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Investigation of the use of adhesives and magnets for affixing tapping equipment to off-load distressed dangerous goods tank-cars

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Abstract

When a rail or highway tanker carrying a hazardous commodity is involved in an accident it is sometimes difficult to move the tank or empty the contents. For example, if the tank structure is such that the tank cannot be moved and the existing valving is damaged or inaccessible, it is not a simple matter to offload the contents of the tank. In these situations it may be necessary to tap into the tank so that the contents can be pumped out. Once the tank is emptied it can then be moved safely.

The tapping process requires that a tapping flange be attached to the tank wall. In many industrial applications this flange is welded or chained to the pipe or pressure vessel. In this application welding is not possible because of the potential hazards and the use of chains may be limited by accessibility. One possibility is to use steel on steel adhesives and/or magnets for attaching the tapping flange.

The feasibility of using adhesives and magnets is reviewed in terms of existing tapping technology, an analysis of the tapping environment, and an industry survey of adhesives and magnets.

From this study it appears that both adhesives and magnets are suitable for affixing a tapping flange to a tank-car and recommendations are made on a program for developing tapping equipment and associated procedures.

1. Introduction

A typical accident involving a dangerous goods tank truck or rail tank-car ends with the tank overturned in a ditch. In some cases it may be impossible to move the tank due to structural damage or use the installed valves because they are damaged or cannot be reached due to the orientation of the tank. If this occurs, some other

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method must be used to unload the tank. After many variables have been considered, including accident location and tank structural integrity, the decision to tap into the tank may be made. This involves attaching tapping equipment to the tank so that an opening can be drilled in the tank wall to permit controlled unloading. Although the tapping of pressure vessels is a mature technology, the methods usually employed to attach the tapping flange, welding or chaining the flange in place, cannot always be used in this application. The potentially flammable or toxic environment limits the use of welding and accessibility may limit the use of chains. Two possible alternatives are to use a suitable adhesive or a magnetic device to secure the tapping flange on the tank-car.

The objective of this work was to determine whether adhesives or magnetic devices can be used for affixing tapping fittings to tank-cars to offload dangerous goods at accident sites. This involved developing specifications for evaluating magnets and adhesives and applying these criteria to commercial adhesives and magnets to evaluate their potential in attaching drilling/tapping devices to distressed tank-cars to offload dangerous goods.

A number of terms are used in the industry to describe penetrating a pressurized boundary. For simplicity and consistency this paper will refer to this general operation as 'tapping', which will cover sealing to the shell, penetrating the shell and installing valving and any necessary conduits.

The scope of the study was limited to the consideration of propane as the commodity to be offloaded from the distressed tank. The tank of interest is a rail tank-car of 130,600 l capacity.

2. Tapping equipment and procedures

Commercial tapping machines have been used in situ to install penetrations on piping and vessels for many years. The equipment consists of a saddle that is fixed by clamping or welding to the pipe or vessel shell. The saddle incorporates a straight through valve large enough to admit the cutting equipment. The tapping machine then connects to the valve directly or via an adapter. The cutting tool is advanced through the open valve to cut through the pressurized shell.

After the cutting tool has made a hole through the shell, the tool is retracted, the valve is closed and the machine disconnected. A valved opening is then in place on the pipe or vessel shell.

2.1. Unloading

In a tank-car, the liquid always settles to the bottom due to gravity forces. During this study the authors were told that in the few cases where tapping was attempted the operators tapped through the bottom of the tank directly into the liquid. In some cases this required digging a trench to gain access to the bottom of the tank. In our opinion this is unnecessary and only complicates the process by making tapping tool operation more difficult.

