FIREBALL
A Brief Report on Pilot Experiments to Measure the Insurance Risk of Hydrocarbon Refrigerants in Motor Cars

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Abstract

Hydrocarbon refrigerants have economic, environmental and performance advantages over nonflammable refrigerants. The Mobile Air Conditioning Society claims flammability too dangerous for hydrocarbons to replace R12 in car air-conditioners.

This report describes four ignition tests. The results, hydrocarbon data and crude assumptions about accident statistics allow estimation of the increase in insurance risk due to replacing R12 with hydrocarbons. Replacing R12 with hydrocarbons decreases the insurance risk by about $2 per operating year.

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1   Introduction

The advantages of saturated hydrocarbon (alkane) refrigerants such as 67% propane/33% butane by mass as a replacement for R12 in car air-conditioning are (Maclaine-cross 1993):

1. Their ozone depletion potential is zero.

2. In quantity they cost only 2$/kg and their low density means that only 40% of the mass is required compared to R12 or R134a. For a medium sized Australian car the charge of hydrocarbon is about 300 g the same as a large aerosol can.

3. Propane and butane are non-polar and so completely compatible with R12, its lubricants and desiccants. R12 lubricants and desiccants are cheaper than those for R134a but in any case they do not need to be replaced. My estimate is $50 to change to propane/butane but $200 to change to R134a.

4. Propane and butane occur naturally in petroleum deposits and so the energy consumption and byproducts of their manufacture are minimal. They are the least polluting refrigerants.

5. Hydrocarbon increases cooling capacity by typically 10% compared with R12 (Maclaine-cross 1993). Recent refrigerant data (Gallagher *et al.* 1993) suggests a reduction in energy consumption by the car air-conditioning of 5%. Measurements on energy consumption would require considerable funding. This data also suggests energy savings would be about 5% greater again with cyclopropane or if the air-conditioner was designed to take advantage of hydrocarbon refrigerants.

6. The 500 g saving in refrigerant mass using hydrocarbons gives a vehicle fuel and pollution saving additional to that from superiority in refrigerant properties.

7. It has fewer toxic combustion products than R12. Technicians may be injured or killed by leaking R12 because it is unodorized, they are welding or brazing and some of its combustion products are toxic. Hydrocarbons have fewer toxic combustion products than hydrofluorocarbons like R134a also.

For the consumer the only disadvantage of hydrocarbon refrigerants is that their vapour is flammable when mixed with air. The two aspects to this disadvantage are risks in servicing and risks in operating the motor vehicle. The risks and precautions in servicing are similar to those with LPG used as transport fuel which are well known (Katz and Lee 1990) and require no research. The mass of refrigerant is only 1% of that in a fuel tank so the risk is correspondingly reduced. A prudent insurer would inquire about the total quantity of flammable material being held on site by any automotive business and require compliance with AS 1596–1989.

People consider it foolish not to fly because airliners crash or to only ride bicycles because car drivers die in collisions. The risks and benefits must be assessed for any decision. This applies also to using flammable refrigerant in car air-conditioners.

The risk of creating and igniting a flammable mixture of hydrocarbon refrigerant in operating the motor vehicle has been claimed very high (Keebler 1993, MACS 1993). The claims imply such accidents will cause great personal injury and property damage. My students, colleagues and I have been unable to locate any reports of test results or accident statistics which support these claims despite an estimate that 50,000 vehicles are using flammable refrigerants in the US (Keebler 1993) and US bans on flammable refrigerants as early as the 1950's (MACS 1993). We would appreciate any help in locating such literature. The fact that a proposition is widely believed is not evidence of its scientific truth.

Table 1: Data on the fire and explosion hazard of hydrocarbon refrigerants.

Code	Name	Density liquid	Flammability limits by vol.	Autoignition temperature
R290	propane	560 kg/m^3	2.1% to 9.6%	494–549°C
RC270	cyclopropane	677 kg/m^3	2.4% to 10.4%	
R600	n-butane	624 kg/m^3	1.8% to 8.6%	482–538°C
0.67R290/0.33R600 by mass			2.0% to 9.3%	

Four simple preliminary tests have been made to allow calculation of the probability of refrigerant ignition:

1. by engine in normal operation;

2. in passenger compartment;

3. of refrigerant jet;

4. on puncture of refrigerant container.

