while capable of rupturing violently, cannot produce a BLEVE.

These factors would suggest that the mere doubling of the specified PRV discharge flow rate in going from gas/vapour to pressurised liquid containment may not fully address the issues.

In view of the issues noted in this Appendix, it is submitted that the PRV sizing equation given in Clause 2.2.5 of AS 2613 may not be applicable for automotive fuel containers designed to AS/NZS 3509.

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Table 7.3 – PRV Design Details

Parameter	Manchester Tank	APA Manufacturing
Manufacturer	SCG Thailand	SVM Thailand
Model	7545K	SVM 635
Set Pressure	2550kPa	375psi (2586kPa)
Flow Capacity	13.6m^3/min (air)	12.4m^3/min (air)
Pressure at Flow Capacity	3300kPa	460psi (3172kPa)

C5 Summary of PRV Sizing Issues

It is shown in this Appendix that three commonly cited calculation methods (AS 2613, AS 1210 and NFPA 58) give different results for the minimum free air capacity of PRV's. Calculations according to AS 1210 and NFPA are based on the area of the vessel, whereas the AS 2613 formula is volume dependent. The AS 2613 and NFPA 58 equations are independent of the physical properties of the contained liquid, while these are included in the AS 1210 formulation.

In the area based equations, the area is raised to the power of 0.82. This power is believed to have been empirically derived from fire tests on large tanks carried out in the 1940's and 1950's in the USA. While a formula involving area raised to the power of 0.82 may be appropriate for a large tank, it does not seem appropriate to LPG container tanks caught in vehicle fires, where full flame engulfment is to be expected (and has been observed in practice in these tests).

The requirements of the volume based equation of AS 2613 has been questioned in the present report, though this refers to the magnitude of coefficient in the equation rather than it being volume based. However, in principle, an area dependent formula would give a better representation of heat absorption than one based on volume.

As also noted, only the AS 1210 formula considers the physical properties of the contained liquid. In principle, any formula that ignores these properties cannot be accurate in all cases, as the composition of the contained liquid can vary widely. (Although the NFPA formula cited above, NFPA 5.7.2.5, is independent on the liquid properties, in another section of the standard (Section 12.8.4) dealing with refrigerated containers, these properties are included as factors in the sizing equation.) Furthermore, AS 1210 Clause 8.4.3 "Type and minimum bore" (Pressure Relief Devices) states in subsection (9d) that the minimum bore for any relief valve used on a vessel shall be 12 mm for liquid (the valves used in these tests had a bore of 7.5 to 8mm diameter). While the PRV used with the containers that are the subject of this report are *intended* for use with gas, it has been shown in Section C2 above that the tanks can become liquid full as a result of thermal expansion of the contained liquid. Similarly, during the practical tests both liquid and two phase flow was apparent from venting PRV's. Fisher [C7] notes that "Generally, two phase flow requires a larger relief area than all vapour or subcooled liquid flow".

Finally, it is noted that it is stated in the Handbook of Compressed Gases [C8] that *"Pressure relief valves are designed to maintain the pressure in the container at a level determined by the spring force. Therefore such devices do not protect the container against possible rupture when continued application of external heat or direct flame weakens the container wall to the point where its rupture pressure is less than the operating pressure of the relief valve."* Essentially the same point is also made in Reference C6. Given this statement from the CGA, it is evident that additional protection measures, as outlined in the body of this report, are required to give a high level of assurance that a container rupture/BLEVE/VCE will not occur when a container is caught in a vehicle fire.

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Table C-1 summarises some of the requirements of PRV's in the cited standards

Table C-1 - Comparison of Standards Requirements

Standard	AS 1210	AS 2613	AS 1425	NFPA 58
Calculation Basis	Area	Volume	N/A	Area
Gas Properties Dependent	Yes	No	N/A	No
PRV Flow (Test Container) (m^3/min free air)	15.3	8.16	N/A	11.72
Set Pressure (kPa gauge)	2550	2550	2640	2550
Flow Rating Pressure (kPa gauge)	3086	3188	3300	3060

Notes: Developed pressure of LPG (propane) is 2550 kPa-gauge (As 2030.5)

Capacity calculations are for the example container given in Section C3 containing propane.

The capacity required under AS 1210 is expected to be greater than in the above table for certain mixtures of propane and butane.

AS 2613 requirements appear identical to the US standard CGA S-1.1 (Ref 6 below).

While the AS 1210 calculation procedure gives a higher required free air flow rate than does the AS 2613 formula in this example, this may not be the case for vessels of different geometries, specifically the relative required flows depend on the ratio of the volume to the area raised to the power of 0.82 (that is, volume/(area)^0.82).

Appendix C References

C1 Perry's Chemical Engineers Handbook (G A Perry and D W Green), 7th Edition 1997

C2 http://www.cheng.cam.ac.uk/~pjb10/thermo/pure.html

C3 S I Chemical Data G H Aylward and T J V Findlay, John Wiley & Sons 1971

C4 R P Lapina How to estimate compressibility factors and specific heat ratios for hydrocarbon gases Chemical Engineering, February 8, 1982, p 95-98

C5 NFPA 58 Liquefied Petroleum Gas Code 2008 Edition, National Fire Protection Association.

C6 CGA S-1.1 Pressure Relief Device Standards Part 1- Containers for Compressed Gases, Thirteenth Edition, Compressed Gas Association, Inc.

C7 H G Fisher in Emergency Relief System Design Using DIERS Technology, Introduction A perspective on Emergency Relief System Design Practice, American Institute of Chemical Engineers, 1992

C8 Handbook of Compressed Gases, Fourth Edition, Compressed Gas Association, Inc, Kluwer Academic Press 1999.

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Appendix D – BLEVE Mechanism

The BLEVE phenomena is widely known and recognised for the potential hazards it creates [1-16]. It has been described as "... the worst possible outcome of a fire engulfed pressure vessel." [10]. While the exact mechanism is still the subject of considerable debate [1-6], it is generally accepted, as noted above, that a strong (hot) BLEVE will occur when a liquid above its superheat limit temperature (SLT) is suddenly depressurised to essentially atmospheric pressure. The SLT, which is the highest temperature at which a metastable liquid can exist at a given pressure, for propane (typically the major component in LPG), is usually quoted at approximately 53°C [1, 3, 6, 9] for depressurisation to atmospheric pressure. For comparison, the SLT of water referenced to atmospheric pressure is reported [1] to be 280°C, though there is some variation in documented figures.

It may be noted that a BLEVE is strictly a physical explosion and can occur with a non-flammable liquid such as water [2]. When the liquid is flammable and the vessel rupture is caused by fire the vented liquid will usually, but not always [2, 10], ignite. The resulting fireball may generally be expected to add greatly to the total energy release and present a severe thermal radiation hazard [1]. It may also produce a substantial blast overpressure (which follows the blast wave of the BLEVE physical explosion [1]). Shaluf [8] ranks the thermal radiation of the fireball the greatest hazard associated with a flammable liquid BLEVE, followed in order by the flying fragments and the blast wave produced by the physical explosion.

From the above, it is apparent that the loss of containment of a pressurised liquid is a prerequisite for a BLEVE. This can occur in several ways, including the high energy impact of a projectile onto a vessel, corrosion and metal failure. However, the mechanism of concern in the present report is that of fire engulfment of the containment vessel. Fire heating of the vessel will cause weakening of the metal that comprises the vessel wall and this may eventually fail. It is also the case that fire engulfment will usually result in the heating of the contained liquid and, if the temperature reaches the SLT, a strong BLEVE may be expected [3].

When a container containing a pressurised liquid and vapour is engulfed in a fire, it may be expected that the "vapour wetted" area of the vessel will become much hotter than the "liquid wetted" area. This is due to the much more efficient heat transfer to the liquid than the vapour. Temperatures in the vapour wetted area can reach well in excess of 600°C, at which point the metal becomes so weakened that it can fail, even if the PRV is operating within specifications [10-13] and so preventing excessive pressures occurring in the vessel. This effect was convincingly demonstrated in the current tests using high speed photography.

Other factors that influence the likelihood of a BLEVE occurrence (and its strength should a BLEVE take place) are the PRV setting and the wall thickness of the containment vessel. It is reported [10, 13] that the stored energy (in the form of superheated liquid) and hence the hazard presented by a BLEVE is reduced when the PRV has a large "blowdown" setting. Early PRV opening is also said to be advantageous [14] as it appears to result in lower vapour space wall temperatures (due to the liquid swell that occurs on PRV opening). Blowdown is defined in AS 4942 as simply "The difference between the set pressure and the re-seating pressure." However, where reference is to percentage blowdown in the above citations, the following equation applies.

$$\%\,Blowdown = 100\left[1 - \frac{reseating - pressure}{opening - pressure}\right]$$

Birk and Cunningham [3] have noted that the wall thickness of the vessel is an important factor, observing that "It was very obvious when conducting these tests that fire impingement of thin-walled uninsulated tanks would always result in BLEVE's." They also note the significance of mass fill level of the contents of a vessel and combine it with the average liquid temperature and burst pressure to prepare a "BLEVE map".