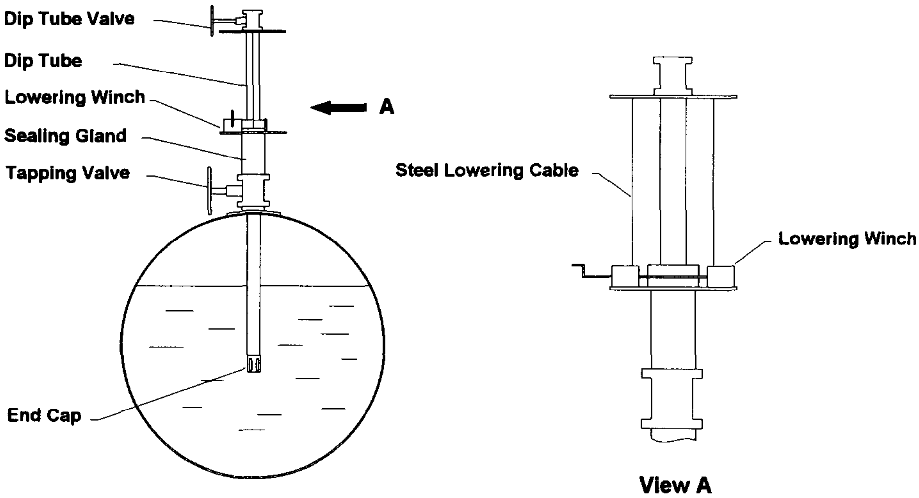

Fig. 1. Dip tube design concept.

In this report we will consider unloading through a hole installed by tapping into the upper half of a tank-car. This requires a dip tube extending down into the liquid and connecting to unloading hoses and pumps. The dip tube assembly, shown in Fig. 1, consists of a sealing gland, dip tube, lowering winch, and dip tube valve.

The dip tube is used in a manner similar to that of the tapping machine. After the dip tube is mounted on the tapping valve, the valve is opened fully allowing the tube to be lowered through the valve and into the tank. Once the tube is in place, pumping equipment can be attached to the dip tube valve, the valve opened and the liquid cargo unloaded.

3. Tapping environment

In almost all cases a clean steel surface to which the flange can be attached will not be available. The distressed tank-cars considered here may have jacketed thermal protection, have a special coating for thermal protection, or be without thermal protection altogether. In addition, the tank surface may be sooty, oily or painted. All of these situations must be considered when using either magnets or adhesives to attach a tapping flange.

If the tank does have an outer jacket, enough of the 3.2 mm ($\frac{1}{8}$ in.) steel jacket must be removed to allow the drilling equipment to be attached to the primary tank wall. Though the existence of a steel jacket may cause some delay, it does not pose any significant problems for the tapping of the tank once it has been removed.

For most adhesives to set properly, surfaces must be clean and, whatever their chemical nature, must be coherent, in the sense that they must not be powdery or friable. Therefore for many adhesives, the tank surface will require some cleaning and preparation before the adhesive can be applied. Surface preparation must be based on the recommendations of the specific adhesive manufacturer and tested under realistic conditions.

The holding power of magnetic devices is inversely proportional to the size of the gap between the magnet and the steel to which it is attached. Therefore the presence of paint or corrosion on the tank surface will reduce the magnet's effectiveness. As a result magnets will also benefit from some surface preparation.

Another concern is whether the tank is out-of-round by any significant amount. Comparing standard tank-car diameters to the relatively small dimensions of the proposed tapping saddle, a good fit should be possible unless damage or local manufacturing errors cause excessive gap. However, since the existence of a gap is likely, the effect of gap size on bond strength is an important criterion for selecting adhesives or magnets.

4. Tapping mechanical forces

Three independent forces contribute to the overall mechanical force acting at the flange–tank interface during the tapping process. They are: (i) machine force — forces/moments resulting from the mass of tapping machine components and dynamic forces applied by the operators; (ii) drilling force — force resulting from the motion of the drill bit (rotation and advancement); (iii) pressure force — force resulting from the pressure differential between tank internal pressure and atmospheric pressure that appears only after the drill penetrates tank wall.

4.1. Machine force

The forces due to the tapping machine mass and the dynamic forces of the operators are potentially the largest forces and are the most difficult to predict. Ideally the hole for the tapping process would be drilled at the top of the tank. This would then allow the tapping machine to be positioned vertically (or close to it depending on the tank pitch), minimizing the stresses at the flange due to the device weight. However, for this analysis it will be assumed that the machine axis is horizontal, the position in which the maximum stresses will be exerted, even though it may not be possible to use it in that orientation.

The weight of the components will produce a moment and a shear force to be resisted by the adhesive joint. Torque will be applied to the operating handle to turn the drill. This torque, typically 180 N m for this size of cutting tool, does not stress the joint, but the tangential force at the outer end of the machine adds to the moment at the shell. Assuming a moment arm of 0.25 m on the cutting tool and allowing for extra loading caused by the operator using the machine as a handhold this force is taken as 900 N.