The operational risk claims can be divided into a number of scenarios:

1. Leaks;

2. Fatigue fracture of circuit in operation with loss of refrigerant;

3. Frontal collision puncturing circuit with loss of refrigerant.

I assume the owner holds both comprehensive and third party injury cover as usual in Australia. The last scenarios are high probability accidents and the insurer bears the cost of replacing the refrigerant. The increased cost of nonflammable R12 compares with the increased cost of damage and injury by fire using flammable alkane in all scenarios. If the increased cost is greater, flammable refrigerant reduces insurer risk.

2   Ignition Tests

The following tests could be readily repeated by any professional engineer familiar with the relevant product safety data sheets.

2.1   On engine

On the 18th December 1993 at 5:39 p.m., I drove my 5-door KE Laser (PGV496) around the block. The air temperature was 29.5°C. I then took a Taymar butane welding torch ignited it and blew it out. The torch then resembled a large flammable refrigerant leak. I played the torch all over the engine, the ignition, the carburettor, the exhaust and catalytic converter using 150 g of butane. I was not able to reignite the torch from any part of the engine.

Table 1 shows that about 500°C is required to ignite a flammable mixture of butane. An electric arc or fusion is the only possible ignition source. Modern spark plug leads have plug terminal insulators which prevent a spark from a loose lead. All electrical faults except a direct electrical short across the battery will cause the failure of fuses inside the passenger compartment. A direct electrical short across the battery would cause failure in a day and could only exist for a short period in a car's life. A collision is necessary to create ignition sources in a modern engine.

2.2   In passenger compartment

OZ-12 is a commercial propane/butane mix sold as a replacement for R12 in the US and now banned in many states. Keebler (1993) described an experiment by the International Association of Arson Investigators (IAAI). They introduced 150 g of OZ-12 into a vehicle interior and artificially ignited it. The resulting pressure rise blew the windows out of the car. Cockroach bombs have a propane/butane hydrocarbon propellant. There has been at least one ignition accident in Australia with property damage from failure to follow the dosage instructions and avoid ignition sources. Neither of these scenarios is credible for a car but are related to the following.

Car air-conditioning has an evaporator and sometimes a control valve in the passenger compartment behind the dashboard. These are nearly always on the passenger side to avoid the steering mechanism and controls. A rapid leak from a fatigue fracture occurring just before garaging the car would result in a passenger compartment filled with refrigerant. If after an hour, a driver entered the vehicle with a cigarette would this ignite the flammable mixture?

On the 25th December 1993, I wound down the windows of my MF Barina (SCK302) and sealed them with plastic sheet and adhesive tape. The car was completely sealed except for the air-conditioning vent with lights and ignition off. The temperature in the garage was 26.0 °C. At 2:41 pm, a 150 g Mortein Roach Bomb was triggered on the front passenger's seat and the door closed. At 2:44 pm the spray finished. I lighted a cigar and entered the driver's side door at 2:45 pm. No flame, ignition or explosion occurred even when the cigar was waved near the floor and over the back seat.

The active constituents of the bomb, 10 g/kg Permethrin 25:75 and 6 g/kg Phenoxycarb, do not effect the flammability of the hydrocarbon propellant. A Barina is a small car and 150 g will produce a flammable mixture. Propane and butane are however significantly heavier than air so when the driver's door is opened the flammable mixture exits at the bottom and fresh air enters at the top. The propane and butane remaining in the compartment are insufficient to create a flammable mixture.

2.3   On refrigerant jet

The orifice at the top of a cockroach bomb represents a small leak that might occur in an accident situation. The total charge of the cockroach bomb discharges through such an orifice in about 3 minutes so a 300 g refrigerant charge would take 6 minutes.

On the 15th January 1994 at about 5:30 pm, the temperature in a sheltered outdoor position for the experiment was about 21.2°C. I held the bomb and discharged it horizontally at chest height. A lighted match was raised underneath the jet about 100 mm from the orifice. The jet ignited when the match flame touched its lower edge. The jet flame blew out when the match flame was removed. If the match flame was raised into the jet, the match was extinguished.

