Hydrocarbon Refrigerant Leaks into Car Passenger Compartments

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7th November 1996

Abstract

Hydrocarbon refrigerants are popular for car air-conditioning. A common claim is that the passenger compartment could exceed the lower explosive limit from a sudden leak and then a spark ignite a flame causing overpressure. The *Code of Practice for the Use of Hydrocarbon Refrigerants in Motor Vehicle Air Conditioning* contains clauses limiting refrigerant charge and leak rate so the passenger compartment cannot exceed the lower explosive limit. These clauses have an engineering explanation. The only significant ignition sources in passenger compartments are however matches and butane lighters.

Contents

1 Introduction

The Independent Australian Hydrocarbon Refrigeration Association has published a *Code of Practice for the Use of Hydrocarbon Refrigerants in Motor Vehicle Air Conditioning* for its members and the hydrocarbon refrigerant industry to comply with (IAHRA 1996). It describes maintenance and repair requirements for MVACs using HC refrigerants and how existing small MVACs should be converted from R12 or R134a to HC refrigerant. These requirements have many environmental and safety objectives but only preventing overpressure in the passenger compartment is considered here.

IAHRA (1996, Section 6) includes a specification for HC agreed to by the three suppliers for their MVAC refrigerants. The original *Greenfreeze* composition developed in Germany with support from Greenpeace was 50% propane and 50% isobutane by mass. All the commercial HC refrigerants for MVAC[1] are very close to this mixture in their properties. Other HC refrigerants exist (Maclaine-cross 1996, Maclaine-cross and Leonardi 1996) but they are not ‘drop-in’ replacements for R12 in MVACs.

1.1 Hydrocarbon refrigerant flammability

The *Greenfreeze* composition is flammable in air at atmospheric temperature and pressure between 2% and 10% by volume (Maclaine-cross 1996). The lower value is referred to as the lower explosive limit (LEL) and the upper value as the upper explosive limit in safety literature. Explosion refers here to the increase in gas volume which occurs as the flame passes. The maximum flame velocity is 0.38 m/s at the stoichiometric composition, 3.6% by volume.

Do not confuse HC refrigerant/air mixtures with explosives which have detonation velocities well over 1000 m/s. HC refrigerant alone does not detonate. Inside a refrigerant circuit, it is neither explosive nor flammable unless you add compressed air by mistake but with compressed air R134a can also be explosive and flammable.

Hydrocarbon refrigerants were first used in Australian MVACs in 1975 (Spencer 1996a). In June 1995, three suppliers commenced marketing them and over 50,000 Australian MVACs now use them. The US market started in 1992 and there are over 200,000 now in the US (Small 1995).

Do not expect an ‘explosion’ at the LEL in a car passenger compartment. For a typical compartment the LEL is about 160 g of HC refrigerant. At a 110% of the LEL, a lit match in the compartment appears to burn normally. Actually it ignites a slow colorless flame, which by natural convection goes to the compartment roof. The temperature is not high enough to ignite car furnishings but may ignite other materials like hair spray. The volume of the gas in the compartment certainly increases so technically there is an explosion. Even if the car is completely closed up, the flow through the door seals limits the pressure rise to well below that necessary to damage windows. An occupant who touched the compartment roof would notice that it was hot and would also feel the hot gas near the roof. These events may distract a driver so it is desirable that HC concentration in the passenger

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[1] In Australia at present, the trade names are Care 30, ER12 and HC12a.

compartment not exceed the LEL.

In Florida and California in 1993, 500 g of HC refrigerant was carefully added to the passenger compartment of a car and ignited blowing the windows off. It was claimed that an accidental leak in a car air-conditioner using HC refrigerant could do this (Keebler 1993). Such an accident with overpressure in the passenger compartment has not yet been reported despite over 400,000 operating years (Small 1995) of HC MVACs in the US alone.

1.2 Flammability risk assessments

Arthur D. Little (1995) made a very detailed risk assessment for HC in MVACs. They noted that serious injury to the occupants was physically possible only if the car crashed subsequent to the overpressure. They estimated the frequency of such accidents as 4.16×10^{-10} per car year. This means that if all Australia's 5 million MVACs were converted to HC such an accident might occur once in 500 years. They implicitly assumed that the frequency of suitable fractures was 1.68×10^{-6} per car year.

Maclaine-cross *et al.* (1995) made a video of tests measuring the passenger compartment concentrations of HC refrigerant from a large evaporator leak simulated by a solenoid valve in the vapour line. Two electronic HC meters measured the peak concentration as 62% of LEL about two minutes after the valve opened. A naked flame was held in the 1987 Falcon throughout the experiment to see if ignition was possible. The car had its fresh air vent blocked and the passenger compartment fan was at its maximum flow. The expansion valve was in the engine bay and only low pressure vapour lines entered the passenger compartment. The air conditioner had a liquid line receiver and was initially charged with 300 g. The flow rates of refrigerant and fresh air into the passenger compartment were not measured. However the 62% of LEL after two minutes is consistent with fresh air (Maclaine-cross 1996) on a similar 1987 Falcon and flow rate of refrigerant leaks in the laboratory (Cai 1996, Tosovic 1996).