More recently Birk and VanderSteen [12] have studied liquid stratification in vessels that are subjected to fire impingement and engulfment. They point out that the pressure of the vapour in

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the vessel is determined by the hottest liquid (usually at the top) rather than the average temperature. They also note that stratification is much reduced when the PRV opens.

A further factor that delays and reduces the likelihood of a fire engulfed (or impinged) vessel suffering a BLEVE is that of thermal insulation [14-16] as is considered in detail in the report proper.

In summary, strong BLEVE's can flatten the original containment vessel, produce high velocity fragments and cause great damage to surrounding structures as well as giving rise to powerful vapour cloud explosions when the contained liquid is flammable. Although the scale of vessels tested in the present work was much smaller than was the case in most of the literature cited, these effects were observed on a proportionately reduced scale.

Appendix D References

These are as given in the report proper.

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Appendix E – Metallurgical Report from Altrum

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Attention: Mr. Cornelis De Groot
Energy Safety Branch
Department of Commerce

Job Title:

Analysis of the Failure Mechanism of an LPG Vessel

Authors: Nicholas John Langford
Jonathan William Langford

Altrum Job Number: J049

Altrum Reference: J049-R-02

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EXECUTIVE SUMMARY

Altrum Pty Ltd was requested to investigate the remnants of an LPG tank involved in an explosion during a vehicle fire. The intent of the investigation was to confirm the mode of failure of the vessel that led to the suspected BLEVE within the tank and subsequent explosion.

The items from the tank had suffered considerable predation as a consequence of sample removal in prior investigations by other parties. Rectangular sections had been removed for tensile testing, hardness testing and sectional examination prior to receipt by Altrum (refer Fig. 2 and Fig. 7).

In discussion with personnel from DoC, it was agreed that the extent of the metal thinning be determined and if possible related to the causative mechanisms for the tank explosion.

A simple model based on yield and tensile strength data for equivalent grades of steel at elevated temperatures indicates that the metal may have been at a temperature of 600-700°C at the location of the failure.

From inspection and measurement of the failed tank components and reference to data on steel properties at elevated temperatures, it was concluded that that the top of the vessel had been subjected to intensive localised heating. This heating, in combination with elevated pressures within the tank due to heating of the tank contents, led to a destructive failure of the shell, which in turn provided the conditions necessary for a BLEVE to occur. It is possible that the design pressure of the tank was not exceeded prior to rupture.

Poor weld quality was observed in certain areas but we are unable to determine at this stage whether this was consequential in the failure of this particular vessel.

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1.0 INTRODUCTION.

1.1.1 Altrum Pty Ltd was requested to investigate the remnants of an LPG tank involved in an explosion during a vehicle fire. The intent of the investigation was to confirm the mode of failure of the vessel that led to the suspected BLEVE within the tank and subsequent explosion.

1.1.2 The vehicle in question was a taxi parked partially off road and subjected to arson. The vehicle was a station wagon taxi allegedly with a tank full of fuel.

1.1.3 The image provided on the FESA web site suggests that the vehicle had been parked with a downward inclination of several degrees at the near side of the vehicle. The vehicle was not inverted at any stage during the fire, and so remained within the normal design orientation. The tank components resulting from the explosion are shown on the ground at upper left of image, having been removed from the vehicle prior to taking this photograph.

Figure 1. Vehicle the subject to arson, as shown on the FESA web site.

1.1.4 The fire seems to have originated in the passenger compartment. A portion of the off-side rear tyre remains. The right inner tyre guard has detached in the fire or has been detached subsequently.

1.1.5 It is said that the roof was blown off and landed 100m away. The tank heads and shell apparently remained in the vehicle.

1.1.6 FESA attribute the tank destruction to a BLEVE [Boiling Liquid Expanding Vapour Explosion].

2.0 VISUAL EXAMINATION OF TANK COMPONENTS.

2.1 SHELL OUTER

2.1.1 The LPG tank outer shell is shown in Figure 2 under. The image shows sample points and markings from previous investigations.

Figure 2. Outer view of LPG shell as received by Altrum.

2.1.2 The upper edge of the shell shows a highly plastic fracture that has propagated through a region at the upper apex of the tank at a distance of between 2 and 35mm from the longitudinal weld and spaced from the valve plate by a distance of approximately 110mm. A portion of material had been removed for analysis

by others, and may have contained a section where the fracture was at the weld bead.

2.1.3 The upper part of the image region shows a trapezoidal darker region immediately above and aligning with the upper edge of the valve thickener plate. This region is much convoluted compared with other edges of the shell. The dark region increases in vertical size towards the left size of the image.

2.1.4 The dark region shows more extensive oxidation than the region below the valve level where remnants of paint primer are visible.

2.1.5 The bottom region of the image shows the fracture edge spaced between 2 and 35mm from, but approaching close to, a distorted longitudinal weld bead in the region of the vertical rectangular aperture.

2.1.6 The region adjacent to the longitudinal weld is more heavily oxidised and darker than the primer coated area closer to the centre of the image.

2.1.7 Transverse crease marks show towards the centre and the shell has been plastically flattened.

2.1.8 The valve plate shows residue of aluminium top coat on the exterior fillet welds. The patterns around the valve plate holes appear to indicate seal integrity. Cracks were noted at two of the corners of the valve plate weld.

Figure 3. Valve plate outer view showing through corner crack (white arrow).

2.1.9 The cracks were visually inspected. One of these cracks is definitely a through crack with light visible through the crack. The through crack measured 15.0mm in length, and the other crack measured 14.6mm linearly between end points. Both occur at the toe of the weld at the junction with the shell. Weld fusion appears poor in the area of the cracks, and one of the cracks has occurred where a weld stop/start has been executed on the corner of the valve plate. It is not possible to determine if the cracks occurred prior to the BLEVE, or were a result of bending of the shell during and after the BLEVE (see further notes, section 2.3).

2.2 SHELL INNER

2.2.1 The shell inner Figure 4 shows scaling each side of the valve plate and towards the lower left. These scale patterns are not reflected in a marked degree to the patterns observed on the obverse side of the plate.

Figure 4. Tank inner view showing oxidation areas and chalked thickness contours.

2.2.2 The surfaces adjacent to the fracture edges show as black and lustrous, changing to a dull blue film in the areas where there is less thinning, with a large area where light oxidation has occurred. The black and blue films are typical of the heating of metal in the presence of hydrocarbons in a reducing environment, but they are only a qualitative indicator of heating as representative and controlled test data for comparison is unavailable.

2.2.3 The coloured lines are plate thickness contours established by calliper gauging of the shell plate.

Figure 5. Internal weld of valve block showing tendency to roll-over and possible lack of fusion.

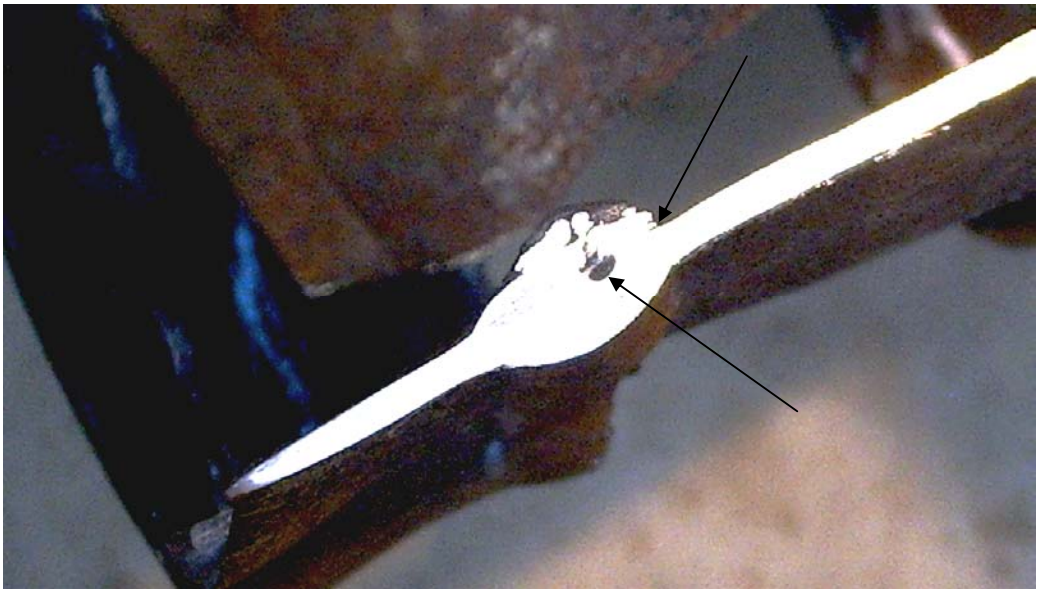


Figure 6. Cross-section of longitudinal weld showing porosity and lack of fusion at right weld root

2.2.4 The internal welds show a number of defects associated with slag inclusions, porosity and lack of fusion. These extend through over 50% of the total weld depth, but still leave material equivalent or greater than the plate thickness.

2.2.5 No attempt has been made to establish the extent of any Heat Affected Zone (HAZ) around the weld. The manufacturer's data report indicated that the vessel had been normalised after manufacture, which should have the effect of removing any microstructural changes which were produced during welding thermal disturbance of that area.