Chemical engineering (Bird, Stewart and Lightfoot 1960) shows that before ignition, a flammable mixture exists in a layer around the outside of the jet. The high velocity of the jet causes rapid mixing with air into a nonflammable mixture. The flame velocity for propane and butane in air at atmospheric pressure is between about 0.1 and 0.5 m/s (Ward 1978). The experimental observations are consistent with this data. From this experiment and data, I draw two conclusions. An ignition source which is temporary, like a spark, would ignite a small fraction of the refrigerant amplifying the effective size of the spark. Ignition will occur only if the ignition source is precisely located relative to the spray.

2.4   On puncturing container

Rapid plastic deformation and friction can create temperatures sufficient for local ignition. Whether this will ignite the refrigerant can be determined experimentally.

On the 15th January 1994 at 4:51 pm, the temperature in a sheltered outdoor position for the experiment was about 21.2°C. A 150 g Mortein Roach Bomb was placed on its side between two bricks. A crowbar was rammed through it, severing it half way around its circumference. The bomb emptied in about 0.5 s. No flame, ignition or explosion occurred.

At 6:00 p.m. another 150 g Mortein Roach Bomb was placed on its side between two bricks. A crowbar was rammed into it making a jagged 10 mm by 5 mm hole. The bomb emptied in about 3 s. No flame, ignition or explosion occurred.

Considerable force was required to make both holes since the bombs were reinforced by internal pressure. The sudden release of internal pressure by the hole caused the hydrocarbon to spontaneously boil, expanding as a bubbly mixture and then breaking up into a droplet spray. The expansion of the bubbly mixture was responsible for rapidly ejecting the liquid from the bomb. The hydrocarbon temperature after ejection from the bomb would be about -30°C. The velocity of ejection from Bernoulli's principle would be about 40 m/s. The jet creates a small nonflammable hydrocarbon cloud surrounded by a flammable mixture. In the open air, all the ejected hydrocarbon will pass though a flammable mixture stage but the mixture becomes nonflammable due to dilution only seconds after being ejected.

3   Operational Risks

3.1   Leaks

The main sites for leaks in car air-conditioning are the hoses, the joints, the compressor shaft seal and the charging valves. A single leak of 1 mg/s would empty a 300 g refrigerant charge in 3.5 days. The probability of any technician missing a leak larger than this is negligible. It is however too small to support a flame whatever the source of ignition. Such an ignition source would need to be within 10 mm of a leak. Ignition of small leaks is impossible.

3.2   Fatigue fracture

Fatigue is failure of materials under alternating stress. Alternating stress is present while the engine is operating. The heat exchangers are aluminium and the hoses elastomer and both suffer fatigue fracture down to low stress levels. Poor design or installation can result in such fractures. They usually result in leaks which cause total loss of refrigerant in days.

A fatigue fractures occurring in the engine bay during operation may be as common as one in ten thousand operating years. The experiment described in Section 2.1 shows that ignition sources are not usually present and ignition sources are believed present on less than 1% of the vehicle population. The experiments in Sections 2.3 and 2.4 show that the quantity of flammable mixture present from a leak is at any time about 10%. The probability of an ignition source contacting and igniting leaking flammable mixture is estimated as less that one in ten. A flammable mixture might be created and ignited in this manner once in ten million operating years. The damage due to ignition would be less than $1000 on average and it will be assumed to be covered by the policy.

Fatigue failures which cause total discharge of refrigerant in minutes are very uncommon. Fatigue stress levels on passenger compartment equipment are low and only a fraction of the air-conditioning components containing refrigerant are there. Sudden fractures are certainly less common than once in a million operating years into the

passenger compartment. Hydrocarbon refrigerants contain 25 mg/kg ethyl mercaptan. This allows refrigerant to be smelt (van Gemert and Nettenbreiger 1977) at 0.002 of the lower flammability limit. A fatigue fracture causing a sudden major discharge into the passenger compartment would have its flow rate limited by the expansion orifice to below 10 g/s. A non-smoker would have 15 s warning of a flammable mixture to wind down the driver's side window and create a nonflammable situation. Even if all vents were closed, 25 L/s infiltration would create a nonflammable mixture in three minutes.