Maclaine-cross (1996) reported measurements of passenger compartment volumes and fresh air flows on ten Australian cars with ACs (Razmovski 1994, Rajasekariah 1995). No ignition sources were found on these ten cars which could ignite a flammable mixture in the passenger compartment or engine bay. Even dashboard cigarette lighters were unable to ignite HC refrigerant. Maclaine-cross calculated the risk for each car individually and found for most popular Australian cars the overpressure accident scenario was impossible and for the rest the frequency was less than 8×10^{-10} per car year. He explicitly assumed the frequency of suitable fractures was 1×10^{-6} per car year and that more than half the assumed refrigerant charge leaked in less than 1s. The ignition source assumed was an occupant lighting a cigarette with a match or butane lighter seconds after the release in total disregard of the danger.

The assumptions about fractures and leak rates (Arthur D. Little 1995, Maclaine-cross 1996) were made without considering the design of MVACs. This omission will be remedied below.

1.3 Objectives of IAHRA (1996)

BS 4434–1995 contains many excellent recommendations for HC and other refrigerants safety. Most Australian MVACs already comply with BS 4434-1995 but some only comply with the less stringent SAE (1995). Regardless of which specification the MVAC was designed to, compliance with IAHRA (1996) is intended to make all MVACs converted to HC equally safe.

The Federal Office of Road Safety (FORS) convened a meeting of government, industry and technical specialists to discuss the draft code on the 26th March, 1996. The operation, design and failure of MVACs and mechanics of fractures, leaks and passenger compartment ventilation were discussed. It was agreed to draft IAHRA (1996) so leaks could not cause the lower explosive limit of the refrigerant to be exceeded in the passenger compartment. This report assesses the effectiveness of these clauses and possible ignition by door switches or sources in the passenger compartment.

An instantaneous complete fracture in a passenger compartment liquid line forms a cloud (about 50 L) which may distract or obscure the vision of a driver. All refrigerants used in MVACs are asphyxiants. A 10 g/s leak would not be noticed in a car travelling at high speed but at concentrations about the LEL for HCs all refrigerants increase drowsiness and driver fatigue. These hazards are thousands of times more frequent than ignition (Section 5). HCs used in accordance with IAHRA (1996) are significantly safer than other refrigerants with less comprehensive codes.

Safe use of flammable vapours requires preventing the occurrence of any:

- leaks;
- formation of flammable mixtures from leaks;
- ignition of any flammable mixtures.

The effectiveness of such measures depends on the air conditioner charge and design and fresh air flow rates (Section 2). IAHRA (1996) has many clauses preventing leaks and formation of flammable mixtures (Sections 3 and 4). The design and maintenance of modern cars is deliberately such that ignition of hydrocarbons does not occur in the passenger compartment (Section 5) so any ignition clauses would be redundant.

2 Infiltration, Ventilation and Refrigerant Charge

A new, correctly installed, high quality MVAC may leak as little as 0.2 L of refrigerant liquid a year but leakage may be as high as 1 L/year. A reservoir of refrigerant liquid in the engine bay is provided either in the suction line (suction line accumulator) or the liquid line (liquid line receiver, Figure 1). When the system is fully charged, this contains up to 0.5 L of liquid refrigerant in excess of that required for normal operation. Many systems will operate effectively with 1 L of liquid in excess of normal operation requirements.

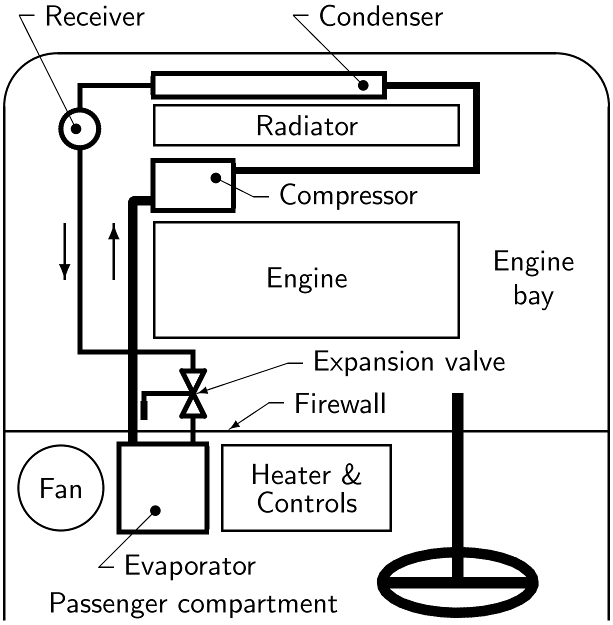

Figure 1: Schematic of car air conditioner with liquid line receiver and expansion valve in engine bay.

Liquid refrigerant passes through an expansion valve which should be close to the evaporator in the passenger compartment. The expansion valve on many systems is in the engine bay so only vapour lines enter the passenger compartment (Figure 1). If it is in the passenger compartment a liquid line at high pressure and a vapour line at low pressure enter the passenger compartment.

The flow rates of fresh air into all moving motor vehicles are more than 5 L/s. A speed of only 20 km/hour is 5.6 m/s with a velocity pressure over 18 Pa. Cars with fresh air vents open or fans operating or both had ventilation rates up to 173 L/s when stationary in a shaded and sheltered position (Table 1, Maclaine-cross 1996).