The moment exerted on the adhesive joint by weight is found by summing the weight of each component multiplied by the corresponding distance outward from the shell. The T.D. Williamson, Inc. Model T-101 a tapping machine [1] was considered

Table 1
Summary of machine forces

Load	Weight	Distance	Moment
Williamson T-101a	133.5 N	0.82 m	109.5 N m
Adaptor	44.5	0.26	11.6
Valve	89.0	0.12	10.9
Saddle and flange	89.0	0.01	0.9
Applied force	900	1.45	1305
Total shear	1246 N	Total moment	1438 N m

to be a typical hand-operated tapping machine and has been used throughout the analysis. These forces are summarized in Table 1.

4.2. Drill force

The axial cutting force on the drill is applied within the machine by a screw feed device and this causes a reaction that applies a separating force on the adhesive/magnetic joint. This force depends on the rate of feed of the drill and the hole size.

Formulas for calculating the axial thrust and torque in drilling have been established in analytical expressions presented in [2]. From this it is estimated that a 38 mm drill of normal geometry cutting mild steel would feed about 0.15 mm per revolution under a feed force of 6700 N. A drill diameter of 38 mm was chosen to represent the upper limit for machines of the type Williamson model T-101a.

4.3. Pressure force

The internal pressure of the vessel will depend on the commodity and its temperature. Fig. 2 illustrates the relationship between vapour pressure and temperature for propane. As can be seen from the figure the pressure drops as the liquid temperature drops. This means that in cold weather situations the tank pressure may be very low (this depends on the commodity). For propane the pressure in the tank is atmospheric at $-42\,^{\circ}$C.

The pressure force will result from the internal pressure acting over the projected inside area of the machine once the shell has been penetrated. Gaps or voids in the seal between the tapping flange and the shell will allow pressure to act on a larger area and this also increases the pressure force. The inside details of the valve and saddle have not been established, but the net projected area will be larger than the hole to be drilled to allow clearance. Assuming a 76 mm diameter area and 1380 kPa internal pressure (higher than the vapour pressure of propane or ammonia at 32 °C, 1041 and 1138 kPa respectively), the pressure force will be 6292 N. Fig. 2 illustrates the relationship between the actual pressure force and temperature for propane.

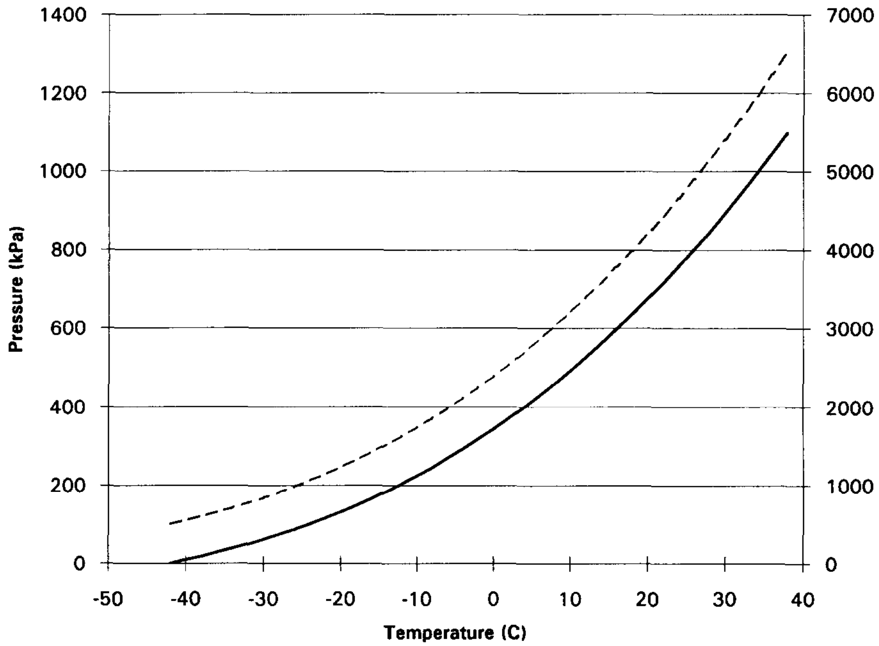

Fig. 2. Vapour pressure [3] and pressure force (on 0.005 m^2) for propane. (——) Vapour pressure, (– – –) pressure force.