2.3 DISHED ENDS

2.3.1 The explosion had detached the heads from the shell. The heads had distorted elliptically, the points at the apex of the minimum radii showed plastic deformation directed along the major axis of the tank and ductile tearing along the weld toe.

2.3.2 The interior surfaces of the heads (Fig.5) showed a mill scale surface with rust staining. The exterior surfaces showed aluminium paint, primer and soot deposits.

Figure 7. Inner view of heads showing mill scale and rust.

2.3.3 The circumferential fractures show mechanical damage, such as rubbing, burring, general deformation and staining, which is probably a combination by the fire event and subsequent handling. Examinations of the circumferential welds near the upper apices above, showed a coarse fibrous ductile fracture with indications of a shear lip and an irregular fracture surface as displayed in Fig. 8.

Figure 8. Macrograph (X2) of circumferential fracture (lower sector) showing an irregular tear with indications of shear lips (lower left) at the weld/plate junction.

2.4 SAFETY RELIEF VALVE COMPONENTS

2.4.1 The safety relief valve forms part of the LPG multi-valve.

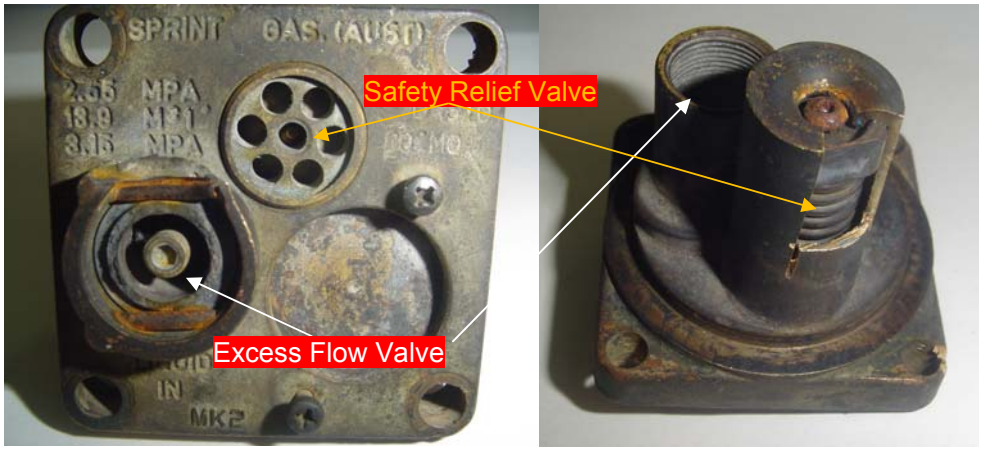


Figure 9. Safety Relief Valve (part of LPG Multi-Valve) as received. External face (left-hand view) and internal face (right-hand view).

2.4.2 A section of the Safety Relief Valve housing had been removed by others prior to receipt by Altrum.

2.4.3 There is some damage over the external portion of the housing of the Excess Flow Valve. This is thought to be impact damage from the explosion.

2.4.4 The internal surfaces of the valve have a distinct black stain that is easily removed with a metal scraper. This is not present on the external surfaces of the valve. This may indicate that the stain on the internal surface is not a result of exposure to the fire after the explosion.

Figure 10. Poppet removed from Safety Relief Valve on left, compared to new item on right.

2.4.5 The rubber seal of the poppet of the Safety Relief Valve is not present, and appears to have disintegrated or burnt away in the fire. It is not clear whether this occurred before or after the explosion. This can be compared to a new item, as per Figure 10.

2.4.6 The Safety Relief Valve assembly could be easily removed by hand. This would indicate that the spring rate has reduced from the original design spring rate. A new spring was not available for comparison purposes.

3.0 MEASUREMENT OF SHELL PLATE THICKNESS.

3.1.1 The average plate thickness measured by ball anvil micrometer at ten locations away from heat affected regions and edges was 2.52 ± 0.01 mm.

3.1.2 Marked thinning of the plate was observed along the edges of the longitudinal tear. In places the thickness was less than 1.0 mm as is shown in Figure 11. The thinned area approximated a knife-edge, which made thickness measurement difficult, but readings of down to 0.50mm were obtained.

Figure 11. Digital calliper recording thickness of plate edge adjacent to valve plate.

3.1.3 Gauging of the shell plate provided thickness contours that were overlaid on a digital reconstruction of the torn edges restored to their approximate original shape (Fig 12).

3.1.4 The contours show an elongated thinning band of less than 1.8 mm thickness alongside and crossing the longitudinal weld (magenta line).

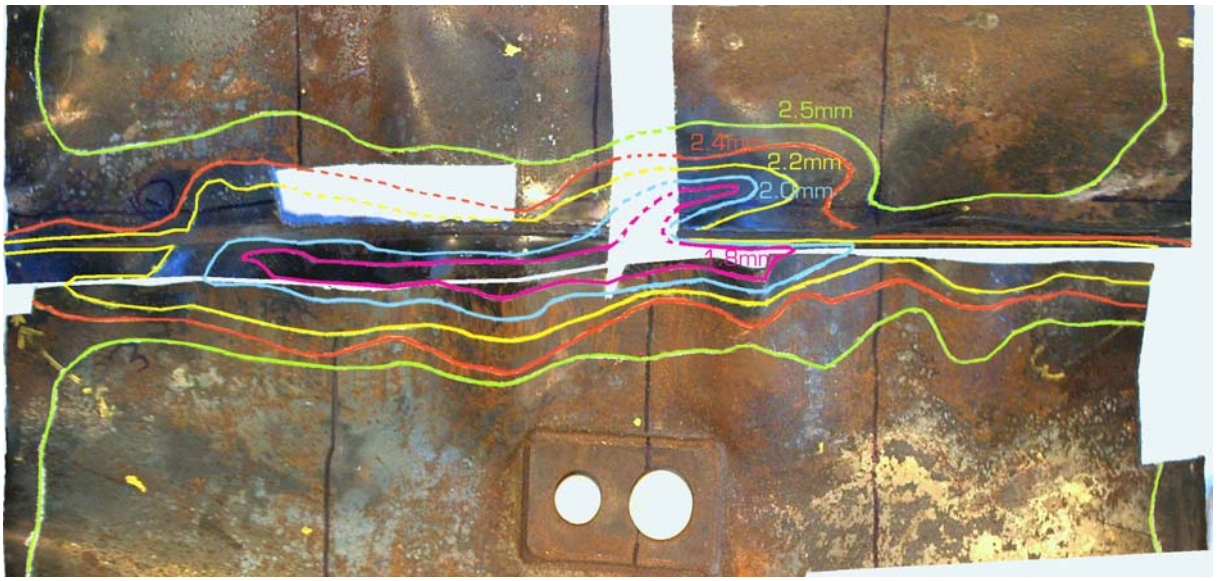


Figure 12. Plate thickness near the digitally reconstructed longitudinal weld area.

4.0 GRAPHICAL THREE-DIMENSIONAL MODEL OF THE THINNED REGIONS.

4.1.1 Utilising the contours in Fig 12. a three dimensional model has been constructed. Extracted images from this model are presented in Appendix A of this report.

5.0 CALCULATIONS AND MATHEMATICAL MODELLING

5.1.1 A basic determination of the temperature range of the metal can be made from the yield and tensile strength curves for steel similar to that used in the construction of the LPG tank.

5.1.2 Figure 13 below provides rapid stress rupture curves for the yield and tensile strength of Timken carbon steel material (C=0.1-0.2%, Mn= 0.3-0.8%. Si<0.25%) as a function of temperature. This material is similar to that used for the construction of the LPG tank.

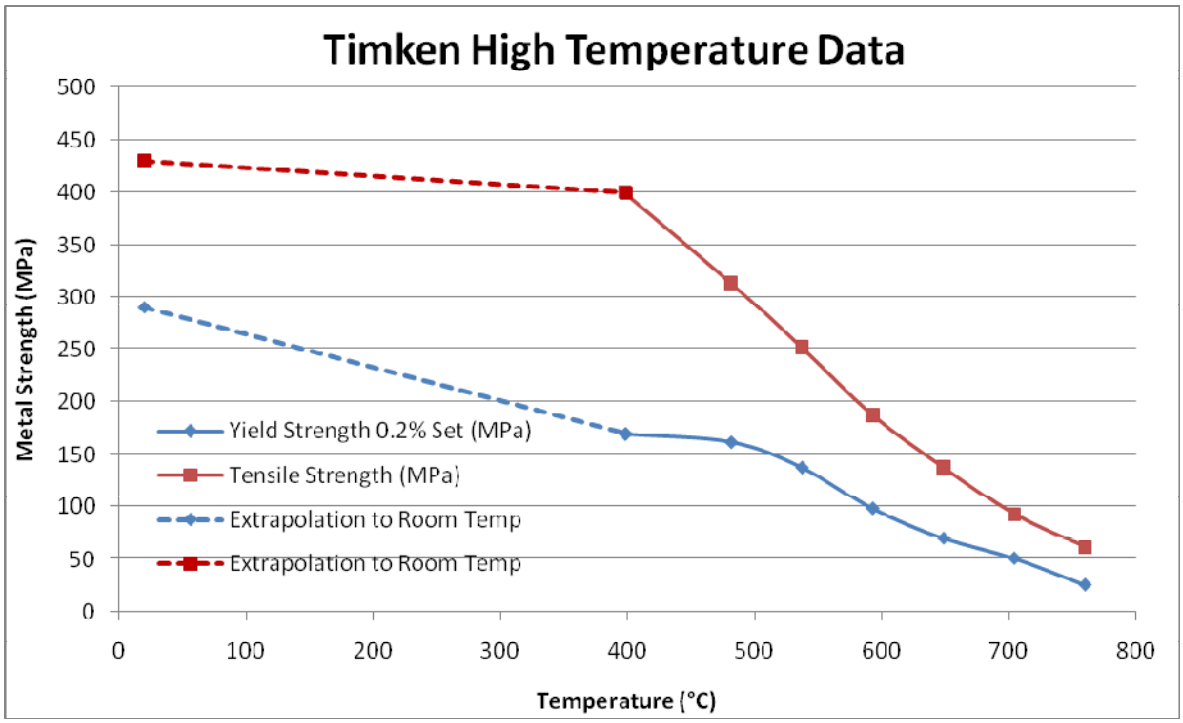


Figure 13. Short term Tensile rupture and Yield strength values for a low carbon steel similar to the tank shell. [The Timken Roller Bearing Co.]