Table 1: Passenger compartment volume and fresh air flow, maximum charge of hydrocarbon refrigerant, flow rate and expansion valve position and ratio of charge to volume for ten Australian cars. P=in passenger compartment, E=in engine bay.

Model	Year	Volume m^3	Fresh L/s	Charge g	Flow g/s	TX valve	Charge %LEL
Kingswood	1970	5.81	2.52	280	10	P	121
Volvo	1978	6.48	22.0	367	15	P	142
Commodore	1979	3.81	85.0	420	20	E	276
Pulsar	1984	4.16	77.4	333	10	E	200
Corolla	1985	5.68	149.7	233	10	P	103
Falcon	1987	4.44	134.5	433	20	E	244
Laser	1988	3.48	85.1	233	10	P	167
Berlina	1989	4.36	173.0	367	20	E	210
Magna	1989	6.12	100.7	233	15	P	95
Astron	1989	5.50	136.0	283	10	P	129

Popular Australian cars manufactured after 1986 have had high flow rates of fresh air through the passenger compartment whether the control lever for the fresh air vent was open, closed or did not exist (Maclaine-cross 1986). Their fresh air flows when the car is stationary are just above the minimum permitted in building design. This 100% fresh air design also gives improved AC performance in temperate and humid climates and requires less passenger compartment space. Demister performance standards may have been the major motivation for this improvement (FORS 1995).

Passenger compartments with doors, vents and windows closed and fan off have the lowest fresh air rates. It normally depends on wind and the density difference between compartment and ambient due to temperature.

Addition of HC or other heavier gas to the passenger compartment however increases the density. The 2% HC by volume LEL mixture has a density 1.5% higher than air at the same temperature. A temperature increase of 4.4 K in the passenger compartment would cancel the density increase from 2% HC. Lowest infiltration rates with HC mixtures occur when wind is negligible and solar radiation heats the passenger compartment sufficiently to make the density inside equal to the density outside.

With the passenger compartment in a shaded and sheltered position, closed and with fan off, the largest flow rate of fresh air reported by Maclaine-cross (1996) was 50.0 L/s for a 1989 Astron. The lowest flow rate of fresh air reported was 0.61 L/s for a 1984 Pulsar with a passenger compartment volume of 4.16 m^3. This fresh air rate is only 0.5 air changes per hour. Razmovski (1994) measured the corresponding wind as only 0.1 m/s which was much lower than for other measurements. This air flow rate is regarded as the lowest that will ever occur even inside a closed garage.[2]

The HC charge recommended is 333 g (Table 1, Spencer 1996b). The Victorian Automobile Chamber of Commerce recommends a R12 charge of 800–1000 g for this car. IAHRA (1996, Clause M 5) requires less than 40% of this or 320–400 g HC. With a HC charge of 400 g, by conservation of mass any uniform leak rate below 28 mg/s would be too small to allow the lower explosion limit of 2% by volume to be reached with 0.61 L/s fresh air (Appendix A, first equation). A uniform leak rate of 28 mg/s causes the entire charge to leak out in four hours. Any leakage which peaks below 28 mg/s will not cause the HC concentration to exceed the LEL in any passenger compartment.

The ratio of refrigerant charge to passenger compartment volume in Table 1 is greater than the LEL for nine of the ten cars. It is possible for all of this to leak into the passenger compartment but it also simultaneously leaks out of the passenger compartment to atmosphere. To determine whether passenger compartment concentration will exceed the LEL we must consider refrigerant leak rates simultaneously with fresh air rates (Section 3, Appendix A).

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[2] Ducting tape and silicone sealant in a laboratory might produce less fresh air but the car would not then be operable. Five non-smoking occupants require a minimum fresh air flow of 25 L/s but 0.61 L/s is unhealthy even for a single child.

3 Refrigerant Leaks and Safety Valves

IAHRA (1996, Clause J 2) requires a design, device or modification which will prevent the LEL from being exceeded (on average) in the passenger compartment. The requirement is that this should work even if faulty maintenance or manufacture causes an instantaneous complete fracture of a line or fitting anywhere in the passenger compartment. Such fractures have only been recorded for flexible hoses and the MVACs installed by major manufacturers are all metal in the passenger compartment. One way to achieve the objective of Clause J 2 is a safety valve in the engine bay between receiver and expansion valve.

Such a safety valve works by delaying the release of refrigerant to the passenger compartment so that the ventilation system removes it before the concentration increases. The valve performance depends on the design of the valve, vehicle, air conditioner and the accident scenario. Table 1 gives data on car passenger compartments and air conditioners from Maclaine-cross (1996) and Spencer (1996b) for liquid line receiver systems. For suction line accumulators, safety valves are simpler and perform better so this rarer system will not be discussed. The fresh air volume flow rate is with vent open and fan running for a stationary car in a sheltered outdoor position. The HC refrigerant maximum charge is calculated by dividing the maximum R12 charge mass by three (Spencer 1996b).