4.4. Stresses

The analysis of the principal stresses within the adhesive, resulting from the mechanical forces acting at the flange/adhesive interface, was based on a rectangular flange 254 mm × 254 mm with a 76 mm central hole. By choosing a large contact area of the flange, required strength of bond for adhesives was significantly reduced for all modes of stress. The calculated strengths were multiplied by a safety factor to account for possible stress concentration factors.

4.5. Moment

The detailed stress distribution in the adhesive is complicated by the difference in elastic properties between the adhesive and steel. However, with a thin adhesive layer and the flange or saddle chosen to match roughly the flexibility of the shell, a simple bending moment analysis will yield the tensile stress.

Moment of inertia about x–x axis (neglect central hole):

$$I = \tfrac{1}{12} b h^3 = 3.47\,\mathrm{m}^4.$$

Peak stress:

$$\sigma_B = \frac{Mc}{I} = 520\,\mathrm{kPa}.$$

Table 2
Forces and stresses at flange–tank interface

Estimated forces at flange–tank interface	Tensile force	15,109 N
	Shear force	1246 N
	Moment at flange–tank interface	1421 N m
Estimated stress at flange–tank interface	Tensile stress	773 kPa
	Shear stress	387 kPa
Target strength for adhesives (safety factor of 4.5)	Tensile strength	3.45 MPa
	Shear strength	1.72 MPa

4.6. Drill thrust and pressure

The tensile load is distributed over the flange area of 0.06 m^2. Allowing 8900 N drill force to allow for inadvertent overloading, added to 6292 N pressure force, total force of 15,190 N results in a stress of:

$$\sigma_T = \frac{F}{A} = 253 \text{ kPa}$$

4.7. Resultant stress

Adding the tensile stresses, $\sigma_{total} = \sigma_B + \sigma_T = 773$ kPa, Shear $\tau_{total} = F_{shear}/\text{area} = 21$ kPa. In a bulk material, the shear stress developed would be

$$\tau = \sqrt{\left(\frac{\sigma_{total}}{2}\right)^2 + \tau_{total}^2} = 387 \text{ kPa}.$$

A thin adhesive layer is constrained by the stiffer steel material so that this shear cannot come into play. However, the adhesive shear strength will be considered in the selection process, since the true behaviour can only be determined accurately by testing.

Table 2 summarizes the estimated forces and stresses at the flange–tank interface.

5. Specifications

Based on the above stress analysis and consideration of the tapping environment, the following is the criteria upon which the adhesives and magnets were evaluated.

Adhesive specifications: (i) chemical compatibility (will be in contact with liquid propane); (ii) required tensile strength: 3.45 MPa; (iii) required shear strength: 1.72 MPa; (iv) service temperature range: − 40 °C to 40 °C; (v) environmental conditions: rain, snow, etc.; (vi) Adherend surface may be dirty, wet, oily, painted, etc.; (vii) gap between surfaces from 1 to 2 mm; (viii) desirable cure time of 2 h or less; (ix) both surfaces to be bonded are steel.

Magnet specifications: (i) required tensile strength: 200 kN; (ii) required shear strength: 100 kN; (iii) service temperature range: − 40 °C to 40 °C; (iv) environmental conditions: rain, snow, etc.; (v) tank surface may be dirty, wet, oily, painted, etc.; (vi) gap between surfaces from 1 to 2 mm (0.039 to 0.079 in.).

6. Industry survey

The following sections outline problems specific to magnets and adhesives and present the results of the industry survey.

6.1. Adhesives

A consideration unique to adhesives is cure time, the time from which the adhesive is applied until it has achieved its full strength. Cure times at 25 °C typically range from a few minutes to several hours; however, at colder temperatures the cure times may be several times this value. In many cases where tapping could be used, the ambient temperature will be significantly below the nominal cure temperature of 25 °C. This results in cure times longer than acceptable and in cases of very low temperatures the adhesive will be unable to cure to its full strength. To ensure practical cure times, methods of locally heating the area to which the adhesive will be applied must be used when the ambient temperature is much below 25 °C.

A simple heat transfer model was used to determine the heating rate required to maintain part of a tank wall at a sufficient cure temperature. The model shows that the amount of heat required to maintain the local tank wall area at 20 °C can be practically applied over a range of ambient temperatures using existing technologies.