5.1.3 Using the hoop stress on the vessel shell produced by the internal pressure, it is possible to produce a plot of the upper and lower bounds of metal temperature required to produce a rupture as a function of internal pressure. This is presented in Figure 14 below. The equation used to determine the Hoop Stress was:

Stress (MPa) = Pressure (MPa)*[Diameter(mm)/2]/[Thickness(mm)]

5.1.4 The lower bound temperature would represent the temperature at which rapid metal stress rupture would begin to occur. With increasing temperature above the yield point, the rate of metal stress rupture will increase accordingly, leading to rapid failure.

5.1.5 The upper bound temperature would represent the temperature at which almost instantaneous failure occurs.

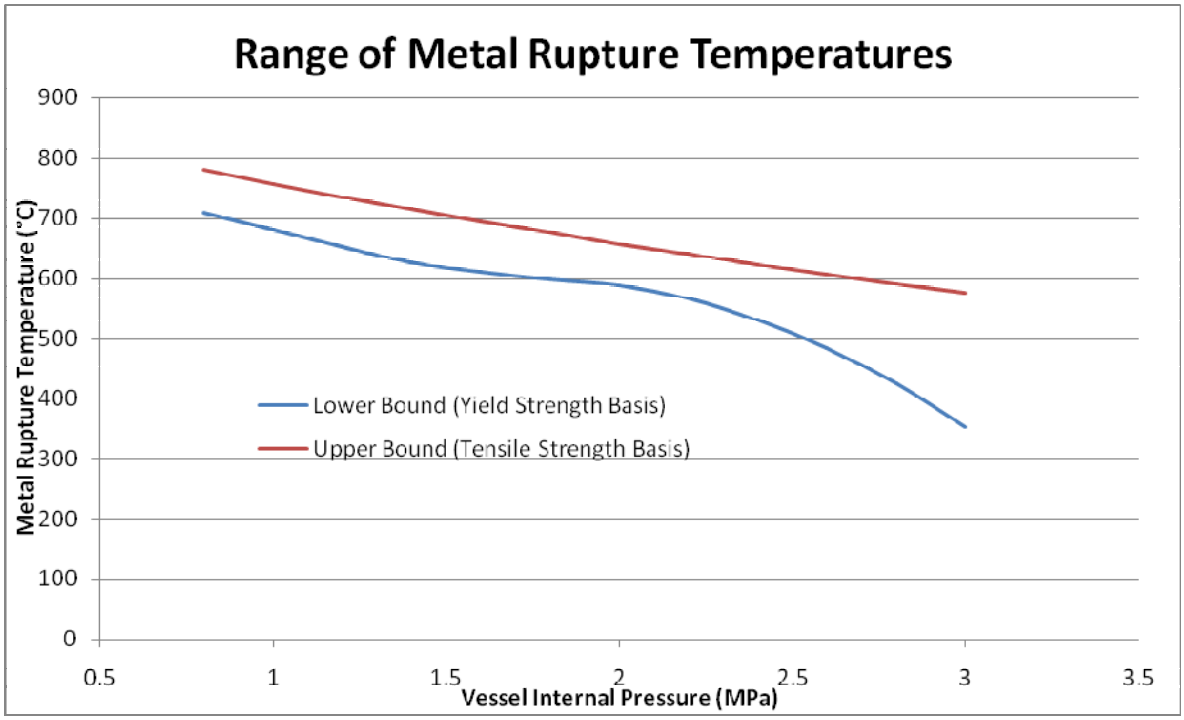


Figure 14. Plot of Upper and Lower Bound Metal Rupture Temperatures as a Function of Vessel Internal Pressure

5.1.6 The actual temperature at which the failure is likely to have occurred would fall somewhere between the upper and lower values. Above the lower bound in the above graphic, the temperature would have to be sufficient for short time stress rupture to occur, given that it is supposed that the failure occurred within minutes of the fire being lit. However, there is no intermediate data available to develop a curve of failure rate as a function of temperature for this failure mode.

5.1.7 If the conjecture is that failure occurred within minutes of the commencement of the fire, it would be necessary for the steel to be subjected to extremely rapid metal stress rupture, which would suggest that the likely steel temperature leading to failure would be towards the upper bound curve of Figure 14.

5.1.8 Previous investigation into this failure indicated from microstructural observations that the steel adjacent to the fracture had not attained a temperature greater than 723°C (AC_1 - lower critical temperature).

5.1.9 It has been reported that the pressure relief valve operated during the fire, which would indicate that the internal pressure was in excess of 2.55MPa. Under these conditions, failure may be expected at approximately 600-700°C steel temperature.

5.1.10 It is not possible to confirm the actual pressures that may have been experienced within the vessel. The initial flow through the relief valve may have been liquid phase or two phase flow, which may have allowed the pressure to rise well above the 2.55MPa relief pressure. It was also noted after the fire that the relief valve seat was missing and the spring strength was reduced. If either of these had occurred during the initial deflagration, then the release of material through the relief valve may have occurred at a lower pressure.

5.1.11 The above temperature of 600-700°C would be achievable on an unquenched surface (such as the metal above the liquid level) in the event of a close proximity fire. The basis for this would be a simple heat transfer model with a flame temperature of 1150°C and a gas phase temperature of 50°C as displayed in Figure 15.

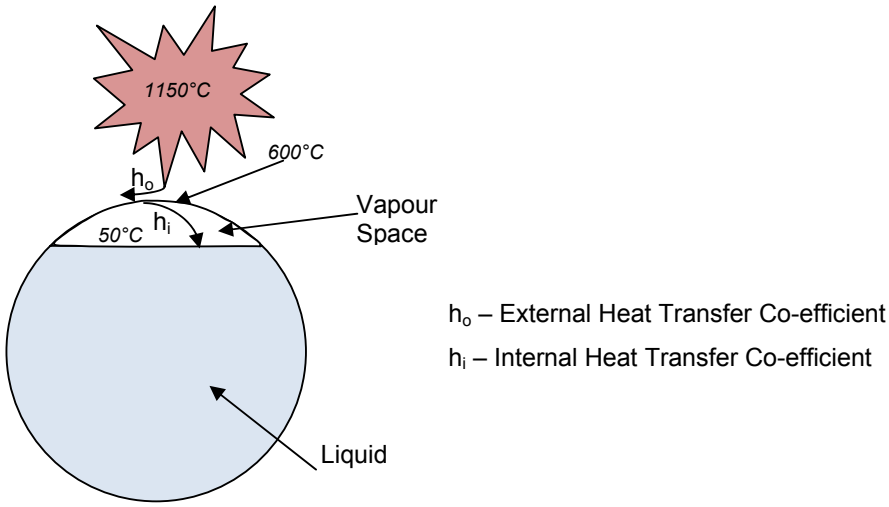


Figure 15. Simple Heat Transfer Model

5.1.12 Assuming similar heat transfer co-efficients on both sides of the metal (flame side and gas side), the equilibrium metal temperature will then be the arithmetic mean of the two temperatures, or about 600°C. In practice, the heat transfer co-efficient on the flame side is likely to be higher due to greater turbulence, and the flame will provide significant radiant effects, both of which will serve to skew the metal temperature toward the flame temperature.

6.0 DISCUSSION.

6.1 PRIOR FINDINGS

6.1.1 The tank parts as supplied to Altrum had been subjected to earlier metallurgical evaluation. This had established that:

- The steel was a low carbon aluminium treated steel of 0.15%C and 0.89%Mn.
- The microstructure of blocky ferrite and fine pearlite (spherodite) accorded with the steel analysis and heat treatment claimed in the tank specifications.
- Readings obtained using a low load Vickers hardness test were not abnormal.

6.1.2 The parts received by Altrum had been previously sampled at several locations. The fracture surfaces were aged and stained by the fire, its suppression and by multiple handlings. None-the-less it was felt that careful visual examination of the parts could provide information leading to a mechanistic explanation for the vessel explosion.