An instantaneous release of all the refrigerant charge to the passenger compartment (Arthur D. Little 1995, Maclaine-cross 1996) would exceed the LEL in most cars (Table 1, last column). The majority of the refrigerant is in the engine bay for all operating conditions. It must leak from the engine bay to the passenger compartment through small valves and pipes. The time for this process is always longer than a minute but depends on design and operating conditions as discussed in the following paragraphs. The overpressure from a complete instantaneous release without combustion is 2 kPa at the LEL and ambient temperature. From a video of a car explosion, Yan (1996) found that an overpressure just over 2 kPa removed the windscreen and rear window. With a window removed dilution to below the LEL occurs in about one second (Maclaine-cross 1996). An instantaneous release and also its subsequent ignition are both physically impossible for the above reasons and will not be considered further.

Table 2 gives predicted peak concentrations in the passenger compartment for eight release scenarios with ten Australian cars using the data of Table 1. The concentrations are expressed as a percentage of the lower explosive limit (%LEL). The eight release scenarios are for no safety valve, a simple safety valve and a complex safety valve. The leak types are a sudden major release, an instantaneous complete fracture and a large leak in the evaporator. The position of the instantaneous complete fracture in the passenger compartment is wherever gives the largest concentrations for the safety valve used. For all scenarios, all the refrigerant charge is assumed to leak through the passenger compartment to atmosphere eventually. The peak concentrations differ between scenarios for a given car because the mass flow rates of the leaks differ.

When the AC is on there is much liquid in the receiver and some in the evaporator, condenser and compressor sump as well as the liquid and suction lines. The AC is expected to be on whenever the outside air exceeds 20°C and the engine is operating. The high side pressure used for flow calculations was 1200 kPa and the low side pressure 400 kPa with AC on. If the outside air temperature is below 20°C the condenser being in front of the radiator is the coldest point in the system. The bottom of the condenser is also the lowest point so liquid refrigerant gathers there by evaporation and condensation in under an hour after last AC operation. Only refrigerant dissolved in compressor oil remains elsewhere but with a leak this evaporates so slowly it contributes negligibly to passenger compartment concentrations. The pressure used was 600 kPa with AC off. These are the two most frequent distributions of refrigerant in MVACs.

BS 4434-1995, Clause 1.3.70, defines a *sudden major release* as the majority of the refrigerant charge being released in under five minutes. A refrigerant leak rate which declines linearly with time with half occurring in the first five minutes satisfies this definition. Leaks through a 1 mm orifice in an MVAC suction line approximate this behaviour (Cai 1996). Column 3 in Table 2 gives the peak concentrations resulting from this leak pattern. None exceed the LEL. For some applications other than MVAC, BS 4434 requires this peak concentration to be less than 20% of the LEL which is true for all cars after 1980 in Table 2. Safety valves affecting refrigerant flow are irrelevant because the refrigerant leakage is defined in BS 4434.

If the expansion valve is in the passenger compartment and there is no safety valve, instantaneous complete fracture in the liquid line can give frictional, isenthalpic, flashing flow from the receiver to the passenger compartment (Boucher and Alves 1973, Gallagher *et al.* 1996). For a liquid line with 8 mm internal diameter and a total pressure loss coefficient of 4 the initial flow rate calculated is 250 g/s. If the AC is off, the flow is from condenser to passenger compartment and the total loss coefficient used is 8. Combined with the lower pressure this reduces the initial flow rate to 125 g/s. If the AC is operating, a fracture downstream of the expansion

Table 2: Peak average concentration in the passenger compartments of ten Australian cars as a percentage of the lower explosion limit (LEL) for eight release scenarios.

Safety valve		None			Simple		Complex		
Leak type		Sudden	Instantaneous complete fracture						Large
Initially AC is		BS4434	on	off	on	off	on	off	on
Model	Year	Peak concentration %LEL							
Kingswood	1970	92	114	114	114	113	70	69	77
Volvo	1978	46	103	103	102	99	28	17	63
Commodore	1979	21	121	80	121	80	52	25	80
Pulsar	1984	18	85	50	85	50	37	17	50
Corolla	1985	7	51	50	44	26	19	9	26
Falcon	1987	14	103	59	103	59	46	21	59
Laser	1988	12	83	82	72	44	32	15	44
Berlina	1989	9	87	48	87	48	39	18	48
Magna	1989	9	47	47	44	36	19	9	35
Astron	1989	9	64	63	54	30	24	11	30

valve produces the normal refrigerant flow rate since the expansion valve is choked. If the AC is off and the fracture is downstream of the expansion valve, only vapour flows at about 20% of the normal refrigerant flow rate.

About half the mass will flash from the preceding initial flows reducing the vapour pressure of the remaining liquid to close to ambient. The mass flow rate is then limited by heat transfer to the liquid to about 10% of the normal operating refrigerant flow rate (Cai 1996, Tosovic 1996). Table 2 shows the maximum concentrations calculated using the equations in Appendix A for these flows. Figure 2 shows the flow rate and resulting concentration graphically for the 1984 Pulsar with AC off.