Two methods of local heating were investigated, chemical heat packs and electric-resistive blankets. The chemical packs typically consist of a foil-backed plastic bag containing a mixture of two powdered acids as one component and lime as the second component. At the time of use the two components are mixed together within the bag and water is added, initiating a heat generating chemical reaction. Once the reaction is complete, the pack forms a hard brick which maintains its temperature for approximately 1 h (depending on application). The packs can be placed directly on the steel tank and covered with an insulating blanket for increased heat transfer to the tank wall.

Electrical-resistive blankets can be manufactured with a rubber coating electrically insulating them to eliminate any ignition hazards. Similar blankets have been used in curing adhesives on aircraft wings containing aviation fuel.

Although neither the resistive blankets nor the chemical heat packs are currently available in a form that can be used directly, they can be adapted for this application. This makes local heating a practical solution to potentially long adhesive cure times.

Table 3 presents a summary of the properties of the adhesives surveyed during the study (this is not an exhaustive list). It was difficult to obtain a complete set of

Table 3
Summary of adhesives survey

Type	Cold weld system	Epoxy	Acrylic	Cyanoacrylate
Mixing required	Yes	Yes	No	No
Work-life at 25 °C	1.5–30 min	20–30 min	15 min unlimited	10 min
Cure time at 25 °C	3–5 hrs 2–4 min rapid cure type	2–3 h	3–6 h	—
Ability to cure at sub-zero temperatures	No	No	No	No
Use temperature	300 °C max	− 50 to 110 °C	− 60 to 150 °C	− 50 to 80 °C
Tensile strength	54–93.2 MPa	—	27.6 MPa	—
Shear strength	12.3–24.8 MPa	16.5–31 MPa	20–25 MPa	22.1 MPa
T-peel strength	—	0.45–0.71 kg/mm	0.64 kg/mm	—
Coefficient of thermal expansion (cm/cm/°C)	5.2×10^{-5}	8.5×10^{-5}	8.0×10^{-5}	—
Gap limitation	—	—	0.2–1.52 mm	—
Solvent resistance	High	High/moderate	High	High
Moisture resistance	High	High	High	Moderate/high
Shelf life	Up to indefinite	12 months	24 months	12 months

This table is based on the data provided by manufacturers. This list may not be comprehensive.

properties for each adhesive through either technical literature or personal communication. However, it appears from the limited data obtained that most of these adhesives at least partially meet the requirements of this application (i.e. they appear to be strong enough, and can survive the environment).

The following is a brief explanation of terminology used in Table 3 [4].

Work-life: The length of time from when the adhesive is first prepared by the user until it is no longer workable.

Tensile strength: The strength of an adhesive bond in tension.

Tensile shear: The strength of a lap joint in tension.

Shear strength: The strength of an adhesive in shear, usually tested in torsion. In most manufacturer's specifications, only one of tensile shear or shear is given.

T-Peel strength: The resistance of the adhesive to peeling. This is given in terms of force per unit width of the adhesive bond.

Coefficient of thermal expansion: The percentage of expansion of the adhesive per °C. This is important for cold tapping because the flange and tank may undergo significant temperature changes (i.e. in cold weather the metal will have to be heated for curing) and to maintain the adhesion, the thermal expansion of the adhesive and metal must be matched.

Gap limitation: The ability of adhesives to fill gaps in the event that the two substrates do not mate precisely. This is very important because of the possibility of the tank-car becoming out of round during an accident.

Solvent resistance: A qualitative assessment of an adhesive's resistance to solvents. This gives a reasonable indication of the affect of propane on the adhesive.

6.2. Magnets

Two types of magnets were considered in the industry survey, permanent and electromagnets. Each have their own advantages and therefore both are considered in the following sections.

Both electro and permanent magnets are sized by their nominal holding power. The actual holding power of a magnet varies inversely with the distance between the magnet and the steel surface to which it is being attached. In the case of tapping, this gap could be caused by poor alignment between the magnet and tank-car and oxidation or paint on the surface of the tank-car. As a result, the best magnetic attachment would be achieved by ensuring accurate mating between the magnets and the tank-car and cleaning the surface of the tank to expose a clean steel surface. Alternately, the holding power can be sized to compensate for a possible gap.