6.2 FURTHER FINDINGS OF THIS REPORT

6.2.1 It was noted that portions of the edges associated with the longitudinal fracture had thinned markedly. The regions towards the centre of the plate averaged 2.52mm yet in the fracture edges were in regions the thickness of a dull knife edge at 0.50 mm.

6.2.2 The explanation for such extreme reduction of the plate thickness (80%) would be that the steel had undergone high temperature stress rupture in that location. Steels of the shell composition show an increase in ductility before fracture and a pronounced reduction in strength as temperature increases towards the lower critical temperature. The presence of a knife-edge is indicative of a ductile failure.

6.2.3 As is shown in Figure 11, there is a marked reduction in plate thickness at the fracture edge. Figure 12 shows that the thinning extends along the top of the tank and the extent of this thinning is further illustrated in Appendix A.

6.2.4 The thinning observed must be a consequence of stretching of the crown of the vessel. This would be caused by a combination of temperature induced reduction in material strength and the elevated vapour pressure generated by the heating of the vessel contents producing a consequent increase in hoop and longitudinal stresses in the vessel wall.

6.2.5 The stretching pattern seems to accord with more heavily oxidised areas exposed to a higher temperature, as is shown in the image of the outside of the shell (Figure 2).

6.2.6 The rectangular valve plate shows cracking at the corners towards the longitudinal seam (Figure 3). One of these cracks penetrates to the inside of the tank and has dimensions approximately 0.2 x 15 mm. Whether this cracking occurred prior to the explosion or as a consequence of the explosion was not requested and has not been investigated. It is however noted that the internal weld geometry is poor at this point and is doubtless caused by the difficult

internal access. The internal welds particularly at the corners may be associated with lack of side fusion and penetration.

6.2.7 Residual aluminium top coat around the valve plate suggests that temperatures in this region were lower than the crown of the vessel.

6.2.8 The interior of the shell (Figure 4) shows less definitive evidence of heating at the crown of the tank. This is due no doubt to the fire continuing after the explosion. The lustrous areas observed near the fracture are likely to be the consequence of the hydrocarbons reacting with the heated metal in a reducing environment.

6.2.9 The longitudinal weld seam showed multiple weld defects.

6.2.10 Examination of the heads showed that they were less oxidised than the shell. The circumferential welds displayed ductile fracture and tearing. The distortion of the heads is attributed to torsion applied by the residual circumferential weld connection once the bulk of these welds were torn away whilst the heads twisted and blasted free.

6.2.11 It is estimated that the shell steel temperature was in the order of 600-700°C in the areas associated with the highest level of thinning. It is noted that approximately half of the longitudinal fracture occurred through metal that had not thinned by more than 25%. Once a rupture had occurred at the thinnest point (or other thin and compromised area), the resulting crack would propagate more-or-less longitudinally through the metal shell (perpendicular to the hoop stress) along the line of least resistance. The observed fracture appears to travel through the thinnest section of metal at each cross-section of the vessel (refer Fig. 12).

6.2.12 With the above metal temperatures, it is possible for the vessel to fail without the pressure relief actuating. It is also feasible that the pressure relief valve operated and provided additional fuel for the heating of the vessel, given that the valve block is in the proximity of the observed thinning. Given the damage to the valve and other anecdotal evidence, it would appear that the relief valve did operate in a manner to vent gas during the fire event.

6.2.13 A section of the shell had been removed for testing during previous investigations. At the location of the test piece sample, the fracture was very close to the longitudinal weld, and given the presence of defects in the weld at this location, it is not possible to rule out the weld as an initiator of the fracture. Better quality construction may have allowed the vessel to retain integrity for a longer period of time, although it is unlikely to have prevented the failure. Further examination of this section would be advisable if it is available, to determine if any possible propagation point may have existed in the weld.

6.2.14 Other than defects in the weld, the weld itself should not have been a particular point of propagation of the failure. The normalising of the vessel after construction should have removed the effects of a Heat Affected Zone and produced a metal with consistent properties across the weld interface.

7.0 CONCLUSION

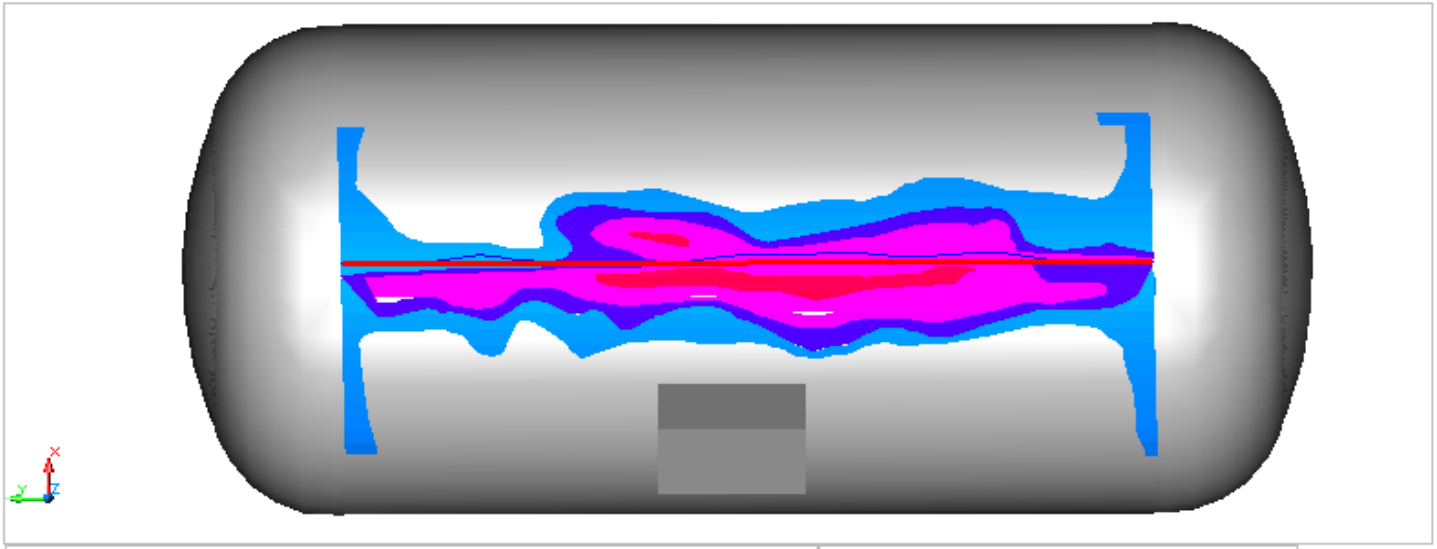
7.1.1 The arson event caused the top portion of the vessel to heat to a temperature estimated to be in the range 600-700°C, at which temperature the resolved stress in the shell due to the rising vapour pressure was sufficient to cause rapid stress rupture of the shell and a consequent BLEVE, resulting in the catastrophic failure of the LPG tank.

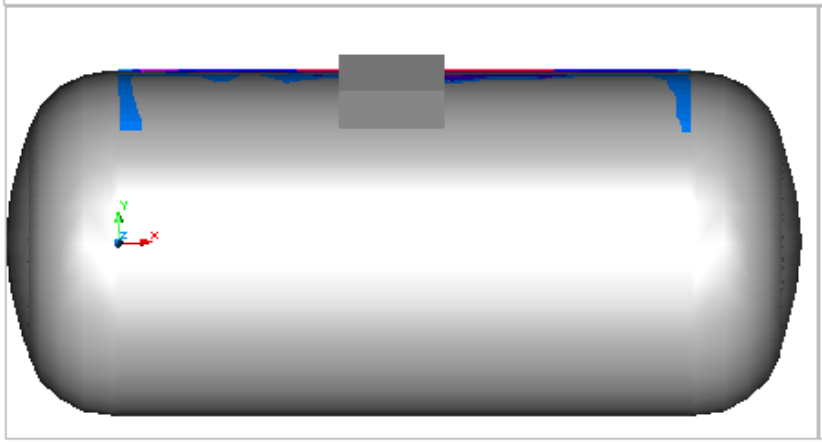
7.1.2 Given the above steel temperatures, it is possible that the failure could occur without the relief valve actuating. However it is likely that the relief valve did allow LPG to vent from the vessel, which may have been contributory to the external heating of the LPG tank.

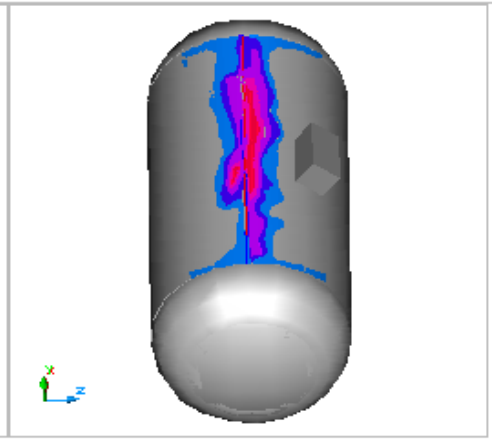
7.1.3 Poor weld quality was observed in certain areas but we are unable to determine at this stage whether this was consequential in the failure of this particular vessel.