Simple safety valves which close on high flow rate and remain closed while the pressure difference is substantial are widely used in LPG systems (AS 1596–1989). An instantaneous complete fracture upstream of the expansion valve would cause the safety valve to shut in milliseconds so complete fractures are now worse downstream of the expansion valve. Table 2 shows that simple safety valves have the same effect on maximum concentrations as moving the expansion valve to the engine bay.

The complex safety valve assessed operates to close:

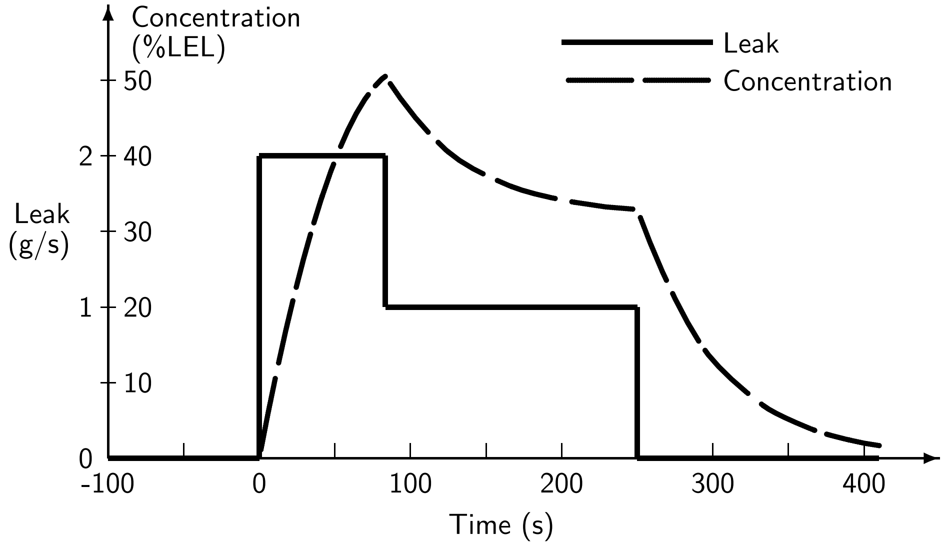

Figure 2: Hydrocarbon refrigerant flow rate and concentration as a function of time for a hypothetical worst leak into the passenger compartment of a 1984 Pulsar with air conditioner off.

- 10 s before the compressor clutch disengages to remove liquid from components with a path to the passenger compartment;
- on a fall in supply electric potential or evaporator pressure;
- or if a very large leak is sensed in the liquid line.

If the AC is on, the worst position for an instantaneous complete fracture is between the expansion valve and the evaporator. The loss in evaporator pressure is expected to close the valve after only 20% of the charge has leaked to the passenger compartment at the normal flow rate. When the valve is closed reverse leakage through the compressor valves is at 1% of operating flow. The worst leak is in the evaporator at 20% of operating flow which will not drop the evaporator pressure sufficiently to close the complex valve until 50% of the charge has leaked.

If the AC is off with a complex valve, the evaporator has been pumped down so only 10% of the charge is available to leak at 20% of operating flow and the rest at 1% of operating flow through the compressor valves in reverse.

The complex safety valve reduces the maximum concentration of hydrocarbon from a worst hypothetical leak for all cars. Its performance could be improved by increasing the fresh air flow rate or by using an HC sensor in the passenger compartment. Proprietary valve systems with significantly better performance than the complex valve in Table 2 are under development. Many of these devices already satisfy the IAHRA (1996), Clause J 2a requirements. Most Australian cars satisfy the Clause J 2 criterion without any safety valve. Vehicles with low fresh air like the 1970 Kingswood only just satisfy it with the complex valve.

4 Failures, Fractures and Leaks

Fractures do not just appear. They grow from some initial weakness in a highly stressed area. Any fracture which penetrates a wall causes a leak or failure of refrigerant containment. If the maximum stresses are small a fracture will grow only if the stresses fluctuate and only a fixed microscopic amount per fluctuation. This is called fatigue and is a common failure type in motor vehicles. Typically fatigue fractures take years to grow. Large maximum stresses causing complete fractures to grow in seconds are extremely rare except for emergency situations *e.g.,* a collision or a petrol fire.

Six failures claimed to result in exceeding the LEL in the passenger compartment are:

- instantaneous fracture in collision;
- sudden fracture from faults;
- sudden fracture from excessive pressure;
- pitting corrosion of the evaporator;
- fatigue fracture from cyclic stresses;
- failure of O-ring joints.

The IAHRA (1996) clauses preventing these failures causing the LEL to be exceeded are discussed in the following.

4.1 Instantaneous fracture in collision

The condenser of a car air conditioner system is in front of the radiator. Collisions resulting in fracture of the condenser are common (Arthur D.

Little 1995, Maclaine-cross 1996) and a complete instantaneous escape of almost all refrigerant charge to the atmosphere frequently occurs. With favourable winds a small fraction of the released refrigerant might enter a damaged passenger compartment but fresh air also entering by the same path immediately dilutes it preventing a flammable concentration.

Dieckmann *et al.* (1991) thoroughly investigated wrecks from side impacts and found:

> A total of 9 right[3] A-pillar impacts were tested. CDC[4] magnitudes of 3 to 5 were estimated for all of these and significant evaporator displacement was observed for several. While significant evaporator displacement occurred, no damage or deformation of the evaporators was observed. No AC system leaks were found in this population. In addition, window breakage was observed in all cases, a point of interest in establishing the potential for flammable mixtures and explosive overpressures.