Magnetic holding powers quoted by the manufacturers are from tests conducted under ideal conditions (i.e. for a magnet attached to a flat, clean steel surface). Because of this, manufacturers recommend a safety factor of 2–3 be used when sizing magnets for holding, depending on surface conditions. The strength of a magnetic bond in shear is approximately 25% of its tensile strength.

6.3. Permanent magnets

Specially equipped permanent magnets have the capability to switch their holding power on and off using a cam mechanism. This allows permanent magnets to be positioned without the need for a force greater than the actual holding power of the magnets. Most of these magnets are designed for lifting metal sheets and forgings, but are suitable for holding applications.

Permanent magnets have the advantage that they simply need to be positioned and their magnetic power switched on without the need for additional power supplies or equipment. They are not however, as flexible as electromagnets and are heavy, approximately four times that of an equivalent electromagnet.

6.4. Electromagnets

Electromagnets are extremely versatile and have a very high power-to-weight ratio. The magnets consist of a coil imbedded in epoxy in an outer case. This case can be machined to the user's specifications allowing magnets to mate precisely with the curvature of the tank-car.

Although they require between 12 and 220 V DC to operate, the magnet's coil, associated cable and power supply can be electrically insulated and water tight. This makes electromagnets suitable for tapping, allowing the magnets to operate in all weather conditions and in a flammable environment.

A greater selection of electromagnets is commercially available than for permanent magnets. A large number of cross-sections and holding powers are available which is important for matching the magnet's size and strength to the application.

Table 4
Summary of magnet properties [5, 6]

Manufacturer	Holding power (N)	Mass (kg)	Size (m)	Power (W)
Permanent magnets	2670–11,120	4.3–53.5	0.19 × 0.16–0.5 × 0.17	Not required
Electromagnets	2891–8896	5.0–21.8	0.14 × 0.07–0.2 dia	22–130

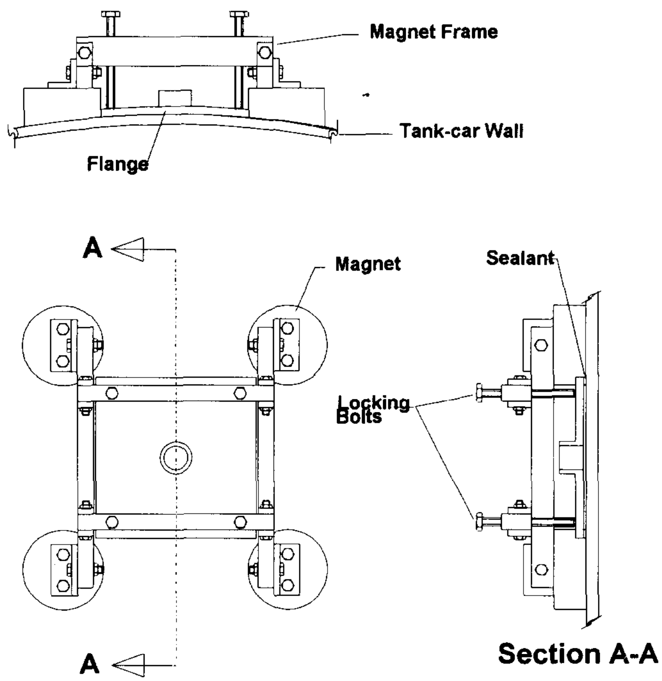

Fig. 3. Concept design for a drilling flange incorporating stock magnets.

Table 4 presents a summary of typical properties of commercial permanent and electromagnets. A much wider range of sizes and powers are available than is shown in the table.

6.5. Design with stock magnets

A concept design incorporating standard magnets is presented in Fig. 3. This consists of a frame, attached to the tank-car using magnets, which provides a platform from which the flange can be clamped against the tank-car wall. This system will not provide a pressure seal if there is not intimate contact between the flange and the tank. This limitation can be overcome by applying a sealant, such as a one-part moisture-curing silicone sealant, between the flange and the tank. An ideal sealant would possess the following characteristics: (i) some movement capabilities; (ii) chemical and environmental resistance; (iii) high and low temperature performance; (iv) high cohesive strength.

In addition, most manufacturers provide a custom design service. This may allow an attachment to be designed which incorporates the magnets within the flange itself.

7. Selection of most promising technologies

One of the objectives of this study was to select adhesives or other technologies that could meet the requirements for this application.