Appendix A – 3D Representation of Vessel Metal Thinning

SHELL METAL THICKNESS REDUCTION - SKETCH 1







LEGEND

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- < 2.0mm
- < 2.2mm
- < 2.4mm
- < 2.5mm

No.	REVISION	DRN	CHKD	APPD	DATE
A	FOR INFORMATION ONLY	JWL			19.06.09

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SCALE: NOT TO SCALE

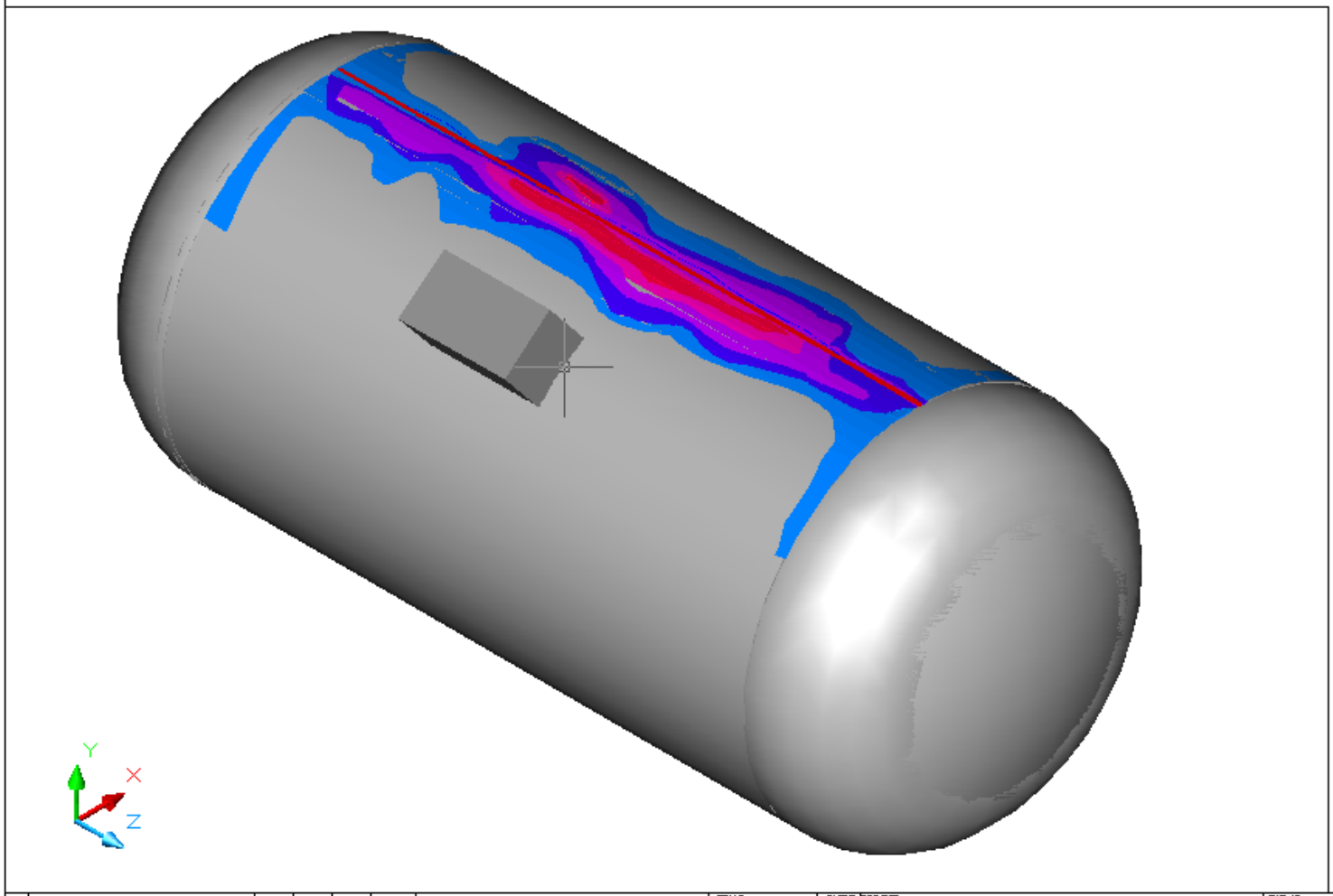
CLIENT/PROJECT: DEPT OF COMMERCE

TITLE: LPG CYLINDER SHELL METAL THICKNESS REDUCTION

DWG #: J049 - sketch - 01

REVISION: A

SHELL METAL THICKNESS REDUCTION - SKETCH 2



LEGEND

- < 1.8mm
- < 2.0mm
- < 2.2mm
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A3