Also the vehicle will be at rest and any sparks from the collision itself extinguished long before a flammable mass has leaked. The flammable mass will leak out of the passenger compartment in less than a minute if windows and doors are intact and in seconds when only one window is shattered. For a rescuer on an intact scene in less than a minute, opening an undamaged door automatically allows any flammable mass to escape in seconds (Razmovski 1994, Maclaine-cross 1996) and prevents any explosion. After an impact severe enough to fracture an evaporator or refrigerant line, the occupants will certainly be unable to light a match or flint lighter the only known ignition sources (Section 5, Maclaine-cross 1996).

Safety valves (Section 3, Clause J 2) are expected to be particular effective in reducing refrigerant concentrations in the passenger compartment for such scenarios.

4.2 Sudden fracture from faults

The design of air conditioners factory installed by US car manufacturers is completely free of features which could cause sudden or instantaneous complete fractures in the passenger compartment. This may not be true of after-market kits. Over-tightening screw refrigerant fittings and omission of

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[3] US cars are left-hand drive.

[4] Collision Deformation Classification

mounting brackets in the passenger compartment is physically possible with some kits and may have occurred in the field.

Clauses B, C, D, E, H and I (IAHRA 1996) are intended to prevent faults causing sudden fracture. Clause J 2 ensures that a flammable mixture in the passenger compartment does not occur if these fail.

4.3 Sudden fracture from pressure

ASHRAE (1995) states 'Components for the low-pressure side frequently have burst strengths in excess of 2.1 MPa.' BS 4434-1995 requires burst strengths up to 5 MPa depending on the pressure relief device. If the AC is off but the engine is operating, liquid refrigerant will gather in the condenser and its temperature will be the ambient temperature. The maximum ambient temperature in Australia is 50°C and so the maximum pressure throughout the air conditioner will be 1200 kPa gauge with HC refrigerant. If the AC is on, condenser and liquid line pressures may be as high as 1600 kPa gauge with HC but the evaporator pressure will then be about 300 kPa gauge.

The pressure/temperature relief device mentioned in Clause J 1 is required by refrigeration safety codes (BS 4434-1995). The high pressure switch in Clause J 1 protects the liquid line which enters the passenger compartment on some systems.

Clause J 2 ensures that a flammable mixture in the passenger compartment does not occur if the devices mentioned by Clause J 1 fail.

4.4 Pitting corrosion

Many Australian vehicles are exposed to sea coast atmospheres laden with salt particles from sea spray. Such particles cause pitting corrosion of the aluminium evaporator with after several years formation of a small pinhole. A 100 μm diameter hole will leak HC vapour at about 10 mg/s causing the entire charge to leak out in about 10 hours. Such a leak is too small to cause the LEL to be exceeded (Section 2). Such a leak is failsafe since the MVAC will not operate or leak further after the charge has leaked out. IAHRA (1996, Clauses O) requires a vacuum pump leak test with a rise of 2 kPa from 10 kPa in 15 minutes 'indicates a leak is present in the system and must be rectified prior to final system charging.' A 100 μm diameter leak would cause a rise of 30 kPa which is certain to be noticed. A new evaporator would be fitted to fix the leak.

4.5 Fatigue fractures

Fatigue fractures can occur because many materials including aluminium and elastomers have no fatigue limit.

The evaporator components are typically subjected to ten stress cycles per hour. If a vehicle has an operating life of 20,000 hours this is 200,000 cycles of stress. The liquid line is of greatest concern because the same size crack leaks liquid at about 15 times the mass flow rate for vapour. The BS 4434–1995 allowable pressure is 1.7 MPa causing a 9 MPa hoop stress in a 10 mm liquid line. The 500 million cycle fatigue strength for the softest temper of 5152 aluminium tubing alloy is 90 MPa (ADC 1973). The factor of safety for common fatigue is more than 10 so no such failures are possible in even soft metal.

With a high stress concentration such as at a scratch, other damage or poor design feature, crack growth and then refrigerant leakage may occur at lower stresses. Any crack will initially be so small that the leakage could not be detected under Clause O but the air conditioner will fail to operate after some months. As the crack grows the leakage rate increases and Section 2 shows that a leakage rate too small to cause the LEL to be exceeded causes all the charge to leak out in hours and would be readily detected under Clause O. For any given crack length, theory of elasticity and fluid mechanics can be used to predict the leakage rate and fracture mechanics whether sudden complete fracture occurs. If a crack length exists which gives a leakage rate below the LEL leakage rate but for which sudden complete failure is impossible, Clause O prevents the LEL being exceeded.