A smoker may ignore the odour warning and has a source of ignition in hand. Over the whole driving population smoking is equivalent to about one cigarette taking three minutes a day or 0.2% of the time. This implies a fire from this risk once in 500 million operating years with perhaps $100,000 damage on average for each fire.

A fatigue fracture may leak for the first time on garaging the vehicle. 300 g of propane/butane in a small 30 m^3 garage creates a concentration of 0.5% by volume. This is only 25% of the lower flammability limit so a gas explosion is impossible if this leaks into the garage. If it remains in the passenger compartment, there is no ignition source when the vehicle is idle. If the door is opened, Section 2.2 shows ignition is improbable and the potential injury of first degree burns to exposed skin is too small to result in an insurance claim.

3.3   On Collision

Low velocity front collisions create about one insurance claim every ten operating years. About one fifth of these are likely to involve loss of refrigerant in the collision. Another fifth will require the refrigerant to be removed before repairs can commence. These less serious collisions are more expensive to repair if R12 is used because the law requires that R12 be recovered by trained and licensed operators before repairs commence. R12 replacement is estimated at $50 and recovery and later replacement at $100 more than hydrocarbon refrigerant. Conversion to R134a after an accident creates even greater costs.

Section 2.4 shows that ignition is unlikely from fracture of the refrigerant circuit and Section 2.1 that ignition is unlikely from an intact engine. I expect damage to electrical wiring and components to create an ignition source for one in ten accidents. A flammable fraction of the leaking refrigerant might contact such an ignition source one in ten times. Ignition of hydrocarbon refrigerant is expected once in a hundred refrigerant loss accidents. Such fires would frequently add nothing to damage and injury but it will be assumed here to add $1000.

Front to rear collisions rarely occur at sufficient velocity to fracture the fuel tank of the vehicle in front. I will assume that this is once in a thousand operating years. Ignition of hydrocarbon refrigerant is expected once in a hundred such accidents and it will be assumed this ignites the fuel 50% of the time with a major fire. I assume that on average this increases the cost of the accident by $100,000.

4   Insurance Risk Increment

Table 2 summarizes the above assumptions and data. Conversion of R12 air-conditioners to alkane hydrocarbons reduces the insurance risk. This was probably not true ten years ago when the cost premium for nonflammable R12 was less than $3 and no recovery was required. An individual insurance company will have a client base and data which would allow refining of these estimates.

The public may be very interested in whether their air-conditioner will catch fire if flammable refrigerants are used. If such events occur, they will receive great publicity because they are rare. Even if the estimates are considerably in error they will still be a

Table 2: Annual insurance risk increment on conversion of R12 air conditioner to alkane hydrocarbons.

Scenario	Payout Increment	Frequency year^{-1}	Risk Incr. $/year
Engine bay fatigue fire	$1000	1×10^{-7}	+0.0001
Passenger fatigue fire	$100,000	2×10^{-9}	+0.0002
Slow collision fire	$1000	2×10^{-4}	+0.20
Fast front/rear fire	$100,000	5×10^{-6}	+0.50
Slow collision R12 loss	-$50	2×10^{-2}	-1.00
Slow collision R12 recovery	-$100	2×10^{-2}	-2.00
		Total Risk Increment	-2.30

negligible insurance risk. The experiments which measure this risk are however worth repeating because they are cheap.

Collisions are very important in determining insurance risk since they may create a source of ignition and a flammable mixture at the same time. If these are in the same place a fire results. The cause of the fire will not be obvious if the damage is serious. Expensive crash testing is necessary to measure this risk with greater accuracy.

Insurance company records and statistics should contain information for refining the risk estimates. A full-time researcher for one year may be necessary to achieve useful results.

5   Conclusion

Changing from R12 to saturated hydrocarbon refrigerant increases the fire insurance risk but reduces the refrigerant loss and recovery risk. For the assumptions and data used here, hydrocarbons reduce insurance risk by $2.30/year. Further research and tests which are considered desirable may change this conclusion.

Two precautions assumed are that the hydrocarbon refrigerant has been odorized with 25 mg/kg ethyl mercaptan and that drivers are instructed to wind down their window completely to remove the odour if it appears.

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