SCALE: NOT TO SCALE

CLIENT/PROJECT: DEPT OF COMMERCE

TITLE: LPG CYLINDER SHELL METAL THICKNESS REDUCTION

DWG N°: J049 - sketch - 02

REVISION: A

Appendix F – Container and PRV Drawings

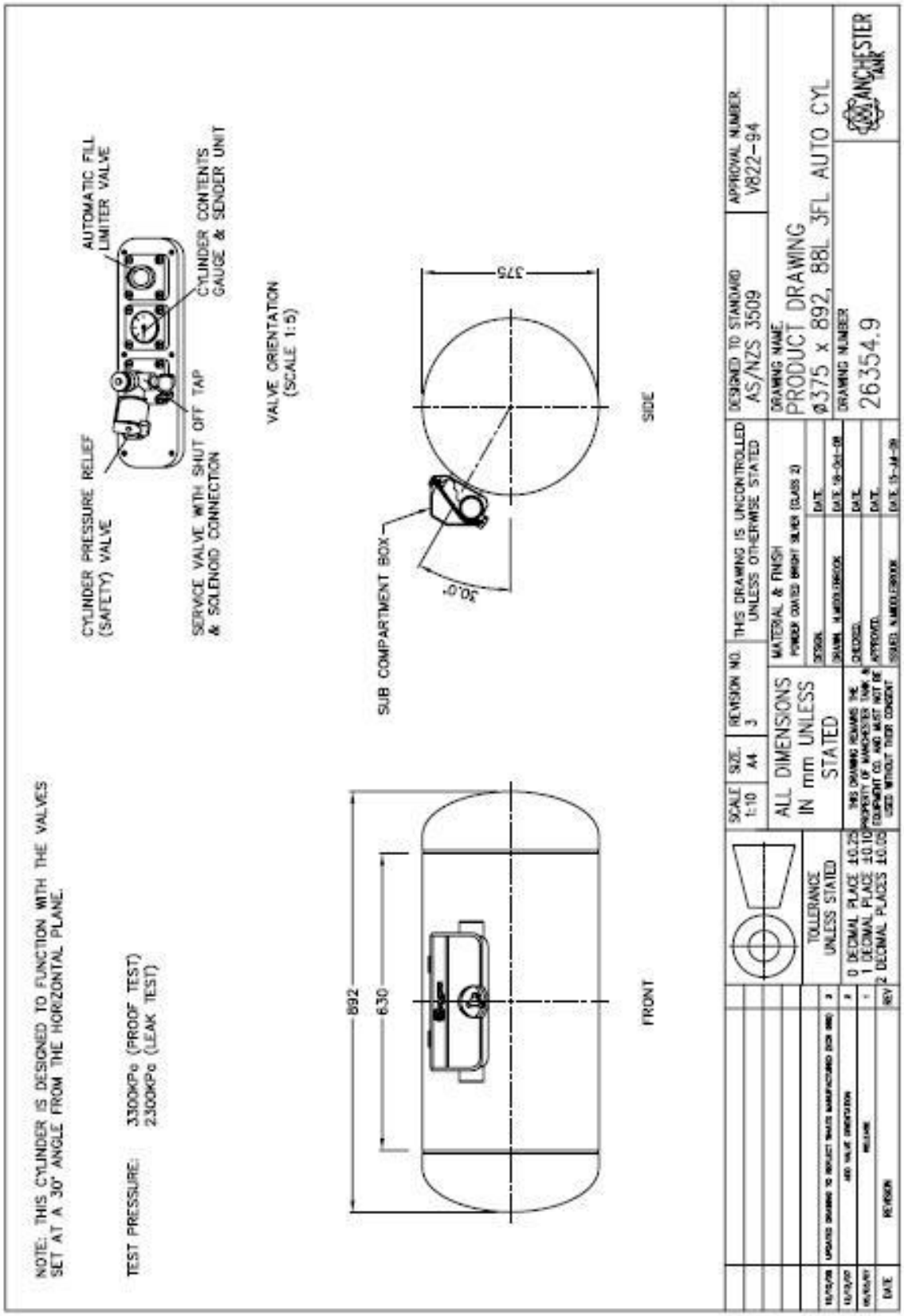

Figure E1 – Manchester Container Design

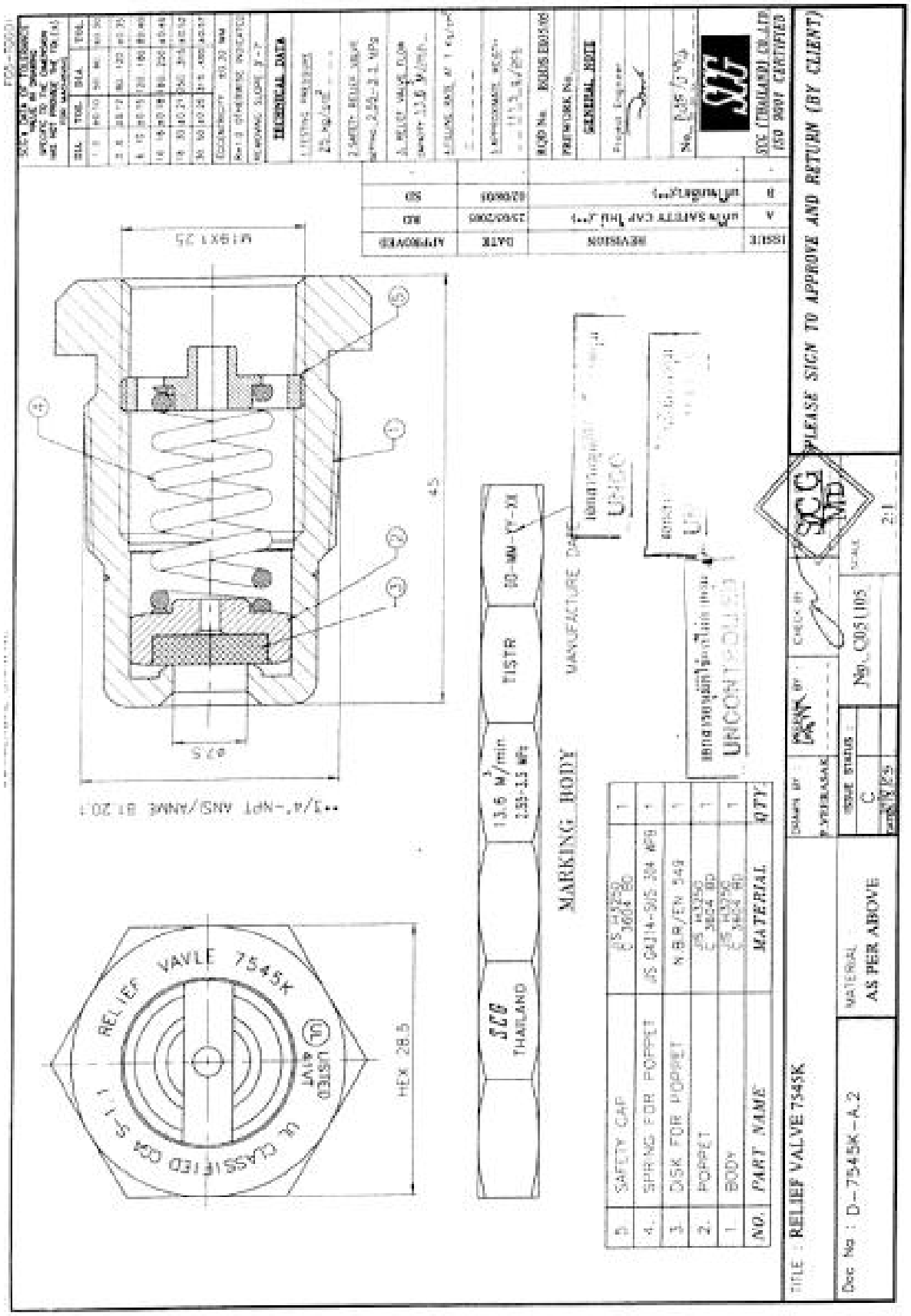

Figure E2 – SCG (Manchester) PRV Design

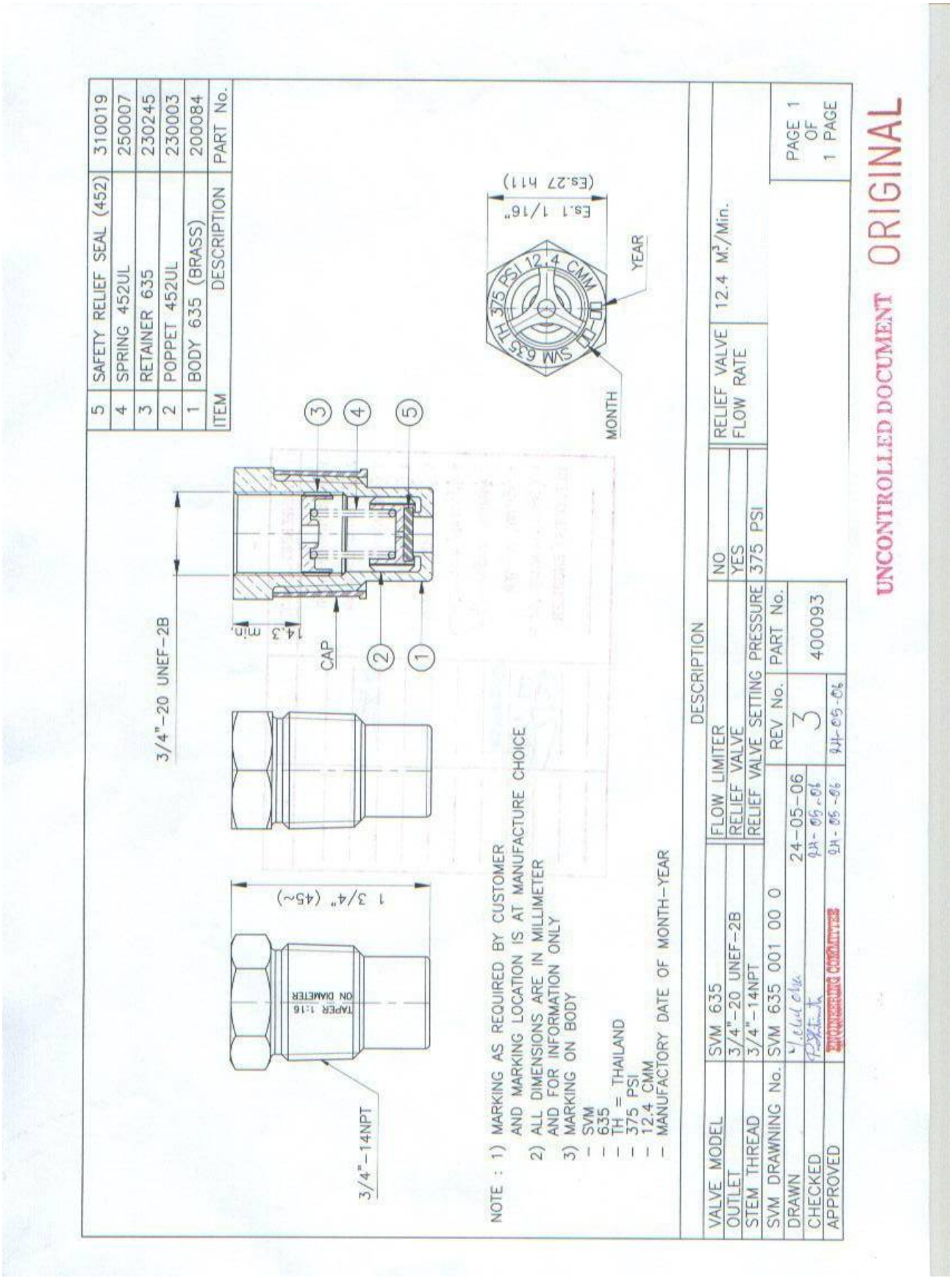

Figure E3 – SVM (APA) PRV Design

Appendix G – AS/NZS 4645.1:2008 Risk Matrix

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APPENDIX C

QUALITATIVE RISK ASSESSMENT

(Informative)

C1 GENERAL

This appendix provides guidance for qualitative risk assessment undertaken in accordance with AS/NZS 4360.

Where a failure event may have several outcomes, the consequence and frequency of each outcome shall be considered. Full evaluation of every outcome may not be necessary, but sufficient outcomes shall be evaluated to identify the outcome with the highest risk ranking.

NOTE: The highest energy release rate may not give rise to the highest consequence or the highest risk (e.g. a small LPG leak which is initially unignited may well have a higher consequence or higher risk ranking than a large immediately ignited release).

C2 CONSEQUENCE ANALYSIS

The severity of the consequences of each failure event shall be assessed. Consequences to be assessed shall include the potential for the following:

(a) Human injury or fatality.

(b) Interruption to continuity of supply with economic impact.

(c) Environmental damage.

NOTES:

1 Other factors such as property damage and loss of reputation may also be considered.

2 Gas distribution networks and some liquid petroleum gas distribution networks may be identified as 'essential infrastructure' where the consequence of a loss of supply is significant. This may be in terms of the potential for economic impact, and in some cases significant fatalities may result from the cascading consequence of loss of the energy supply.

A severity class shall be assigned to each failure event based on the consequences at the location of the failure. The severity class may be selected from Table C1.

Where necessary to make the severity classes applicable to the gas distribution network under study the measures of severity in Table C1 may be modified with the agreement of the stakeholders. Modification should be minimized. Any modification of the severity classes shall be undertaken so that consistency with Table C3 is maintained.

The reasons for any changes to the measures of severity shall be documented and approved.