Consider an all aluminium system in the passenger compartment and a crack normal to the principal stress in the liquid line or other liquid containing component 2 mm long. At the 1.7 MPa allowable pressure the crack will open to 0.5 μm (Timoshenko and Goodier 1951) and leak about 17 mg/s of liquid. This is smaller than the 28 mg/s required to exceed the LEL with the lowest closed fresh air flow rate (Section 2). At 17 mg/s the refrigerant will leak out completely in about 6 hours. Because the crack will close under vacuum it may not be detected by the vacuum leak test (IAHRA 1996, Clause O) but the pressure test (IAHRA 1996, Clause O) will detect it. A 2 mm crack in aluminium will grow catastrophically if the stress exceeds 1100 MPa (Polakowski and Ripling 1966). This is about 120 times the 9 MPa stress occurring at maximum allowable pressure. All aluminium construction is completely safe against exceeding the LEL.

Older MVAC designs still popular on farm and construction equipment have refrigerant hoses in the passenger or operator compartment. Refrigerant hoses have a composite construction. Fatigue fracture of the layers taking the stress may occur with no loss of refrigerant. A blister develops in the sealing layer which may burst suddenly. Because the stiffness of this layer is over a hundred times less than aluminium the tear or fracture can open to over a hundred times the size. This is known to have occurred in an R12 liquid hose with complete sudden loss of refrigerant to the passenger compartment. BS 4434–1995 does not permit refrigerant hoses inside the passenger compartment. IAHRA (1996, Clause H) requires any hoses which have either sustained damage or deteriorated be replaced.

Clause J 2 requires that the consequences of such a failure not be a flammable mixture on average in the passenger compartment. The best way of ensuring this is to use aluminium refrigerant lines in the passenger compartment, put the expansion valve in the engine bay, have fresh air greater than 100 L/s and avoid excessive refrigerant charges (Table 2). Where such design changes are expensive, various safety valves are available.

4.6 O-ring failure

Most MVACs do not have O-ring joints inside the passenger compartment and BS 4434–1995 forbids this. The leakage from a missing O-ring or an incorrectly fastened joint will be detected by both the vacuum and pressure leak test at rates much lower than the lowest capable of exceeding the LEL, 28 mg/s. O-rings can fail in service due to fatigue but these failures cannot develop into a complete fracture like a crack. An O-ring fatigue fracture would initially cause complete loss of refrigerant in days and it would be readily detected and replaced on servicing (IAHRA 1996, Clause O). These initial low leakage rates could not cause the LEL to be exceeded.

5 Passenger Compartment Ignition Sources

Ignition sources known to ignite HC refrigerant mixtures at atmospheric conditions and physically possible on a motor vehicle include:

1. Strongly exothermic chemical reactions including ignited matches and butane cigarette lighters;

2. Heating a flammable mixture of HC above its auto-ignition temperature which has a 490°C minimum (Maclaine-cross 1996);

3. Hot wires or surfaces above 800°C (Dieckmann *et al.* 1991);

4. Electric arcs of sufficient energy including spark plugs.

Neither Razmovski (1994) nor Rajasekariah (1995) found ignition sources 2, 3 or 4 on the ten cars they tested with an extinguished HC torch either inside or outside the passenger compartment (Maclaine-cross 1996). All the cars tested had been well maintained.

If IAHRA (1996) is complied with the LEL will not be exceeded and whether ignition sources are present is irrelevant. Non-compliance with IAHRA (1996) might well be coincident with poor design, manufacture or maintenance generally and hence a greater risk of ignition sources. Sources in the passenger compartment may cause an overpressure accident (Section 1.1).

5.1 Hot surfaces

Motor vehicles are wired with negative earth. Positive leads to the passenger compartment have primary fuses in the engine bay to protect the plastic insulation from damage by conductor heat. Smaller conductors are protected by secondary fuses inside the passenger compartment. These secondary fuses are designed not to ignite HC/air mixtures on failure.

If a bare positive lead is touched briefly to corroded metal on the car body, rapid resistive heating takes place at the metal surface with a noisy spatter of hot oxide and metal. This spatter is often called a spark. Under favorable conditions this spatter could be over the 800°C required to ignite HC. This effect is believed to have caused fires in engine bays after impacts (Arthur D. Little 1995).

In the passenger compartment, there is little corroded bare metal and leads could only be stripped of their insulation by rare manufacturing faults or service damage. A short circuit may blow a fuse, discharge the battery or otherwise attract repair. If not it causes insufficient heating for ignition or erodes the metal until a short is no longer possible in days. I have never encountered a short circuit in the passenger compartment capable of ignition in thirty years of driving. They certainly occur less than once per vehicle year on average.

Smokers using matches or butane lighters create five ignition events per day for every driver (Maclaine-cross 1996) or over a thousand times the rate for hot surfaces created by short circuits.

5.2 Electric arcs

An electric arc is a volume of ionised gas heated by an electric current. Small electric arcs are also called sparks but are a different electrical phenomena to spatter (Section 5.1). They occur on opening a normal circuit not on closing an abnormal short circuit. If they can occur, they will occur every time the circuit is opened.

The minimum energy for reliable spark ignition of propane is about 250 μJ (Lichty 1967) if the arc length is about 1 mm and the peak electric potential about 20,000 V. SIMTARS (1995) found that the ignition characteristic of HC refrigerants were similar to propane their major constituent. Deviation from optimum conditions by using a smaller or larger arc gap produces an increase in the required energy. A smaller gap allows cooling by the electrodes to quench any flame produced.