7.1. Adhesives

Because each manufacturer uses a different method of reporting mechanical properties, it is very difficult to compare adhesives and choose an appropriate 'one'. Mechanical properties of hardened adhesive materials are obtained by testing 'bulk' specimens. A 'bulk' specimen is usually a thin film but it can have many other forms (e.g. a solid cylinder) [5]. Therefore, it is not possible to choose one adhesive or rank the adhesives based on performance until the adhesives are tested using standard tests methods.

Based on the industry survey it appears feasible to use steel-to-steel adhesives for fixing a tapping device onto a tank for the purposes of emergency offloading. Currently, commercially available adhesives must be cured at temperatures meeting or exceeding room temperature. This means that local heating must be used on the tank shell if adhesives are to be cured in cold weather. As indicated previously, practical heating procedures can be developed for this application.

7.2. Magnets

From the results of the magnet survey, it appears that permanent or electromagnets could be used to attach a tapping device to a tank-car. A magnetic device would have to be designed which incorporated either standard or custom magnets and then undergo testing similar to the test program for adhesives.

7.3. Comparison of technologies

Both adhesives and magnets have potential for being used to attach fittings to a tank for the purposes of tapping in an emergency situation. Table 5 summarizes the major advantages and disadvantages of each.

Table 5
Comparison of adhesives and magnets

	Magnets	Adhesives
Cure time	Zero cure time	Minutes to several hours depending on adhesive Requires local heating if temperature < 25 °C
Surface preparation	Requires minimum gap	Requires minimum gap and clean surface
Setup	Depending on the design of flange setup may be very simple Electromagnets will require power source	Setup fairly simple Quality of workmanship will largely determine the quality of bond May require set-up of local heating
Weight	Equipment will be heavy, especially permanent magnets	Very light
Shelf life	Indefinite	Approx. 12 months
Weather	Effectiveness not affected by weather	Curing may be severely effected by temperature and moisture
Development	Requires development to design magnets and flange	Adhesive technology is available Requires development of local heating

8. Safety considerations

Independent of the method used, there are several major considerations which must be addressed when considering tapping into a distressed LPG tank-car. These include under what conditions should tapping be attempted and secondly what are the potential consequences if loss of containment is experienced during the tapping procedure.

8.1. When to tap

During the preparation of this report the authors were surprised to find that there are no written procedures for determining when to tap a tank-car. This does not seem reasonable considering the complexity and significance of the problem.

No general agreement about when tapping may be a viable procedure in the offloading of dangerous goods from pressurized tank cars appears to exist within either Transport Canada (TC) or the Association of American Railroads (AAR).

It is difficult to present general rules as to when the tapping procedure should be conducted because of the wide variation in potential accident circumstances and conditions. Commodities, tank orientation, tank integrity and many other factors vary from one accident to the next. In the opinion of the authors the following are some of the obvious considerations: (i) Does the tank structure or location allow the tank to be moved? (ii) Is the tank leaking? How much liquid is left in the tank? (iii) What is the internal pressure? (iv) Are other unloading fittings accessible on the tank? (v) Has the tank been exposed to fire? Are external fires present? (vi) Is the tank structure sufficiently sound to allow tapping? (vii) What are the hazards to the public? (viii) Does the location allow for vent and burn procedures? (Note : This is not an exhaustive list.)

Of particular importance is item (vi), the integrity of a tank-car. In an accident situation it is likely that a tank-car would be involved in violent collisions with other tank-cars and/or neighbouring objects during a train derailment, resulting in some sort of structural damage. Some concerns which must be given serious consideration before the decision to tap into the tank-car include: (i) If the tank has an outer steel jacket, it may be difficult to establish what damage has been caused to the main tank structure. (ii) Is the wall material of the tank of good quality? Is the wall of sufficient thickness? (i.e. when the tank-car was manufactured, was the steel of the grade required by code?) This may be of particular concern for older tank-cars. (iii) Prior to the accident, did the tank undergo any repairs or modifications which did not meet code or which were not documented?

Tapping into a tank-car weakened by age or mechanical damage could conceivably initiate a catastrophic failure and 'cold' BLEVE (boiling liquid expanding vapour explosion) resulting in loss of life and property. Therefore, it is paramount that each of the concerns outlined above be addressed prior to tapping. Ultimately, the decision to tap must be made by the senior emergency response personnel at the accident site.