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TABLE C1

SEVERITY CLASSES

Dimension	Severity class				
	Catastrophic	Major	Severe	Minor	Trivial
	Measures of severity				
People	Multiple fatalities result.	Few fatalities, or several people with life-threatening injuries	Injury or illness requiring hospital treatment	Injuries requiring first aid treatment	Minimal impact on health and safety
Supply	Long term interruption of supply	Prolonged interruption or long-term restriction of supply	Short term interruption or prolonged restriction of supply	Short term interruption or restriction of supply but shortfall met from other sources	No impact; no restriction of gas distribution network supply
Environment (See Note)	Effects widespread, viability of ecosystems or species affected, permanent major changes	Major off-site impact or long-term severe effects or rectification difficult	Localized (<1 ha) and short-term (<2 yr) effects, easily rectified	Effect very localized (<0.1 ha) and very short term (weeks), minimal rectification	No effect, or minor on-site effects rectified rapidly with negligible residual effect

NOTE: Significant environmental consequences may occur in locations which are relatively small and isolated.

C3 FREQUENCY ANALYSIS

A frequency of occurrence of each threat shall be assigned for each location where risk estimation is required. The frequency of occurrence shall be selected from Table ~~A~~C1.3(a).

The contribution of operations and maintenance practices and procedures to the occurrence or prevention of failure events shall be considered in assigning the frequency of occurrence.

TABLE C2

FREQUENCY CLASSES

Frequency class	Frequency description
Frequent	Expected to occur once per year or more
Occasional	May occur occasionally in the life of the gas distribution network
Unlikely	Unlikely to occur within the life of the gas distribution network, but possible
Remote	Not anticipated for this gas distribution network at this location
Hypothetical	Theoretically possible but has never occurred on a similar gas distribution network

For a threat which exists for a limited period the frequency class should be assessed against the exposure period rather than the life of the gas distribution network.

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C4 RISK RANKING

Table C3 shall be used to combine the results of frequency analysis and consequence analysis and determine the risk rank.

Risks determined to be low or negligible or demonstrated to be as low as reasonably practicable (ALARP) are accepted risks.

TABLE C3

RISK MATRIX

	Catastrophic	Major	Severe	Minor	Trivial
Frequent	Extreme	Extreme	High	Intermediate	Low
Occasional	Extreme	High	Intermediate	Low	Low
Unlikely	High	High	Intermediate	Low	Negligible
Remote	High	Intermediate	Low	Negligible	Negligible
Hypothetical	Intermediate	Low	Negligible	Negligible	Negligible

C5 RISK TREATMENT

C5.1 General

Action to reduce risk shall be taken in accordance with Table C4 based on the risk rank determined from Table C3.

The action(s) taken and their effect on safety management shall be documented and approved.

TABLE C4

RISK TREATMENT ACTIONS

Risk rank	Required Action
Extreme	Modify the threat, the frequency or the consequences to ensure that the risk rank is reduced to Intermediate or lower. For a gas distribution network in operation the risk must be reduced immediately.
High	Modify the threat, the frequency or the consequences to ensure that the risk rank is reduced to Intermediate or lower. For a gas distribution network in operation the risk must be reduced as soon as possible, typically within a timescale of not more than a few weeks.
Intermediate	Repeat threat identification and risk evaluation processes to verify and, where possible, quantify the risk estimation; determine the accuracy and uncertainty of the estimation. Where the risk rank is confirmed to be Intermediate, if possible modify the threat, the frequency or the consequence to reduce the risk rank to Low or Negligible. Where the risk rank cannot be reduced to Low or Negligible action shall be taken to— (a) remove threats, reduce frequencies and/or reduce severity of consequences to the extent practicable, and (b) demonstrate ALARP. For a gas distribution network that is in operation, the reduction to Low or Negligible or demonstration of ALARP must be completed as soon as possible, typically within a timescale of not more than a few months.
Low	Determine the management plan for the threat to prevent occurrence and to monitor changes which could affect the classification.
Negligible	Review at the next review interval.

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C5.2 ALARP

A risk cannot be designated as ALARP until the following has been completed:

(a) Analysis of the means of further reducing the risk, including an analysis of various options.

(b) Review as to the reasons why these further means have not been adopted.

(c) Substantiation that the cost of further risk reduction measures is grossly disproportionate to the benefit gained from the reduced risk that would result.

Options that shall be considered include—

(i) relocation of the network components;

(ii) modification of the design of network components;

(iii) review of pressure levels;

(iv) modification or enhancement of specific operations or maintenance procedures;

(v) modification to gas distribution network marking; and

(vi) threat treatment for operating gas distribution networks shall consider interim control measures (e.g. reduction in operating pressure, access restrictions) to allow time for the implementation of permanent control measures (e.g. repair).

The further risk reduction measures considered and the reasons they have not been adopted shall be documented.

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Appendix H – Method of Test for BLEVE Resistance

It is shown from the pressure temperature plots, the tested containers which did not BLEVE, had in most cases multiple controls added. However all containers that did not BLEVE, still came quite close to actual rupture/BLEVE conditions.

In engineering, a Safety Margin is quite common and therefore should be considered for the BLEVE case. The figure 10.1 below introduces such margin for 5, 10, 15, 20 and 25% by reducing the tensile strength stress/temperature based curves.

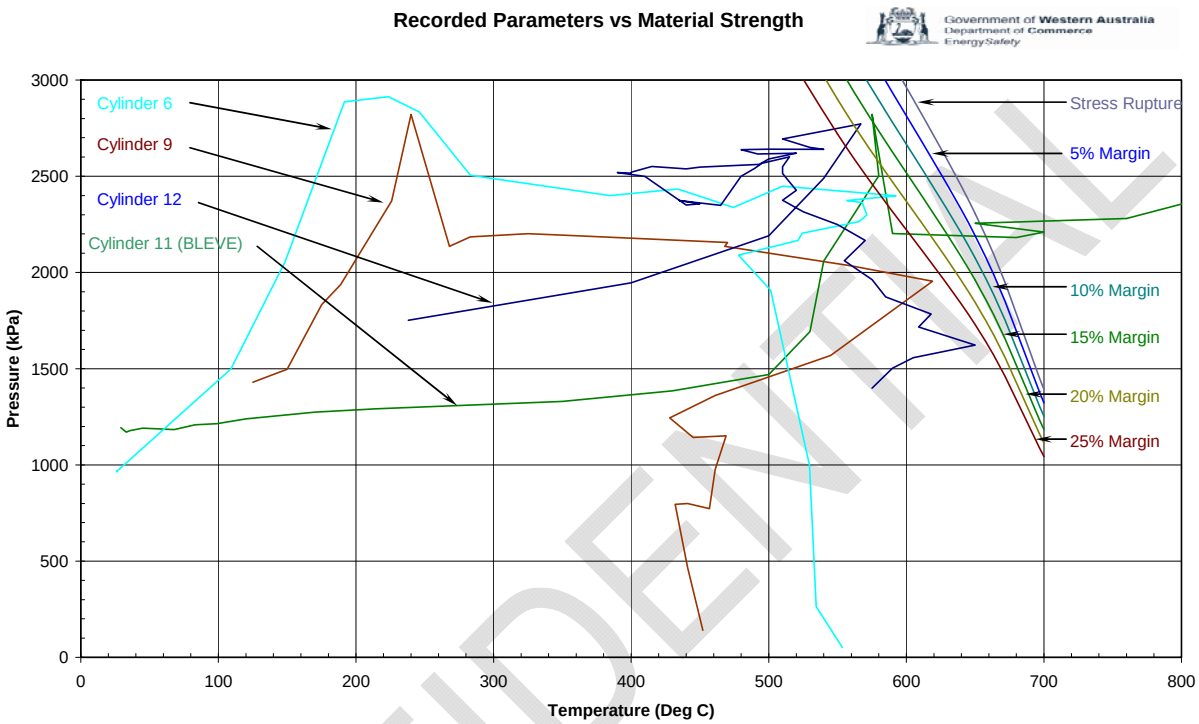

Figure H1 – Pressure – temperature profile with material strength limit margin

While the development of a suitable method of test for BLEVE resistance would be a complex procedure involving inputs from many stakeholders and experts in the area, certain salient points can be identified as essential if the test is to be representative and credible. These are listed below:-

1. The test must be performed using a model of vehicle not more than 10 years old, and the installation under test conditions must be similar to that under the intended installation conditions. This requirement ensures that significant design changes of the vehicles will not occur between the test vehicle and the intended installation. If in future, design changes require the use of more recent vehicles for testing purposes, then this needs to be carried out accordingly. One example would be that the use of plastic floor panels would make a test invalid if the test was carried out in a vehicle with steel floor panels.
2. The vehicle must be a “family sized” wagon, rather than a sedan.
3. Approximately 40 kg of dry flammable material (such as paper, cardboard or pieces of wood) must be added to the vehicle in the area of the container compartment as extra fuel load
4. The wind speed during testing should not exceed 20 km/h.

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5. The container must be filled to maximum fill level with “autograde” LPG, with maximum allowable Butane content and straight Propane. This fill is taken to be the mass that would fill the vessel to 80% of its internal volume with the LPG at temperature 5°C.
6. The vehicle interior must be intact and complete.
7. Installation needs to conform to the intended installation method
8. Both pressure and multiple shell wall temperature recordings need to be taken to prove that the controls and methods used provide a margin of at least 25% from a rupture condition.

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