On spark ignition systems, the energy required is stored in the magnetic field of the ignition coil. When the primary circuit is interrupted, this magnetic energy is released as the field collapses. The inductance of the coil produces the high voltage to arc across the gap. The energy released depends on the size of the coil.

When a non-inductive circuit in the passenger compartment is interrupted, the maximum potential available to form an arc is less than 15 V. The first ionization potential of nitrogen is 15.5 electron-volts/molecule and the breakdown potential for a 25 μm gap in air is about 300 V (Dakin 1968). No arc is possible with non-inductive circuits in the passenger compartment.

The starter motor has a significant magnetic field which collapses when the ignition key is released. The starter-motor relay contacts often produce visible arcs. The ignition key however operates the relay coil whose magnetic field has a volume about ten times smaller than the ignition coil. Ten times less energy is available with an unfavorable gap so the ignition switch arc has insufficient energy to ignite an HC/air mixture. The ignition switch is always totally enclosed and armored for security reasons. If the arc did ignite HC/air inside the switch the flame would not proceed to the passenger compartment.

Switches inside the passenger compartment operate many small motors with permanent magnets. Interrupting the rotor current does not change the magnetic field of rotor or stator much so much less energy is released than from the starter relay coil. The largest such motor is on the blower but this is operated through resistors which further reduce the potentials induced on switching.

Ignition of HC/air mixtures is impossible by any arcs known to occur in the passenger compartment under operating or fault conditions.

5.3 Door switches

The courtesy light in passenger compartments is usually 5 W and can be set with a master switch to operate off up to 4 door switches. The door switches are in parallel and complete the light circuit by shorting the negative lead to the car body. Some mount in the car frame but are not otherwise enclosed.

The switch button is usually outside the passenger compartment seals and the car frame is vented to the atmosphere not the passenger compartment. Any ignition source on the switch will not come into contact with HC/air mixture in the passenger compartment, when the switch operates and hence cannot ignite it.

When the door opens and the switch closes, the lamp series resistance limits the maximum possible heating of the contacts to 1.3 W. Even if dirt falls on the contacts or the wire separates from the switch this cannot be increased. The temperature will be less than 100°C at any door switch. This is insufficient to ignite HC/air.

For the 1994 Pulsar considered earlier, Razmovski (1994) measured a fall of 29.8% in tracer concentration when she opened the driver's door for 3.27 s. Above the 2% LEL, the much larger density difference would make this loss in passenger compartment concentration even larger.

The maximum current through any door switch is less than 0.5 A because of the series resistance of the lamp. The circuit is non-inductive so no arc is possible when the door is closed and the circuit broken.

Door switches are not an ignition source and do not contact any flammable mixture in the passenger compartment when they normally operate.

6 Conclusion

IAHRA (1996) contains many safety and environmental clauses and those relevant to exceeding the lower explosion limit of hydrocarbon refrigerant in the passenger compartment are discussed above. These clauses limit the total quantity of refrigerant used, then ensure that physically possible leak rates are small and ventilation rates are high. This document summarizes the engineering reasons why these clauses are effective.

Competent and conscientious compliance with IAHRA (1996) makes overpressure in the passenger compartment physically impossible from hydrocarbon MVACs. In the case of noncompliance, the only significant ignition sources in the passenger compartment are matches and butane lighters.

These clauses in IAHRA (1996) also prevent driver distraction by a cloud of leaking refrigerant or drowsiness due to asphyxiation which are possible causes of serious accidents with all refrigerants.

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A Predicting Concentrations in a Passenger Compartment

Leaks into a passenger compartment can frequently be divided into two constant flow rate regimes as shown in Figure 2 (page 12). The following formulae give the spatial average concentration in the passenger compartment. Forced and natural convection ensure that except very close to the leak, the local concentration is equal to this average especially a minute after the leak commenced.

If m_i is the mass leaking at rate $\dot{m}_i$ during period t_i, then $t_i = m_i/\dot{m}_i$. If v_l is the specific volume of the leaking gas at the temperature and pressure of the compartment, the volume flow rate of the leak $\dot{V}_i = v_l \dot{m}_i$. For hydrocarbon refrigerants replacing R12 $v_l = 0.5$ L/g. The passenger compartment has a volume V and its fresh air volume flow rate is $\dot{V}_f$.

The volume concentration c_1 at time t_1 after the leak commenced is

$$c_1 = \frac{\dot{V}_1}{\dot{V}_f + \dot{V}_1}\left(1 - e^{-\frac{\dot{V}_f + \dot{V}_1}{V} t_1}\right)$$

At time $t_1 + t_2$ after all gas has leaked the volume concentration c_2 is

$$c_2 = \frac{\dot{V}_2}{\dot{V}_f + \dot{V}_2} + \left(c_1 - \frac{\dot{V}_2}{\dot{V}_f + \dot{V}_2} \right) e^{-\frac{\dot{V}_f + \dot{V}_2}{V} t_2}$$

After time $t_1 + t_2$ and at a time t after the initial leak, the volume concentration c decays following

$$c = c_2 e^{-\frac{\dot{V}_f}{V}(t - t_1 - t_2)}$$

The maximum volume concentration of gas is the greater of c_1 or c_2.