8.2. Potential hazards

Since the tapping flange would be secured to the tank-car using an adhesive or magnetic bond without any type of positive lock, it is important to be aware of the consequences if the bond were to fail after the tank wall is penetrated. If this occurred, a 38 mm hole would instantaneously be formed in the tank-car wall. Assuming the hole has been drilled above the liquid level then vapour would escape from the tank.

There are two possibilities (assuming penetration is above the liquid level): (i) catastrophic tank failure with a 'cold' BLEVE; (ii) single- or two-phase propane jet release with auto-refrigeration of the liquid due to boiling.

Catastrophic failure would occur if the tapped hole somehow initiated a crack that propagates the full length of the tank. Crack propagation would depend on the fracture toughness of the tank, age of the tank and temperature of the tank. The jet release is the more likely outcome. In this case, as the vapour escapes, boiling takes place in the liquid to replace the vapour that has escaped. This boiling cools the liquid (if no other heat source were available) and eventually the tank internal pressure would be brought to atmospheric pressure (i.e. the propane would cool itself to $-42\,^{\circ}$C). This cooling and depressurization may take only minutes.

For a flammable cargo, such as propane, either result may be followed by fire. In the case of a BLEVE, a fireball could result while a jet release would lead to a jet fire. If no ignition source is nearby a propane cloud would drift downwind in search of an ignition source.

In both cases, if personnel are close they will likely be fatally wounded by the blast, jet momentum, projectiles, and/or fire. For this reason, the actual penetration of the shell with a tapping device, held only by an adhesive or magnet without any positive attachment, remains a hazardous task.

Besides total failure, minor leaks in the flange-valving assembly pose a fire and toxic hazard to personnel. Leaks should be handled carefully using procedures already established. However, leaks can cause complete failure of the bond at the tank–flange interface if not properly addressed.

8.3. Reducing the risk

The risks are primarily associated with the elevated pressure in the tank which can lead to bond failure at the tapping flange. There are a number of things that can be done to reduce the risks and they include: (i) perform the drilling operation by remote control; (ii) develop a positive grip device that locks the flange to the tank wall once the tank has been penetrated; (iii) reduce tank pressure to atmospheric by controlled venting of vapour once the tank has been penetrated (i.e. autorefrigerate the liquid).

The idea of venting the tank to reduce the pressure is put forward because it would eliminate the pressure force that can lead to bond failure. This venting operation could be controlled remotely once the drill has penetrated the tank. It should be noted that if this method were used the propane liquid would be cooled to $-42\,^{\circ}C$ and therefore all unloading equipment must be capable of operating at this low temperature.

9. Conclusions and recommendations

Based on the work carried out during this study the following conclusions have been made.

(i) Current tapping procedures for distressed tank-cars are not well defined. This made it difficult to define specific needs for tapping of tank-cars.

(ii) The decision-making process for determining when to tap a tank car is not well defined. This made it difficult to clearly define the conditions under which tanks are tapped.

(iii) Current tapping technologies are mature and well proven in many applications. This made it possible to define the hardware needs for the tapping process.

(iv) Based on the loading environment defined in this report there appears to be a number of commercially available adhesives that can meet the needs of this application under a limited range of conditions.

(v) The main problem with the use of adhesive appears to be the temperature and time requirements for the curing process. Since the bond strength depends on proper curing it is critical that this issue be resolved. There are methods of locally heating an area to promote curing and these should be considered for low-temperature conditions.

(vi) Magnets appear to be promising if incorporated in an appropriate design.

The following recommendations are made:

(i) A test program should be developed to test available adhesives and to select an adhesive for this application.

(ii) A design and test program for a tapping flange using magnets should be conducted in parallel with the program in (i).

(iii) Proper procedures should be developed for tapping into distressed tanks regardless of the means of tapping tool fixture.

(iv) If adhesives or magnets are used then a special tapping procedure should be developed. Because of the severe consequences in the event of a bond failure it is strongly recommended that the actual tank penetration be carried out by remote control using a motor driven tapping tool. It is also recommended that some effort be made to develop a positive locking device that can lock the flange to the tank wall once the wall is penetrated.

(v) Proper procedures should be developed for deciding when to tap a distressed tank. These procedures should be developed in parallel with the tapping procedures.

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